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# DISTRIBUTION OF PRECIPITATION WITH ELEVATION

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# CONTENTS

PAGE NO.

LIST OF FIGURES i

LIST OF TABLES ii

ABSTRACT iii

1.0 INTRODUCTION 1

2.0 REVIEW 4

2.1 Studies Based on Seasonal and Annual Precipitation 4

2.2 Studies Based on Precipitation Events 11

2.3 Modelling of Orographic Precipitation 15

2.4 Indian Studies on Variation of Precipitation with Elevation 24

3.0 REMARKS 31

3.1 Precipitation Data 32

3.2 Modelling of Orographic Precipitation 32

REFERENCES 34

## LIST OF FIGURES

| FIGURE NO. | TITLE | PAGE NO. |
|---|---|---|
| 1. | Mountain ranges in INdia | 3 |
| 2. | Dependance of Annual Precipitation on elevation | 6 |
| 3. | Graph Showing the residual variance vs filtering window | 7 |
| 4. | Altitude vs average annual rainfall relation | 9 |
| 5. | Seasonal variation in the percentage of rainfall variance explained by geographical parameters | 12 |
| 6. | Correlation of six largest rainfall events at Juneau and concurrent values on Mount Juneau | 14 |
| 7. | Parameters selected by optimal regression analysis of fall precipitation | 17 |
| 8. | Schematic wind flow model for orographic precipitation from approximate model | 19 |
| 9. | Observed and computed orographic precipitation from approximate model | 21 |
| 10. | Generalised chart of one day extreme rainfall over Southern half of Indian peninsula | 26 |

## LIST OF TABLES

| TABLE NO. | TITLE | PAGE NO. |
|---|---|---|
| 1. | Mean annual rainfall and number of rainy days in ten zones over Nigeria | 8 |
| 2. | Correlation of monthly rainfall with altitude in Northern Israel | 10 |
| 3. | Concurrent amounts of rainfall at Mount Juneau and city of Juneau for six largest events at city of Juneau | 14 |
| 4. | Heavy rainfall stations in India | 25 |
| 5. | Seasonal and annual rainfall in the Kathmandu valley | 27 |
| 6. | Variation of precipitation with altitude | 28 |
| 7. | Variation of precipitation with elevation in Beas Catchment | 30 |

# ABSTRACT

Precipitation is known to vary largely in space and time due to several factors such as topography, nature of weather system, geography, aerosol content and drop size distribution in cloud etc. Precipitation is generally believed to increase with elevation. Further, the variation of precipitation with elevation is affected by wind fluctuation, orientation of the hill slope with respect to wind flow. The effect of altitude on precipitation on windward slopes was observed to increase exponentially.

In India, systematic and scientific studies on variation of precipitation with elevation are limited mainly because of lack of sufficient information on the amount of precipitation at higher elevation. This is due to non-availability of automated recording precipitation gauges and problems associated with measurement of precipitation at such higher elevation on a routine basis. In this Technical Note studies on the influence of orography on precipitation and its variation with elevation are reviewed with particular emphasis on the nature of precipitation distribution in Indian mountainous regions.

The review indicated that rainfall in the mountainous areas of western ghats is more as compared to the precipitation at corresponding elevation in the Himalayas. The precipitation increases with elevation upto a certain level and decreases thereafter. The level of maximum varies from place to place depending on local topography. The period of maximum precipitation at higher altitudes is genrally earlier than at foot hills.

Information on the variation of precipitation with elevation would be useful in determining the net increase in precipitation due to elevation, thereby helping in the estimation of PMP for mountainous catchments.

## 1.0 INTRODUCTION

Precipitation occuring in the higher reaches of the Indian catchments either in the form of snow or rainfall largely determines the streamflow and water availability in these catchments. Though floods due to snowmelt are relatively less in India, flash floods due to heavy down pour at higher elevations is a common feature.

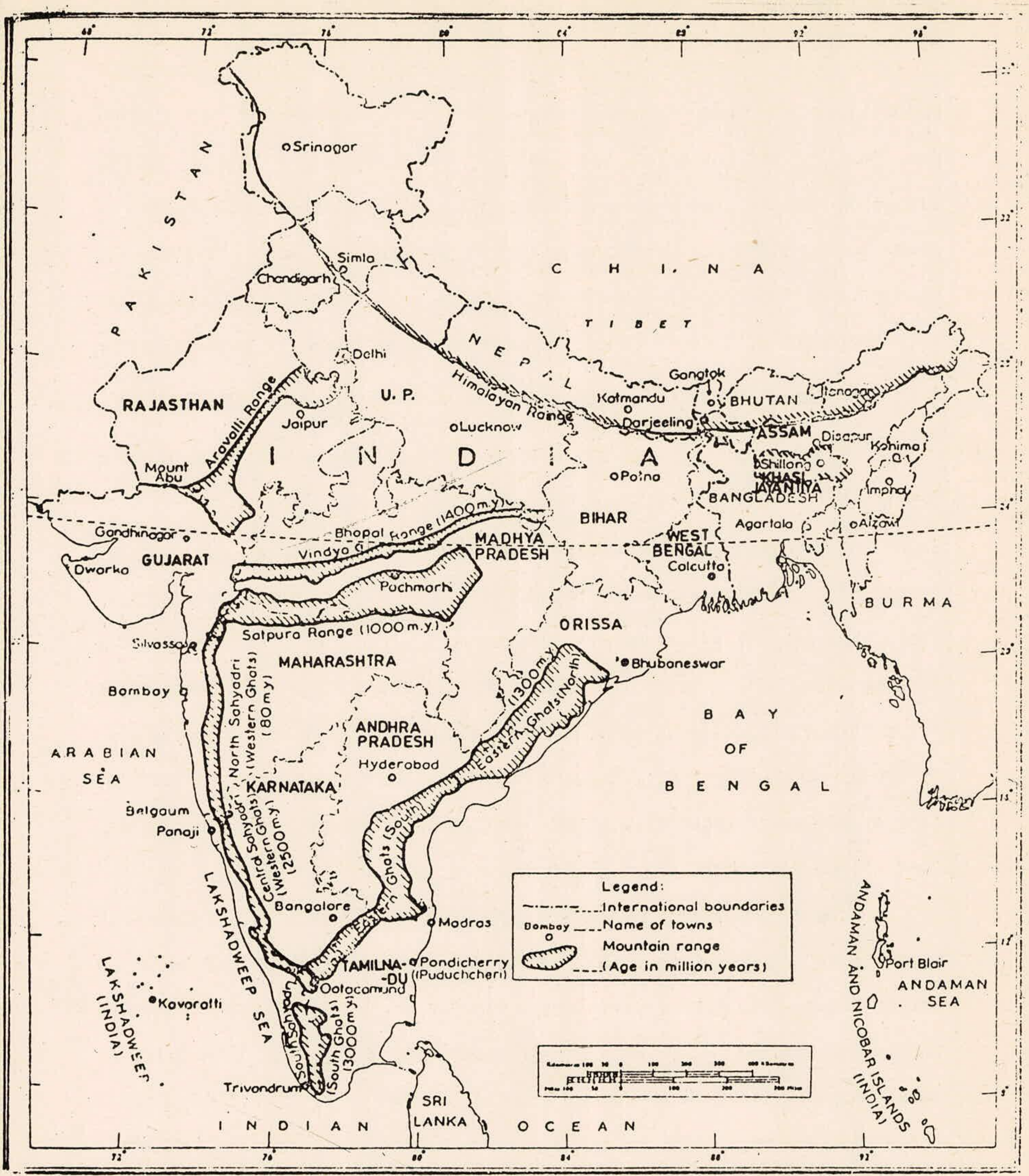
Nearly 35% of the geographical area in India is mountainous. Of these nearly 58% is accounted for by the mighty Himalayas extending from northwest to east. Besides, the Khasi and Jayantiya hills in the northeast, the Vindhya and Satpura hills in central India, the western ghats running all along the west coast from Maharashtra to Kerala and the broken hill ranges of eastern ghats largely determine and guide the country's rainfall pattern during the summer as well as winter. Isolated hillranges like the Aravalis and Nilgiris also influence the rainfall occurrence in those areas. In figure 1 the topographic map of India is presented.

Precipitation has been known to increase with elevation. The variation of precipitation amount with elevation is, however, markedly affected by the wind fluctuations. Other controlling factors being constant, the gradient of precipitation is dependent on not only the wind speeds but also the orientation of the hill ranges with respect to the prevailing wind direction which are the carriers of moist air.

Long before data from higher elevations became available the predominant influence of orography on precipitation was known more in a qualitative and subjective way. Some information on the precipitation occurrence also became available from expedition members to Himalayas and other high mountains the world over. Systematic scientific studies have, however, been undertaken only after the sixties when recording raingauges were set up with the specific purpose of studying the distribution of precipitation with elevation.

In India, such studies were limited mainly due to lack of the necessary instrumentation and other facilities to undertake such studies. Based on the information available from the raingauges and snow gauges located at higher elevations certain studies were conducted.

In this technical note the studies on the influences of orography on precipitation and its variation with elevation are reviewed with a view to have a better insight into the nature of precipitation distribution in the Indian mountainous catchments and examine the possibility of extending the information to areas where it is lacking.



d upon Survey of India map with the permission
e Surveyor General of India

The territorial waters of India extend into the sea to a distance of twelve nautical miles measured from the appropriate base line.

The boundary of Meghalaya shown on this map is as interpreted from the North-Eastern Areas (Reorganisation) Act, 1971, but has yet to be verified.

Fig. 1. Mountain ranges in India

## 2.0 REVIEW

It is known that the seasonal and annual precipitation amounts in mountainous areas are closely related to the topography of the region. The type of precipitation i.e. rainfall or snow would depend on the elevation and the temperature prevailing at the location of the precipitation gauging station. An increase in the precipitation with elevation may be due to an increase in the number of events, in the amount of precipitation per event or to some extent a combination of both the possibilities.

### 2.1 Studies Based on Seasonal and Annual Precipitation

In one of the most detailed studies of orographic influences on precipitation Spreen (1947) correlated mean seasonal precipitation with such factors as elevation, rise, exposure and orientation for western Colorado. Elevation alone accounted for 30% of the variation in precipitation while all five parameters together explained 85% of the variation. Schermerhorn (1967) based on studies for western Oregon and Washington found that station elevation alone does not explain much of the variation in annual precipitation. Other parameters such as terrain elevation, barrier elevation together with an index of latitude were found to explain most of the variation.

Based on precipitation data observed at a dual gauge network in southwestern Idaho, Hamon (1971) concluded that the weak correlation in precipitation-elevation relationships was due to the loss of catch at the unshielded precipitation guages. By separating the annual precipitation into that resulting from winter frontal systems and summertime airmass convective storms, Hamon noted that winter precipitation increased more than four-fold at the 7000 feet elevation in comparison to that observed at the 4000 feet elevation. In case of summer rainfall, however, even a doubling of the rainfall amount was noticed thereby indicating the possibility of a bias in the analysis based on only annual precipitation.

Engman and Hershfield (1969) reported the average number of days and hours with precipitation increase with elevation in both summer and winter in northeastern Vermount, U.S.A. Hendrick et.al(1978) reported a three-fold increase in the hours of precipitation between 400 and 1200 m elevation at Mt Mansfield, Vermount during the winter (October to May). It has thus been established that at least part of the increase of precipitation with elevation was due to the greater duration of precipitation at higher altitudes. However, the authors also found that about 75% of the increase in precipitation was due to higher intensities when rainfall was occurring at all the elevations. Only 25% of the precipitation increase was due to precipitation occurring at higher elevations when there was no precipitation at the lower elevations.

Komarov et.al (1976) modelled the precipitation over the surface of a mountain river basin Varzob in USSR. Snow cover usually forms over the Varzob river in early December at an elevation of 1000 m, in early November at elevations of 1500 - 2000 m and by end of September at elevations of 3500 m. Computations for the Varzob river basin showed that the dependence of precipitation on elevation can be approximated by the equation.

$$x(H,t) = x(H_0,t)\ 1 + k_2(H-H_0) + k_3(H-H_0)^2 \qquad ......(1)$$

Where x(H,t) is the amount of precipitation at an elevation H and time t; $H_0$ is the elevation at which precipitation must be known from meteorological station observations: $K_2$ and $k_3$ are parameters determined for a given basin or region from precipitation observations. $k_2$ and $k_3$ are determined from mean annual precipitation by minimizing the function

$$f(a,b,c) = \sum_{j=1}^{m} x_j - (aH_j^2 + bH_j + c) \qquad \ldots(2)$$

where $H_j$ is the height of the j th meteorological station; m is the number of such stations and a,b and c are empirical coefficients. Long period data of mean precipitation for the period 1964-68 at 11 meteorological stations has been used whose elevations range from 982 to 2800 m and one station whose elevation is 4000m. The values obtained for $k_2$ and $k_3$ were 0.070 and 0.060 respectively without allowance for the Yak-Archa station with 4000 m elevation and .183 and 0.008 respectively with allowance for the station. Figure 2 shows the computation with and without allowance for the station.

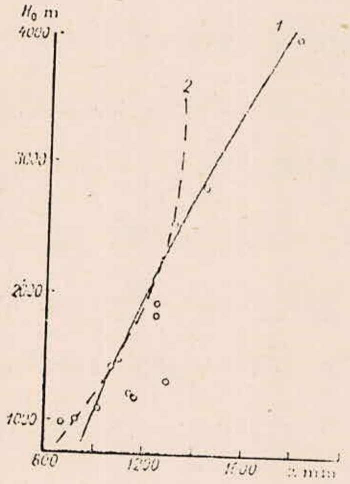


Figure 2 : Dependence of annual precipitation on elevation for $H_0$ = 2650 m (1) with allowance for Yak-Archa and (2) without allowance for the station.

de Montmollin et al (1980) used precipitation data from 45 rain gauges located inside and outside of an area located in the center of French speaking Switzerland. The area is about 1600 sq.km in size and is limited by the Jura mountains, the Alps and the lake of Geneva. The authors attempted to find a relationship between the rainfall and some index of elevation (smoothed altitude in this case) independent of the location of the gauge sites. This relation partly explains the different precipitation values. The residues or the anomalies (difference between observed and calculated values) were interpreted to be local anomalies and calculated by moving window filtering. From the analysis it was found that the residual variances calculated from the different linear regressions between the precipitation and smoothed altitudes decrease gradually upto a filtering window size of 7 km square and increase thereafter. The graph is shown in Figure 3.

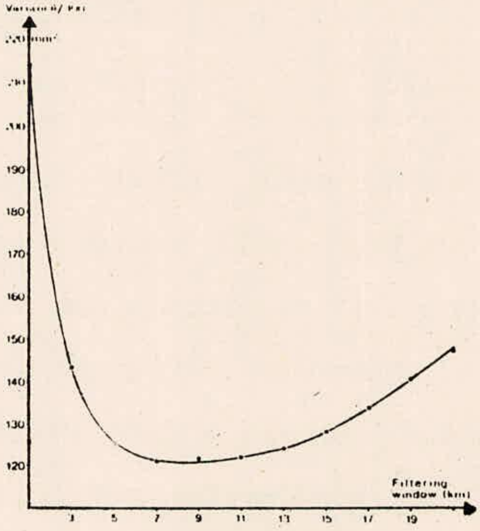


Figure 3 : Graph showing the residual variances vs filtering window

In a study of the variation of the rainfall with altitude in Nigeria, ten zones situated in Nigeria were selected to study the variation of rainfall. The zones were designated on the basis of topography i.e. elevation above mean sea level. The annual mean rainfall received in the different elevation zones together with the annual mean number of rainy days is shown in Table 1.

Table 1 : Mean annual rainfall and number of rainy days

| Zone | Altitude (m) | Mean Annual Rainfall (mm) | Mean Annual No. of Rainy Days |
|---|---|---|---|
| I | 80 | 2150 | 170 |
| II | 80 | 1550 - 2900 | 125 - 190 |
| III | 225 - 305 | 1217 - 1600 | 106 - 151 |
| IV a | 113 - 307 | 1224 - 1800 | 94 - 109 |
| IV b | 150 - 190 | 900 - 1150 | 75 - 90 |
| V | 460 - 2409 | 1400 - 3670 | - |
| VI | 63 - 260 | 1190 - 1320 | 89 101 |
| VII a | 119 - 351 | 710 - 1070 | 58 - 85 |
| VII b | 645 - 1285 | 1281 - 1400 | 108 - 126 |
| VIII | 460 - 750 | 840 - 1085 | 50 - 82 |
| IX | 350 - 415 | 651 - 776 | 62 - 64 |
| X | 325 - 520 | 525 - 600 | 49 - 61 |

Using the average annual rainfall values for more than 6500 stations over the period 1916 - 1950, Bleasdale and Chan (1970) carried out computerised analysis of the distribution of precipitation in the United Kingdom and the influence of orography on precipitation. In the first stage, the computer programme grouped all stations in 50 m bands of height above m.s.l disregarding the geophysical locations and gave print out providing for each 50 m band the number of stations within the band, the mean height for these stations and the mean average annual rainfall for the stations. The results are shown in figure 4. The broad features as may be seen from the figure are the great bias of raingauge locations at lower levels and a near approximation to a straight line.

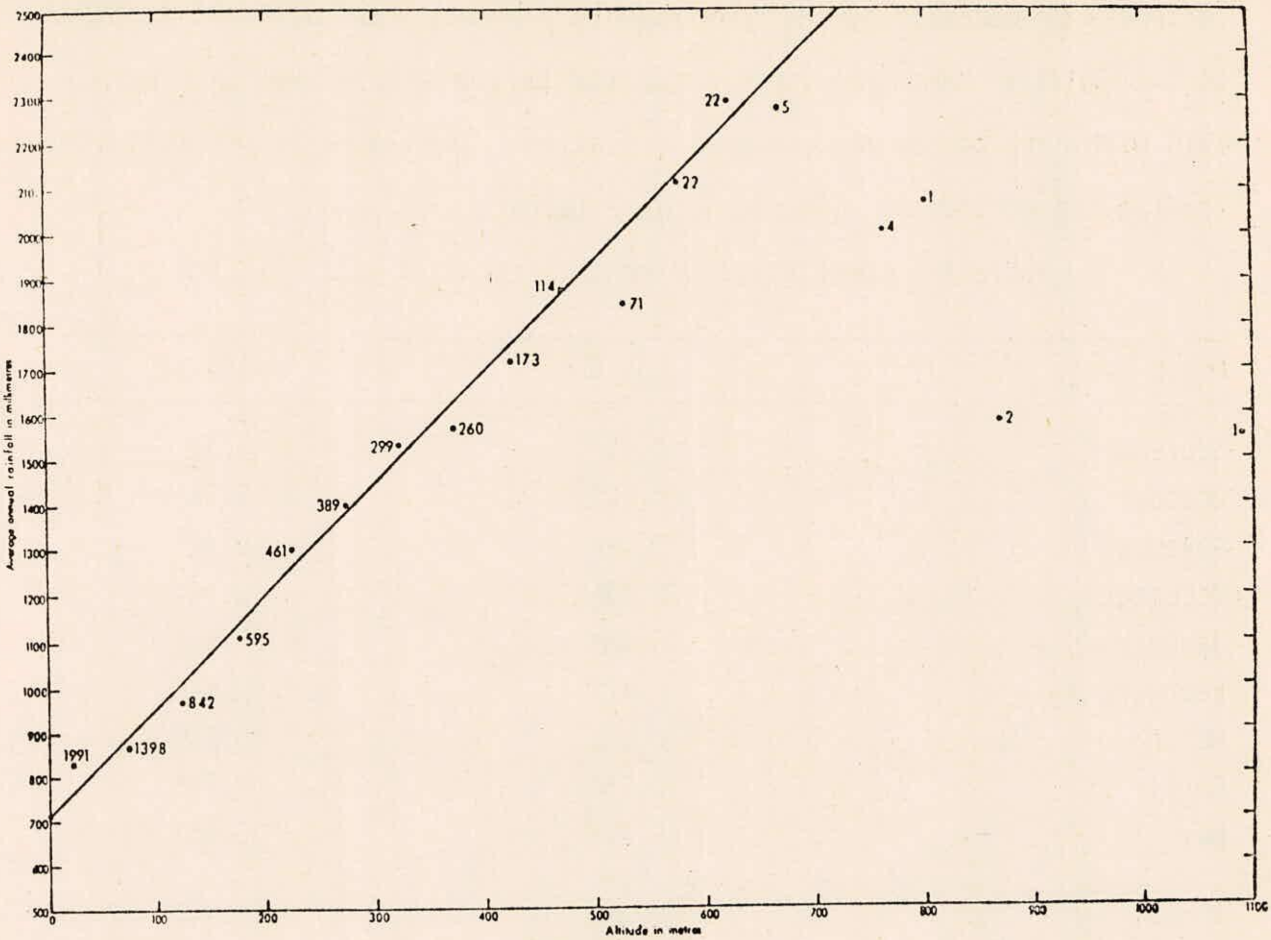


FIG. 4

Computer fitting of a straight line equation of the form $R = a + bH$ regardless of the number of stations contributing to the mean values gave values of 714 mm and 2.42 respectively for a and b as against 700 mm and 2.5 obtained by preliminary fitting by eye. The correlation coefficient was 0.99. In view of the obvious concavity of the line at lower levels, the exercise was repeated with bands of 10 m and 5 m upto 120 m. This confirmed the importance of surface roughness at lower elevations, turbulence in the lowest layers of atmosphere. Further analysis were aimed at isolating secondary influences on precipitation occurrence.

Kutiel (1987) studied the variation of rainfall with elevation in Israel by correlating the mean monthly rainfall from different stations in the Galilee (northern Israel) for the period 1931 - 1960 and 1951 - 1980 with altitude of the respective station. The correlation coefficient for the two periods is given in Table 2 below :

Table 2 : Correlation of monthly rainfall with altitude

| Month | 1931-60 | 1951-80 |
|---|---|---|
| September | 0.03 | 0.19 |
| October | 0.42+ | 0.34 |
| November | 0.49* | 0.48* |
| December | 0.63* | 0.54* |
| January | 0.80* | 0.66* |
| February | 0.82* | 0.81* |
| March | 0.80* | 0.80* |
| April | 0.75* | 0.76* |
| May | 0.70 | 0.55* |
| Annual | 0.78* | 0.73* |

+ Corr. Coeff significant at 5% level

* Corr. Coeff significant at 1% level

The variation of rainfall was expressed in the form of a multiple linear regression equation as in equation (3)

$$R = b_0 + b_1 \text{ Lon} + b_2 \text{ Lat} + b_3 \text{ Alt} \qquad \ldots(3)$$

where R is the mean annual or monthly rainfall,

Lon is the longitude of the station,

Lat is the latitude of the station,

Alt is the altitude of the station,

$b_0$ is the intercept,

$b_1$ is the change of rainfall for $1^0$ longitude change,

$b_2$ is the change of rainfall for $1^0$ latitude change,

$b_3$ is the change of rainfall for 1 m altitude change.

From the study it was conclusively established that rainfall increases with height because of orography. The monthly variation in the percent of variation accounted by altitude is shown in Figure 5.

## 2.2 Studies Based on Precipitation Events

Murphy and Shamach (1966) carried out a comparative study of the concurrent rainfall measurements made during storms at Juneau, Alaska, U.S.A. both at sea level station and a nearby mountain station. Southeastern Alaska is mountainous and extremely glaciated. The topographic relief is in excess of 15000 feet. Precipitation in this area occurs due to frontal systems, orographic effect or combination of both. The Bureau of Reclamation, U.S.A. installed a 60 inches capacity recording raingauge which could run for 60 days unattended at an elevation of 3400 feet on Mount Juneau in 1963. Concurrent with the installation of the recording raingauge on Mount Juneau, a weighing type recording raingauge was also installed on the roof of State Capitol building, Juneau City. The two gauges were separated by a distance of 2.2 air miles. Concurrent recording rainfall data was obtained for varying segments totalling 123 days during 1963 and 1964.

The available data were analysed with the following points in view :

(i) For storms producing large amounts of rainfall over city of Juneau, what were the concurrent rainfall amounts over Mount Juneau.

(ii) In what way the greatest amounts of rainfall recorded at Mount Juneau differ from those observed in Juneau city during the same period ?

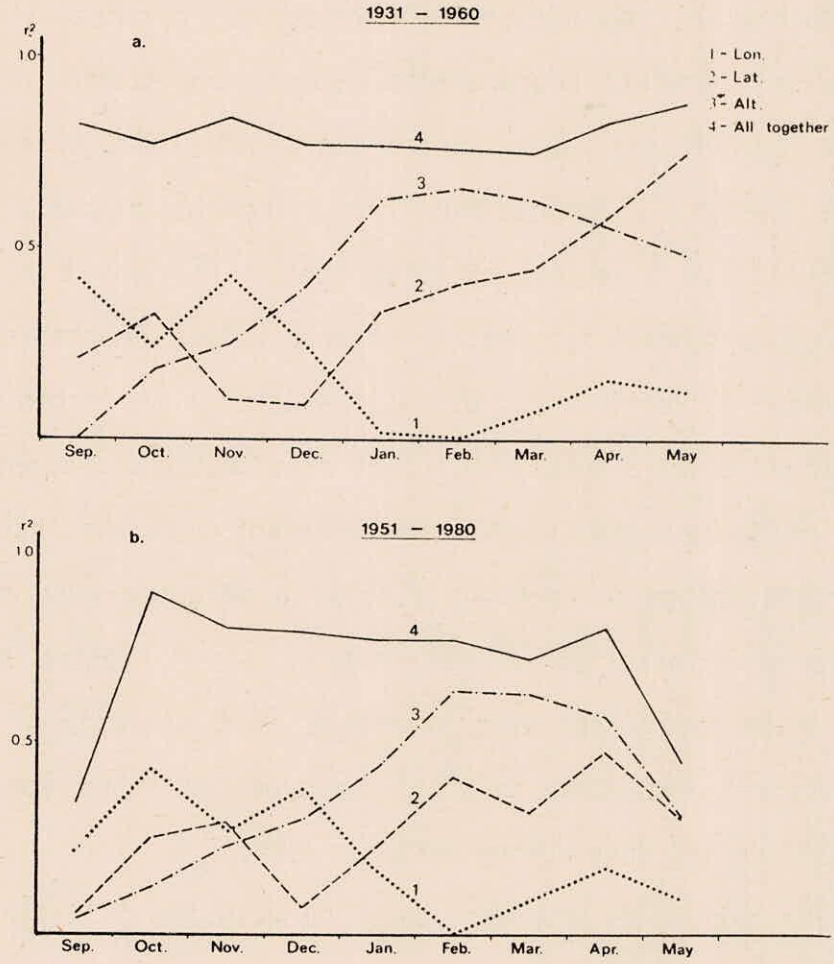


Fig. 5 : The seasonal variation in the percentage of rainfall variance explained by each of the three geographical parameters and by all together for the period (a) 1931-1960, and (b) 1951-1980.

Table 3 shows the six largest amounts of precipitation recorded at the city of Juneau for each duration of 3,6,12, and 24 hours as compared with the concurrent amounts recorded on Mount Juneau. The relationships of these concurrent values are plotted in Figure 6.

Based on the analysis of the limited samples of storms the authors concluded that the greatest amounts observed during 3,6,12, and 24 hours were 2.41, 2.56, 3.15 and 3.27 times higher respectively at Mount Juneau than those observed in the city of Juneau. Concurrent observations of precipitation over 3,6,12, and 24 hours during the severmost spells at Juneau city and Mount of Juneau indicated that the Mount Juneau observations were higher by 3.00, 2.95, 3.43 and 3.23.

Realising the need for individual storm analysis for determining topographic effects, Duckstein et al (1973) investigated the variation of point precipitation with elevation using an event based stochastic model of thunderstorm rainfall and empirical data. Data of summer rainfall which is essentially caused by the airmass convective storms occurring in July, August and September have been considered. The distribution of the number of events per season was assumed to be a Poisson variate while the distribution of point rainfall depths was taken as geometric. The summation of a random number of random variables was used to represent seasonal point precipitation. Assuming the two parameters of the model to increase linearly with elevation, the total seasonal rainfall was found to increase as a quadratic polynomial with elevation. The model was verified using data from cloud seeding experiments designed to investigate the possibility of increasing the thunderstorm rainfall over Santa Catalina Mountains near Tucson, Arizona, U.S.A. From the study it has been concluded that :

Table 3 : Concurrent amounts of rainfall at **Mount Juneau and City of Juneau** for six largest **events at City of Juneau**

| Duration | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 3 hrs | | | 6 hrs | | | 12 hrs | | | 24 hrs | | |
| Date | City of Juneau amount (in.) | Mount Juneau amount (in.) | Date | City of Juneau amount (in.) | Mount Juneau amount (in.) | Date | City of Juneau amount (in.) | Mount Juneau amount (in.) | Date | City of Juneau amount (in.) | Mount Juneau amount (in.) |
| 10–15–63 | 0.50 | 1.50 | 9–29–63 | 0.78 | 1.60 | 9–29–63 | 1.02 | 3.20 | 9–30–63 | 1.67 | 5.40 |
| 9– 7–63 | 0.43 | 0.70 | 10–15–63 | 0.65 | 2.20 | 9–30–63 | 0.90 | 3.50 | 8–25–64 | 1.10 | 3.40 |
| 9– 7–63 | 0.42 | 0.90 | 9–30–63 | 0.63 | 2.30 | 10–10–63 | 0.87 | 1.30 | 10– 1–63 | 0.92 | 3.70 |
| 10– 1–63 | 0.38 | 0.90 | 10– 1–63 | 0.55 | 1.50 | 10–16–63 | 0.85 | 2.90 | 10–16–63 | 1.07 | 4.30 |
| 9–30–63 | 0.32 | 1.30 | 9– 7–63 | 0.55 | 0.90 | 8–28–64 | 0.82 | 3.10 | 10–10–63 | 0.87 | 1.40 |
| 10–10–63 | 0.32 | 0.40 | 10–10–63 | 0.51 | 1.00 | 9– 7–63 | 0.65 | 1.90 | 9– 7–63 | 0.74 | 2.50 |

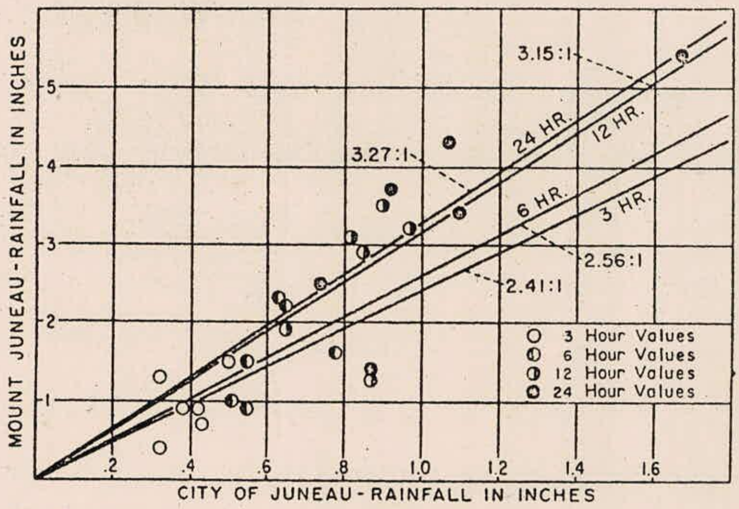


Fig. 6. Correlation of six largest rainfall events at City of Juneau and concurrent values on Mount Juneau (for each duration of 3, 6, 12, and 24 h).

(i) The mean number of events per season increases considerably with elevation.

(ii) The mean amount of rainfall per event increases moderately with elevation.

(iii) The mean total seasonal rainfall increases as a quadratic polynomial with elevation, but a linear approximation was found to be satisfactory.

(iv) The coefficient of variation of the total seasonal rainfall is a decreasing function of elevation.

## 2.3 Modelling of Orographic Precipitation

It is generally recognised that enhancement of precipitation occurs due to the lifting of air as a result of the perturbation caused by the orography leading to cooling, condensation and precipitation of moisture. Bergeron (1965) mentioned that even the modest surface irregularity will increase the precipitation significantly. However, the nature of the orographic precipitation is closely linked with the dynamics of the airflow and micro-physics of the cloud structure. Over uneven terrain other factors like horizontal convergence, convective instability etc. also add to the motion in the vertical thereby influencing the total precipitation.

In 1929, S.K. Banerji was the first to mathematically explore the problem by considering the flow of an incompressible fluid over rigid wall like barriers.

### 2.3.1 Statistical Methods

Optimal regression studies have been carried out in order to relate 12 hour precipitation amounts to circulations on a large scale. Nordo (1973) presented the formula for fall precipitation at the mountain village of Byglandsfjord just east of the mountain divide. Fig. 7

gives a description of the parameters used in the optimal regression.

SE is the sea level pressure difference

S is the sea level pressure difference Ferder minus Utsira

$S_W$ the sea level pressure difference Gvarv minus Bergen

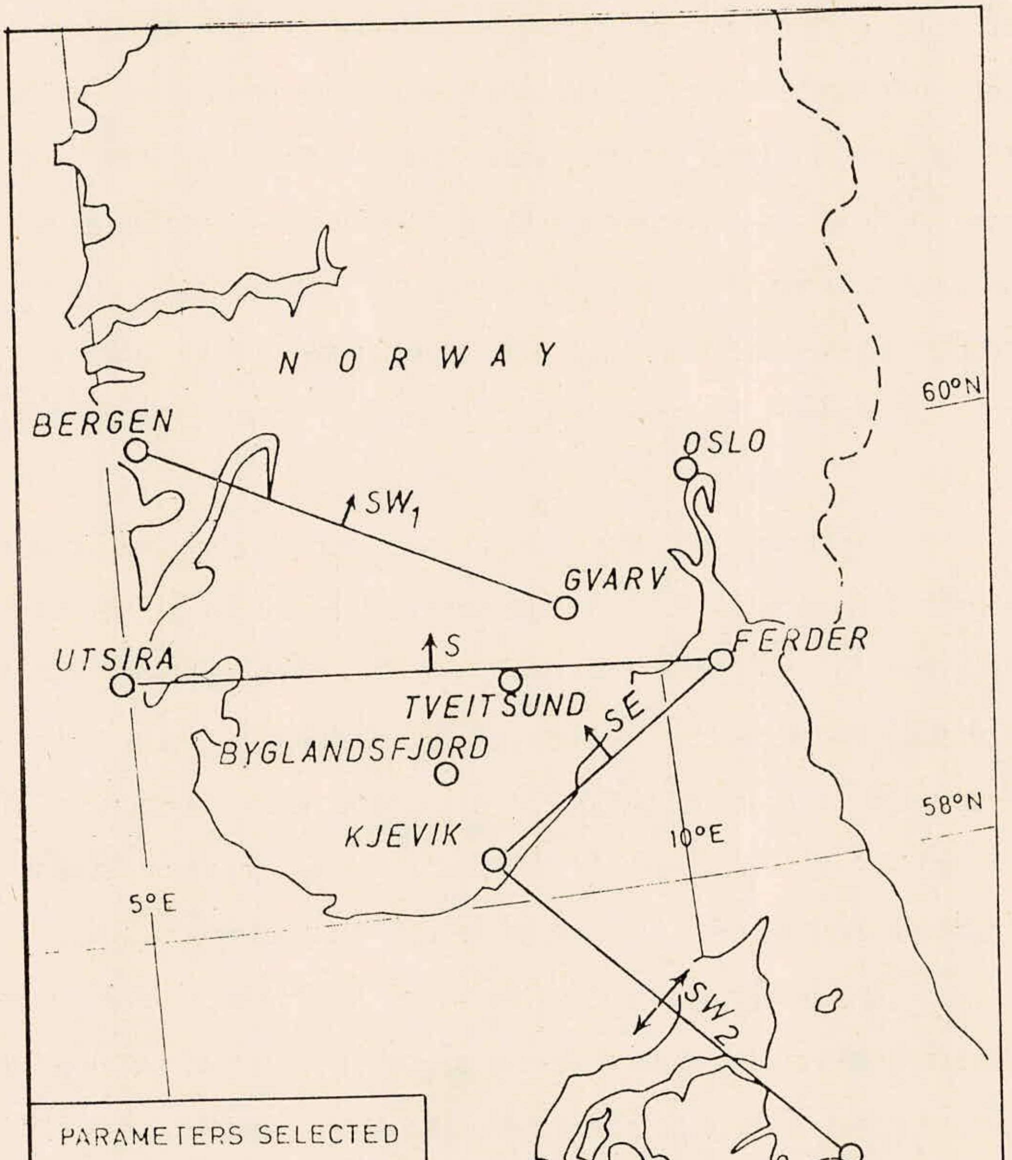
$S_{W2}$ is an alegebraic difference of sea level pressure Fornacs minus Kjerik.

Negative values of SE, S and SW are put equal to zero positive values are kept unchanged. Altogether 455 sets of independent data were used to which 208 were observed. The results are as follows :

| | |
|---|---|
| Observed and Predicted | 171 |
| Observed and not predicted | 37 |
| Total | 208 |

The results indicated that the smoothed envelope of the mountain formations may become a good first order approximation when modelling the orographic effects on a westerly current crossing the rugged mountains of western Scandinavia.

Whitmore (1973) used a semi graphical method of multiple curvilinear regression to derive the relationship between mean annual rainfall and altitude and modifications caused by factors such as aspect, continentality and topographic trend. The study area, South Africa was divided into 5 sub regions to ensure the desired degree of consistency. The author claimed that after only three iterations, an overall accuracy of 20 percent in estimating mean annual precipitation was achieved. The author's assumption that the independent variables used in the multiple regression are really independent (not-correlated) may not hold out as the aspect might be related to the altitude.



PARAMETERS SELECTED BY OPTIMAL REGRESSION ANALYSES OF FALL PRECIPITATION

Figure 7.

### 2.3.2 Dynamic Models

An increase in rainfall amounts over hills of the order of a few hundred metres high is very apparent in certain synoptic situations when compared with rainfall in the adjacent valleys. Bergeron suggested that this enhancement of rainfall was due to the formation of low level, orographically produced clouds which are washed out by raindrops falling from a higher level cloud layer. The low level clouds are formed of droplets large enough to be subsequently removed by precipitation falling from above but too small for independent rain formation. Attempts to demonstrate this low level growth have been made by a number of workers by constructing numerical models (Bader and Roach, 1977 etc.).

The Bader and Roach model was essentially two dimensional, using grid lengths of 100 m in the vertical and 2 km in the horizontal, sufficient to cover the low level cloud. They derived equations to calculate the accretion growth of an individual rain drop falling through the orographic cloud and also, the water content of the low level cloud in each layer of the model, the accretion growth on the rain drops as they fell through each layer was determined.

The orographic model described by Miller (1972) treats the precipitation resulting from forced ascent of moist air over an unbroken mountain ridge as a simplified two dimensional model. The air passing over the mountain would accelerate as the air from deep upwind layer has to pass through a relatively shallow layer at the peak. The model thus, assumed the air to be lifted over the mountain ridge as a laminar flow. A simple diagram of inflow and outflow winds over the mountain barrier as given by Miller is shown in Figure 8.

The model considers the flow of air in a vertical plane at

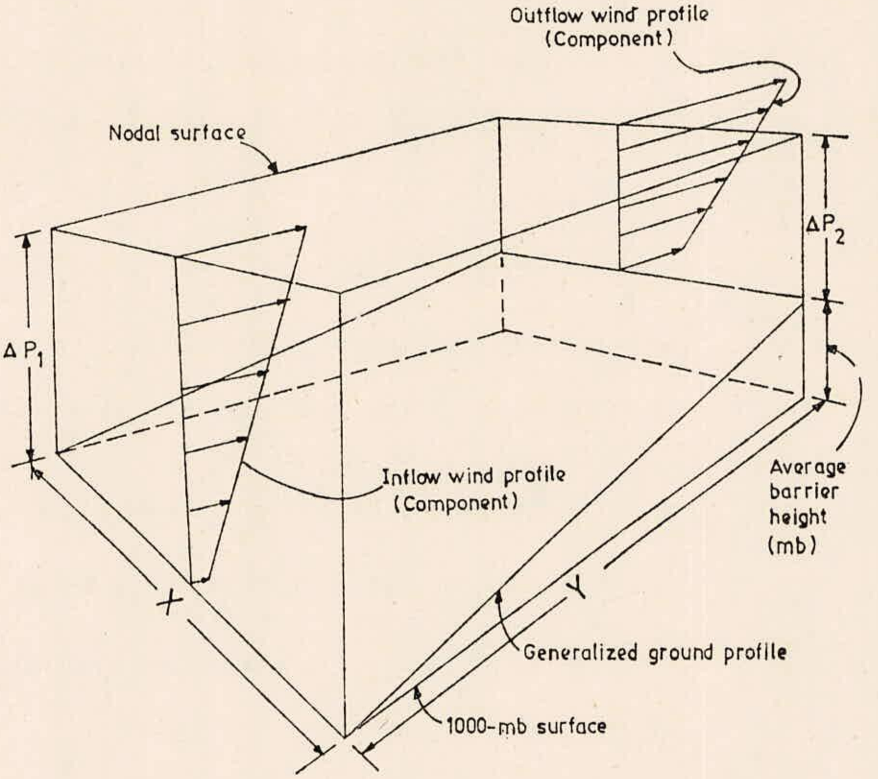


FIGURE 8 - SCHEMATIC WIND-FLOW MODEL FOR OROGRAPHIC PRECIPITATION
(Reproduced from paper of Miller (1972))

Figure - 8

right angles to a mountain chain or ridge. The plane has a Y coordinate in the direction of flow and a Z coordinate in the vertical. The flow may represent an average over a few kilometers of stretch in transverse or X-direction. The wind at ground level is assumed to move along the surface. The slope of the air stream lines above a given point on the mountain slope decreases with height, becoming horizontal at the nodal surface.

The model divides the complete column of air into several layers of flow. The rate of precipitation from each of these layers is given by the equation :

$$R = \frac{\overline{V}_1 p_1 (\overline{q}_1 - \overline{q}_2)}{Y} \quad \frac{1}{g\rho}$$

where $R$ = the rainfall rate in cm/sec

$\overline{V}_1$ = the mean inflow windspeed in cm/sec through the layer

$p_1$ = the thickness of the air in mb at inflow

$\overline{q}_1$ = the mean specific humidity in g/kg at inflow

$\overline{q}_2$ = the mean specific humidity in g/kg at outflow

$\rho$ = the density of water in g/sec

$Y$ = the horizontal distance in cm.

A dynamic model for orographic rainfall with particular reference to the Bombay - Poona region in the Western ghats was developed by Sarkar (1967). The model was based on steady state, two dimensional linearised equation and a saturated atmosphere with pseudo adiabatic lapse rate. Vertical velocities were computed analytically.

From a given characteristic of the air stream on the windward side, the terrain induced vertical velocity was computed from the equation

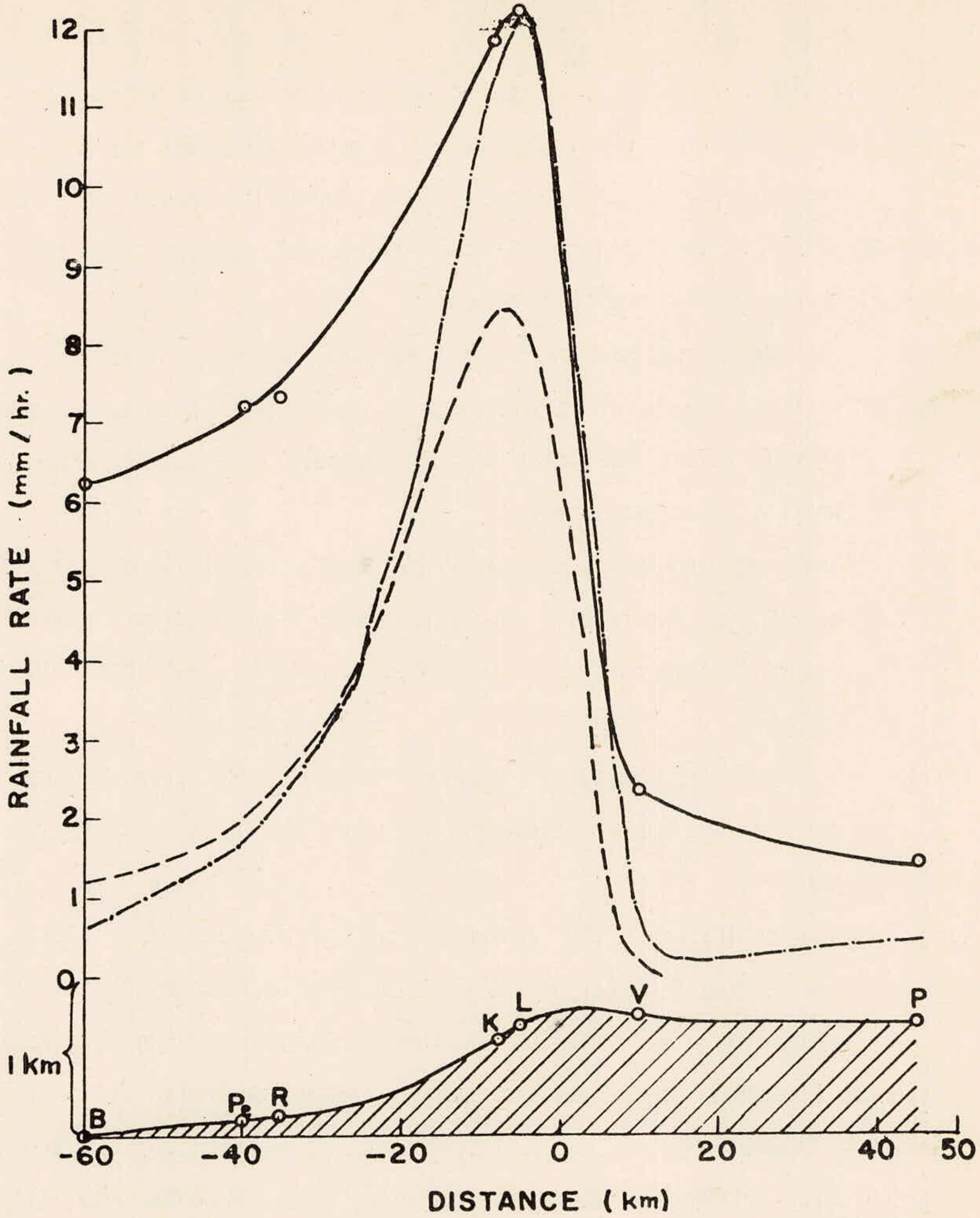


Fig. 9 Observed (upper solid curve), computed orographic from the approximate model (dashed curve) and computed orographic from the modified model (dashed-dotted curve) rainfall distribution for July 5, 1961 along the orographic profile (shaded) from the coast at Bombay (B) inland through Pen (Pe), Roha (R), Khandala (K), Lonavla (L), Vadgaon (V), and Poona (P). (Sarker, 1967).

$$\frac{\partial^2 W}{\partial x^2} + \frac{\partial^2 W}{\partial z^2} + f(z)W = 0 \qquad \ldots (5)$$

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.

The distribution of computed rainfall intensity showed reasonable agreement with the distribution of observed rainfall (Fig.9). Other important conclusions of the study were :

(i) The model computed orographic rainfall increase from West Coast to inland along the slope of the ghats and reached a maximum before the crest of the mountain was reached after which it decreased sharply.

(ii) The contribution of orography to coastal rainfall was only about 20% indirectly suggesting that the observed heavy rainfall along the coast is caused largely by synoptic scale convergence.

(iii) The observed maximum in rainfall close to the peak of the mountain was almost completely accounted for by the orographic model.

(iv) The rainfall on the windward side originates from levels below about 5 km but on the lee-side from above that level.

Sinha Ray et al (1982) had studied the contribution of orography on the total rainfall in the western ghats and Khasi-Jayantiya hills of Assam. An attempt was made 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.

Hobbs et al (1975) had carried out a detailed analysis of orographically enhanced rain over the cascade mountains in the western

Washington state of U.S.A. Direct measurements of the wind field and inference based on the shape of the frontal cloud indicated that as the front approached the mountain the horizontal winds aloft were faster than the average velocity of the front while the lower level winds were considerably slower. The authors attributed the slowing of the low level winds due to the friction caused by local small scale topography.

Marwitz(1980) described the type of orographic precipitation obtained in the San Juan mountains in south west Colorado, USA where orographic rain was said to be usually associated with the approach of the baroclinic zone. As the zone approached, the air was stably stratified and the low level flow as entirely blocked by mountain. During this time, cold air advection occurred aloft and after several hours when air upstream of the mountain has been stablilised precipitation was produced in large parts by embedded convection in a deep layer of cloud.

Smith (1982) proposed a orographic model in which the blocking of low level air by a mountain has caused approaching cold air to override the warm air, producing an unstable layer upstream of the mountain. Smith concluded that under some conditions it was the blocking action of the mountain rather than the forced ascent which causes the enhanced precipitation.

Porch and Mechrez (1984) had studied the combined effect of wind and topography on rainfall distribution analytically and numerically. A general solution for the trajectories of the raindrops in two dimensional equilibrium flows in terms of the stream function describing the wind motion was presented. Though the model could not predict the distribution of rainfall as it has occurred in nature, the analysis was used to demonstrate the basic features of the combined effect of wind and topography.

## 2.4 Indian Studies on Variation of Precipitation with Elevation

In tropical regions like India,the type of precipitation,its intensity and the areal distribution are largely controlled by the elevation and the direction of prevailing winds which vary with season and also show aberrations within a season. Almost all the rivers of India carry heavy discharges during the monsoons when their catchments receive intense and heavy rainfall. Rainfall is abundant along the western ghats and hills of northeast India where upslope winds prevail. Rainfall in 3 hour and 6 hour duration can be as much as 60 and 75 per cent respectively of the 24 hours rainfall.

Heavy rainfall due to orographic effect is confined to the western ghats and the Khasi and Jayantiya hills of Assam. The heavy rainfall over the Western slopes of Western ghats feeds the west flowing mountain streams whereas the floods due to heavy rainfall in the higher reaches on the eastern slopes of western ghats are generally moderated by the reservoirs in the foot hills.

Dhar et al (1978) carried out a study of the heavy rainfall stations in India. For the purpose of the study stations having a mean annual rainfall of 500 cm were considered as heavy rainfall stations. In Table 4 stations receiving more than 500 cm of annual rainfall together with their elevation and mean annual rainfall are presented.

It may be seen from the table 4 that 10 of the heavy rainfall stations lie in the western ghats and the rest are located in the hills of northeast India. There are, however, none in the Himalayan region. There are some stations in the Darjeeling hills with short period means over 500 cm which are not included in the table. During the onset of southwest monsoon the moisture laden monsoon winds first approach the western ghats and the Khasi-Jayantiya hills and precipitate most of the moisture over these regions. By the time they approach the Himalayan regions much of the moisture is lost and,therefore,the less rainfall in this area. In the case of highest one day rainfall,while Cherrapunji, Jowai and Mawsynram had 103.6,101.9 and 99.0 cm respectively,Dharampur a plain station on the west coast in Gujarat received 98.7 cm.

Table 4 : Heavy Rainfall Station in India

| Station | State | Eleva-.tion (m) | Mean Annual Rainfall (cm) | Period of Record |
|---|---|---|---|---|
| Agumbe | Karnataka | 659 | 847 | 1952-1970 |
| Amboli | Maharastra | – | 747 | 1934-1951 |
| Bhagamandala | Karnataka | 876 | 596 | 1907-1970 |
| Buxa | West Bengal | – | 532 | 1891-1968 |
| Cherrapunji | Meghalaya | 1313 | 1102 | 1902-1975 |
| Denning | **Arun.Pradesh** | 698 | 528 | 1929-1949 |
| Gaganbawda | Maharastra | 690 | 596 | 1901-1974 |
| Mahabaleswar | Maharastra | 1382 | 630 | 1891-1976 |
| Makut | Karnataka | – | 517 | 1933-1974 |
| Matheran | Maharastra | 695 | 534 | 1892-1974 |
| Mawsynram | Meghalaya | 1401 | 1221 | 1941-1969 |
| Neriamangalam | Kerala | – | 504 | 1940-1973 |
| Peermade | Kerala | – | 500 | 1901-1970 |
| Pulingoth | Karnataka | 919 | 588 | 1933-1967 |

Dhar and his associates prepared the one day PMP charts for India based on the Hershfield's technique. The map for the peninsular region (Dhar et al,1980) is given in Figure 10. It may be seen from the figure that the PMP values over the westrern ghats exceed 45 cm.

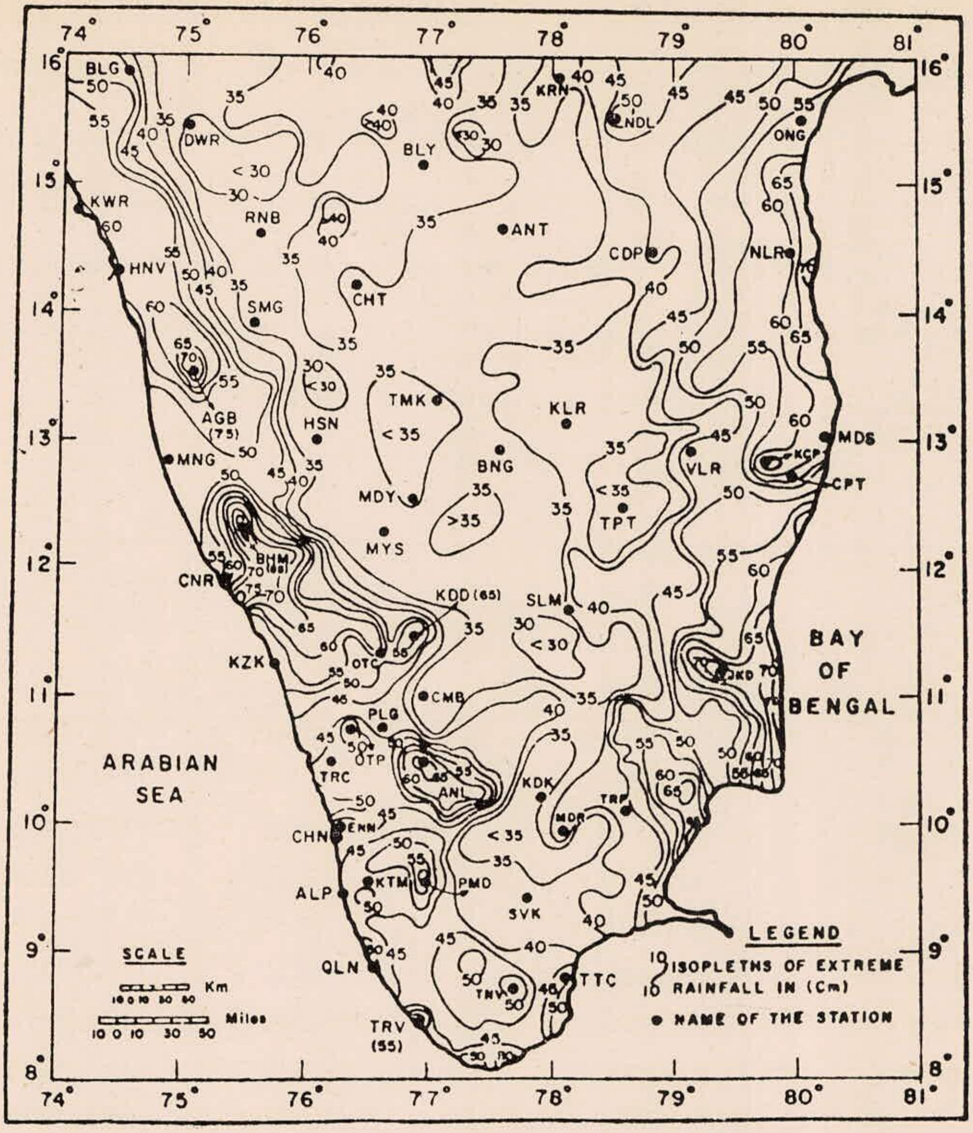


Figure 10 Generalized chart of one-day extreme rainfall (in cm) over southern half of Indian peninsula (Lat. 8° N to 16° N).

*O N Dhar, A K Kulkarni and P R Rakhecha*,

Dhar and Bhattacharya (1976) made a study on the variation of precipitation with elevation in the central Himalayas. A relationship between precipitation and elevation was obtained for the central Himalayas using 15 to 20 years' data of more than 50 stations in this region of the Himalayas. Variation of rainfall with the elevation showed that there are two zones of maximum precipitation. One near the foot of the Himalayas and other at an elevation of 2.0 to 2.4 km. For higher elevations beyond 2.4 km the precipitation decreases sharply as one moves across the central Himalayas.

Nagara (1981) carried out an analysis of areal rainfall in the Khatmandu valley. The Khatmandu valley lies in the hilly region of Nepal where a number of mountain ranges extend generally west to east parallel to the great Himalayan range. The most prominent peaks rising from the valley are Sheopuri(2689 m) in the north and Phulchowki(3132 m)in the south. Based on the data for the period 1971-76 for a few stations in the valley, the variation of precipitation with elevation has been studied. The seasonal and annual rainfall together with the elevation are given in Table 5.

Table 5: Seasonal and Annual Rainfall in the Kathmandu Valley

| Station | Elevation | Nov-Feb mm | Mar-May mm | Jun-Sep mm | October mm | Annual mm |
|---|---|---|---|---|---|---|
| Bhaktapur | 1350 | 48.5 | 222.8 | 1231.4 | 86.2 | 1588.9 |
| Godavari | 1400 | 50.0 | 219.3 | 1717.5 | 88.5 | 2075.3 |
| Indian Embassy | 1324 | 44.2 | 220.2 | 1249.3 | 67.8 | 1581.6 |
| Kokani | 2064 | 45.5 | 295.6 | 2428.4 | 139.4 | 2908.9 |
| Khumaltar | 1350 | 44.3 | 173.0 | 974.3 | 65.4 | 1257.0 |
| Nagarkot | 2150 | 54.9 | 266.0 | 1950.4 | 124.6 | 2395.9 |
| Saankhu | 1463 | 50.8 | 231.6 | 1652.8 | 109.0 | 2044.2 |
| Sundarijal | 1576 | 53.9 | 280.9 | 1887.8 | 91.2 | 2313.8 |
| Thankot | 1630 | 57.6 | 297.9 | 1744.2 | 103.0 | 2202.7 |
| Tokha | 1790 | 50.5 | 303.4 | 2150.1 | 73.7 | 2577.7 |
| Tribhuvan Intl.Airport | 1336 | 43.7 | 189.6 | 1155.0 | 65.1 | 1453.1 |

From the above table it may be seen that rainfall does increase with elevation though not in a systematic way as revealed by the seasonal and annual rainfall values at Kokani,Nagarkot,Thankot and Tokha.

Upadhyaya and Bahadur (1982) carried out a study of the variation of precipitation in Himalayas. The Himalayas Mountain system was conceived to be constituted of three parallel longitudinal ranges.

(i) The outer Himalayas or Shiwalik ranges with height from 1000-1300 m and width from 10 to 50 kms.

(ii) The lesser or middle Himalayas with height ranging from 2000-3300 and width between 60 to 80 kms.

(iii) The greater Himalayas with average height of 6100 m and average width of about 200 km.

Table 6 : Variation of Precipitation with Altitude

| Station | Latitude (N) | Longitude (E) | Height (m) | Annual Precipitation (cms) |
|---|---|---|---|---|
| | | Kangra valley | | |
| Dehra | 31°50′ | 76°13′ | 436 | 131.8 |
| Kangra | 32°06′ | 76°15′ | 733 | 196.6 |
| Palampur | 32°7′ | 76°32′ | 1250 | 263.7 |
| Dharamsala | 32°13′ | 76°19′ | 1387 | 300.9 |
| | | Doon Valley | | |
| Ambari | 30°30′ | 77°49′ | 489 | 183.7 |
| Dehradun | 30°19′ | 78°02′ | 679 | 207.5 |
| Raipur | 30°18′ | 78°05′ | 750 | 209.7 |
| Rajpur | 30°24′ | 78°05′ | 914 | 300.7 |
| Mussoorie | 30°27′ | 78°05′ | 2042 | 247.0 |
| | | Almora Hills | | |
| Almora | 29°36′ | 79°40′ | 1572 | 105.4 |
| Ranikhet | 29°38′ | 79°26′ | 1810 | 133.7 |
| Mukteshwar | 29°28′ | 79°39′ | 2311 | 132.5 |
| | | Nainital | | |
| Haldwani | 29°13′ | 79°31′ | 440 | 199.5 |
| Kathgodam | 29°17′ | 79°32′ | 513 | 209.2 |
| Nainital | 29°23′ | 79°27′ | 1934 | 253.9 |
| | | Joshimath | | |
| Karanoparyag | 30°16′ | 79°15′ | 769 | 142.3 |
| Ukhimath | 30°30′ | 79°15′ | 1220 | 201.1 |
| Birangkhal | 30°15′ | 69°15′ | 1520 | 122.8 |
| Joshimath | 30°33′ | 79°35′ | 1840 | 95.4 |
| | | Kulu & Lahaul Valley | | |
| Kulu | 31°57′ | 77°7′ | 1215 | 100.6 |
| Benjar | 31°38′ | 77°20′ | 1524 | 110.6 |
| Kathoi | 31°18′ | 77°32′ | 1608 | 101.2 |

| Station | Latitude (N) | Longitude (E) | Height (m) | Annual precipitation (cms) |
|---|---|---|---|---|
| Keylong | 32° 35' | 77° 4' | 3166 | 61.4 |
| | | SHIMLA HILLS | | |
| Kasauli | 30° 53' | 76° 58' | 1844 | 163.7 |
| Kotgarh | 31° 18' | 77° 29' | 1949 | 115.3 |
| Simla | 31° 06' | 77° 10' | 2202 | 159.0 |

Data of rainfall from seven sub-regions in western Himalayas having homogeneous topographic aspects were considered for the study of the variation of precipitation with altitude. In Table 6 the annual precipitation in the different sub-zones is shown. It has been seen that the precipitation gradient decreases or even became negative when considerable increase of wind speed occurs with increasing elevation which partly explains the decrease of precipitation after a certain elevation in the Himalayas. This elevation was noticed to be generally around 2000 m.

Based on the study, the authors concluded that the precipitation is influenced by increasing altitude in three ways.

(i) The quantity of precipitation increases with altitude upto a certain level and decreases thereafter. The level of maximum varies greatly from place to place depending on local topography. It was generally observed to be between altitudes of 1500 to 2500 m.

(ii) Average variability of precipitation generally increases with elevation.

(iii) At higher altitudes, the period of maximum precipitation is generally earlier than that on foot hills.

Surinder Kaur and Upadhyaya (1987) in connection with a study of network design for mountainous catchments presented a picture of the variation of precipitation with elevation in the Beas catchment and its variability which is given in Table 7.

Table 7 : Variation of precipitation with elevation in Beas Catchment

| Station | Elevation m | Mean Annual Precipitation (cm) | Standard Deviation | Coeff.of variation % |
|---|---|---|---|---|
| Dharamsala | 1211 | 366 | 184 | 54 |
| Palampur | 1217 | 256 | 96 | 38 |
| Hamirpur | 786 | 142 | 55 | 40 |
| Kangra | 701 | 196 | 53 | 27 |
| Kulu | 1236 | 100 | 30 | 30 |
| Mandi | 752 | 157 | 25 | 16 |
| Jogindernagar | 1221 | 223 | 56 | 25 |
| Sundernagar | 1193 | 159 | 27 | 17 |
| Banjar | 1522 | 109 | 28 | 26 |

## 3.0 REMARKS

Orographic effects on precipitation are the most important in many mountainous catchments of the world. The question as to what extent mountains affect precipitation has been inviting the attention of meteorologists and hydrologists alike. While it has generally been recognised that precipitation increases in dependance with elevation, further scientific developments have also brought in the effect of leeward and windward slopes. Later day studies also indicated the importance of the geographical location of the mountains with respect to the chief moisture sources which are generally the oceans and seas.

Orographic influences sometimes extend well away from a mountainous region when the atmosphere was potentially unstable. It may extend to several kilometers downwind from its area of origin. The exact location of the rainfall maximum might be related to the conditions nearer to the mountains than being directly to local topography. Also the effect of aspect may vary with height.

The rainfall observations from mountainous areas were far too less making it difficult to conclusively establish whether rainfall over a particular region is high or low as compared to other areas. Moreover, rainfall observations in mountainous areas especially in case of snowfall need to be corrected for the effect of wind flow over the gauge.

Studies on the influence of orography on precipitation have been carried out by

(i) increasing the number of stations in mountainous areas to get more direct observations on precipitation

(ii) Correlation methods to relate precipitation with topographical, meteorological and hydrological factors, and

(iii) dynamical orographic models.

### 3.1 Precipitation Data

As compared to a few decades ago, in many mountainous areas sufficient data is available enabling interpolation and extrapolation of data. The available data, however, needs appropriate processing.

The knowledge of inter-relationship between precipitation and other factors such as hydrological, meteorological, physiographical and orographical factors has increased considerably over the years and in years to come use of these relationships to hydrological forecasting is imminent.

### 3.2 Modelling of Orographic Precipitation

Generally, many models avoid the complication of convective activity while modelling air flow over mountainous areas and try to treat the stably stratified air. However, many mountainous areas experience rainfall predominently of convective type. More often, a wind which is not strong enough to produce well defined orographic effects in the distribution of precipitation may still be sufficiently strong enough to transport the convenctive cloud away from the area where it once formed.

The precipitation amount released by upslope winds increases with the humidity content of the air. As the water vapour content usually increases with increasing temperature, the precipitation amounts will depend on temperature. This is well taken care of in some of the dynamical models, such as the one in U.K.

The hydrologist is concerned with basins having characteristic sizes conforming to the meteorologists mesoscale. To provide precipitation information, either analyses or forecasts more useful to the hydrologists dealing with mountainous catchments, efforts need to be made on reducing model grid sizes to 5 to 10 km. However, the present understanding of mesoscale weather phenomena is rather limited. Attention has, therefore, to be paid towards studying the mesoscale weather systems so important from hydrological considerations. While mesoscale precipitation patterns can be studied with ground based radars, satellites may provide infrared soundings on meso-scales thereby facilitating mapping regions of high water vapour content.

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