Nordic Hydrology, 26, 1995, 259-284

Topographical Influence on Precipitation Distribution in Different Ranges of Western Himalayas

Pratap Singh, K. S. Ramasastri and Naresh Kumar
National Institute of Hydrology, Roorkee-247 667, India

Seasonal and annual distribution of rainfall and snowfall with elevation has been studied for outer, middle and greater Himalayan ranges of Chenab basin in the western Himalayas. Rainfall and snowfall exhibited different trends with elevation on the windward and leeward slopes of the three ranges of Himalayas. Seasonal characteristics of rainfall have shown a spill over effect on leeward side during winter, pre-monsoon, and post-monsoon seasons in the outer Himalayas. The role of orography in the middle Himalayas was found to be more pronounced for both rainfall and snowfall in comparison to other ranges of Himalayas. Variation of snowfall with elevation was more prominent in comparison to variation of rainfall. In the greater Himalayan range it is found that rainfall descreases exponentially with elevation and snowfall increases linearly. Rainfall becomes negligible at elevations beyond 4,000 m on the windward side of the greater Himalayan range. Efforts have also been made to explain whether variation in precipitation is due to changes in precipitation intensity or number of precipitation days or a combination of both.

Introduction

Precipitation provides the basic input for hydrological studies. However, it varies greatly in space and time within a range of mountains and also from one mountain range to another. The hydrological processes can not be properly represented until distribution of precipitation is known. The mountainous environment in comparison to the plain areas has strong impact on precipitation distribution. In the mountainous regions orography provides necessary uplift to the moisture laden currents striking against a mountain or chain of mountains which results in copious rainfall on the windward side of the mountains. If basin relief is very high, there may not be continuous rise and beyond a particular altitude the precipitation might decrease with height. The variation in precipitation with altitude is controlled by mean height of clouds and decrease of water vapour with altitude. Thus, precipitation in mountains can decrease with altitude above a certain level. Information on variation of precipitation with elevation for mountainous catchments would be useful in determining the net increase in precipitation due to elevation which in turn will help in estimation of PMP for mountainous areas. Such studies will assist in the realistic assessment of the water resources and flood potential of these regions.

About 35% of the geographical area in India is mountainous and 58% of this is accounted for by the mighty Himalayas. The mountain zone of perpetual snow has given rise to a number of rivers. The role of this control structure in the climatology of the Indian subcontinent is well pronounced. Review of studies on precipitation distribution over Himalayas has shown that only a few studies were carried out while such studies are very important for individual season both for planning and operation of water resources. In particular, detailed studies to assess the orographic effect on precipitation in the Himalayan region were not carried out. The main reason for the limited number of studies has been lack of information on precipitation at high elevations. Availability of precipitation (snowfall and rainfall) data for a few basins has improved in recent years because of good network in the lower, middle and upper parts of the basins. The Chenab basin which has been taken up for the present study is one of the few catchments which has a good network even at high elevations, which helped in undertaking a systematic scientific study to understand the nature of precipitation distribution in the western Himalayas.

Review of Studies on Orographic Effect on Precipitation Distribution

The influence of mountain barriers on precipitation distribution has been attracting the attention of scientists for a long time. Several studies were carried out on distribution of rainfall, snowfall and total precipitation with elevation in different parts of the world. Because all these have shown different patterns of variation with elevation, a brief review on the important rainfall, snowfall and total precipitation distribution studies has been presented in the following sections.

a) Rainfall Distribution

The distribution of rainfall with elevation in the Sierra Nevada mountains showed that rainfall increases up to a height of 1,500 m in these mountains (Linsley *et al.* 1949). Engman and Hershfield (1969) reported that average number of days and hours with precipitation increases with elevation in both summer and winter in north-eastern Vermount, USA. A study on elevation effects on rainfall using an event based stochastic model of thunderstorm rainfall and empirical data was carried out by Duckstein *et al.* (1972). The model was verified using data from cloud seeding experiments designed to investigate the possibility of increasing thunder-storm rainfall in the Santa Catalina Mountains near Tucson. It was noted that the mean total seasonal rainfall could be described by a quadratic polynomial in relation with elevation. In the Andes mountains in the Ecuador two zones of maximum rainfall along the western and eastern slopes at elevation of 1,000 m and 1,400 m, respectively, were found (Rumley 1965). Recently, Loukas and Quick (1993) has shown that rainfall depth per event increased up to mid elevation of a mountainous watershed in the British Columbia, and then decreased at upper elevations. Hourly rainfall intensity was found to decrease with increase in elevation.

Kanestrom (1987) described the studies carried out on the distribution of rainfall and reported that orography played an important role in rainfall distribution in northern Norway. It was concluded that heavy orographic rainfall was caused by forced lifting, strong winds at low levels and high relative humidity. Niemczynowicz (1989) studied the altitude effect on rainfall in the Jämtland area in Swedish mountains. Based on three years (1985-87) intensive measurements of rainfall, the average altitude effect for all collected data was found to be 9.5% per 100 m. Highest rainfall was registered behind the crest of the mountains on the leeward side.

b) Snowfall Distribution

Rhea and Grant (1974) found that 80% of the variance of snow water content in Colorado and Utah can be accounted for in terms of two parameters: the directionally adjusted slope and number of upwind barriers to the air flow. Caine (1975) found an elevational influence in the relative variability of maximum snowpack as well as on the snow accumulation. The latter increased linearly at a rate of 655 mm/km with a correlation coefficient of 0.66 from a zero accumulation level at 2,400 m for San Jaun Mountains in Colorado. However, variability decreases as the elevation increases.

Golding (1968) found a linear relationship between snow water equivalent and altitude. A mean rate of increase for snow water equivalent was reported to be of the order of 873 mm/km between 1,950 m and 2,225 m. Using a stepwise linear regression analysis in the Canadian Rocky Mountains covering a range of elevation from 1,500 to 2,800 m, Loijens (1972) showed that between 81-87% of variance of snow-water equivalent was associated with physiographic variables namely elevation and slope.

Witmer *et al.* (1986) found mean gradient of total fresh snowfall below 1,100 m altitude varied from 80 mm/100 m in south-western Alps to 730 mm/100 m in northern slopes of Alps. In the Swiss Alps, snow-water equivalent was observed to be maximum around 2,700 m altitude, and might decrease slightly above (Martinec 1987).

For the polar regions, data on the altitudinal effect on precipitation related primarily to snow – accumulation records on Greenland and Antarctic ice sheets. These have been summarized by Sudgen (1977). It is reported that accumulation in Antarctica and north Greenland increased to about 1,500-1,600 m altitude and thereafter decreased. In south-east, Greenland and eastern Antarctica the maximum snow occurred at about 700 m. Using precipitation and accumulation data for Greenland, Ohmura (1991) showed existence of the maximum precipitation zone around 2,500 m at 69° North in western Greenland and descending northward to about 1,500 m at 76° North. In the eastern Greenland, the higher values are found along the coast.

c) Total Precipitation Distribution

In one of the most detailed studies of orographic influence on precipitation, Spreen (1947) correlated mean seasonal winter precipitation with such factors as elevation, slope, rise, orientation and exposure for western Colorado. It was found that above described five parameters together accounted for 85% of precipitation variation while elevation alone accounted for only about 30% of variation. Similar results were found by Burns (1953) in discussing the small scale topographical effects in the San Gabriel mountains in California. For the western Oregon and Washington stations also, it was found that elevation alone does not explain much of the elevation in annual precipitation which predominantly occurs in the winter. Indices of barrier elevation with a latitude index explained most of the variations (Schermerhorn 1967).

Hamon (1971) concluded that winter precipitation increased more than four times at the 7,000 ft elevation in comparison to that observed at the 4,000 ft elevation in the southwestern Idaho. A three-fold increase in the hours of precipitation between 400 and 1,200 m elevation during winter season was reported by Hendrick *et al.* (1978) for Mansfield Vermount, USA. Hanson (1982) determined the spatial distribution of mean annual precipitation in the mountainous watersheds located in the south-east Idaho and a linear relationship was shown between annual precipitation and elevation. This relationship was found to be best when the stations were grouped into downwind and upwind sites.

Storr and Ferguson (1972) made precipitation distribution studies for 5 Canadian mountainous watersheds. The gradients for mean annual precipitation and mean summer rainfall were determined to be 636 mm/km and 93.6 mm/km, respectively, implying that rate of increase of snowfall was considerably higher than that for rainfall. Elevation and barrier distance provided highest correlation with precipitation. An examination of variation of precipitation with these two parameters suggested that curvilinear relationship provided better fit. Solomon *et al.* (1968) and Obedkoff (1970) also noted similar relationships between precipitation distribution and altitude. Various high level stations and observatories in the Alps indicated that amount of precipitation increased with elevation to the highest level of 3,000-3,500 m (Barry 1992). Førland (1979) carried out similar study in southern Norway and reported a decreasing trend of annual precipitation with altitude.

d) Snowfall and Rainfall Distribution Studies over Himalayas

The interest in such studies in Himalayas dates from the latter part of nineteenth century. Hill (1881) made a detailed study of distribution of rainfall in the northwest Himalayas and found that rainfall increases with elevation up to a height of about 1,200 m and thereafter it decreases as the elevation increases. Dhar and Rakhecha (1981) attempted to obtain a suitable relationship between mean monsoon (June-October) rainfall and elevation in the Central Himalayas (Nepal Himalayas). This study has shown that i) there exists no linear relationship between elevation and monsoon rainfall, ii) elevation and rainfall parameters can best be related by a polynomial of fourth degree, and iii) zones of maximum rainfall occur near the foothills and at an elevation of 2,000-2,400 m. Beyond this elevation, rainfall decreases continuously as elevation increases until the great Himalayan range is reached. Higuchi *et al.* (1982) studied the rainfall characteristics during the monsoon season in the high mountain areas of Nepal Himalayas and reported that rainfall decreases with altitude in the range from 2,800 to 4,500 m. It is still to be investigated whether variation in precipitation with elevation is due to changes in the number of storms, or in the amount of precipitation per storm or due to a combination of both possibilities.

The snowfall distribution in any part of the Himalayas is relatively unknown because very few studies are carried out to understand snow distribution. Studies in Langtang valley in Nepal between 3,920 and 5,090 m showed that snowfall from winter weather system increases with height in the winter season.

Importance of Seasonal Precipitation Distribution and Grouping of Stations

Substantial differences in precipitation-elevation relationships between adjacent large basins has been observed by Storr and Ferguson (1972). It was suggested that relationship derived for a mountainous watershed may not be directly transferred to other watersheds even in the same region. However, similar form of equations may be applicable to the adjacent watersheds. Significant variation occurs in physiographical precipitation models over relatively short distances in the mountainous areas (Peck and Brown 1962). Fitzharris (1975) observed that improved precisions are possible when separate equations are developed for each zone. The same is applicable for the watersheds of the Himalayas also because of very irregular topography. In the present study attempts have been made to understand the precipitation distribution in the Chenab basin in the western Himalayan region. Reasonably high relief changes within short distances are found in the study area which helped for better estimate of orographic effect on precipitation. Studies were carried out for different ranges in the basin *i.e.* outer, middle and greater Himalayas.

Himalayan catchments experience precipitation in the different seasons from different weather systems. Snowfall is experienced in the winter season and rainfall in all other seasons. Therefore, distribution of rainfall with elevation is studied for each season and each mountain range. Most of the snowfall is restricted to the winter season, therefore, snowfall distribution is studied only for a season. In this study, emphasis has been laid on the analysis of average seasonal and annual precipitation with a view that storm to storm variation is averaged out over a period of years, leaving only consistent pattern of topographic influences on precipitation.

It is a well established fact that precipitation on the windward side of a mountain barrier is always higher as compared to the leeward side. Therefore, consideration of both side stations together may give a false precipitation distribution with elevation. It is to be pointed that for two dominant seasons namely winter and monsoon season, the southern slopes are on windward side and northern slopes are on the leeward side. In the pre-monsoon and post-monsoon seasons clouds are locally formed at both slopes and mostly restricted to the same side if height of mountain barrier is high enough like middle or greater Himalayas. In the present study precipitation stations representing southern and northern slopes have been identified for each range of Himalaya and then studied for each season. The list of stations with respect to orientation in the three ranges is given in Appendix-I.

Study Area, Prevailing Seasons and Data used

The study area includes foothills and very high rugged mountains of the Chenab basin in the western Himalayas (Fig. 1). Snowmelt contribution is quite significant in this river because of heavy snowfall in winter season. To study the rain distribution with altitude, daily rainfall data of 31 stations located at different elevations is used (Appendix-I). The distribution of snow was studied using daily snowfall data of 26 stations. For both rain and snow, data of 17 years (1974-1990) was used. Only for one station data was available for 11-year period. These stations are equipped with non-recording rain and snow gauges. Data for snowfall and rainfall has been recorded separately at each station. Snow water equivalent is obtained by melting snow with the help of measured quantity of warm water and then deducting the added quantity from the total snow water equivalent. Mean monthly, seasonal and annual values have been computed from the daily precipitation data. Similarly, mean annual rainy and snowy days were determined and used to compute mean seasonal/annual rainfall and snowfall intensities. Period from October-September is considered in terms of annual analysis so that complete snowfall cycle is covered. Generally snowfall starts in October at higher reaches in the basin.

The seasonal and annual precipitation distribution over this basin has been studied for each Himalayan range separately. For this purpose, a year has been divided into the following four seasons depending upon broad climatic conditions prevailing over the basin:

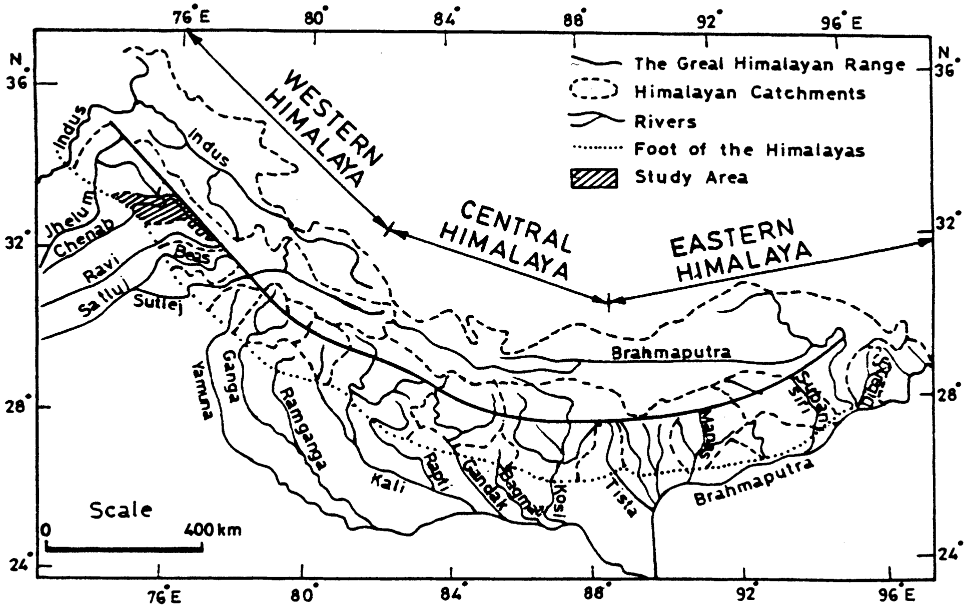


Fig. 1. Different sections of Himalayas and catchments of the Himalayan rivers.

i) Pre-monsoon season (April-June)
ii) Monsoon season (July-September)
iii) Post-monsoon (October-November)
iv) Winter season (December-March)

Precipitation during winter season is caused by extratropical weather systems of mid latitude region originating from Caspian sea and moving eastward. The area comes under the influence of monsoon currents in the monsoon season. Rainfall in the pre-monsoon season is essentially caused by air mass convective storms. The post monsoon season is generally a dry season.

Results and Discussion

a) Snowfall Proportion in Annual Precipitation

The ratio of snowfall to the annual precipitation is mainly dependent on the temperature in the region. It is very well known that temperature decreases as the elevation increases or the ratio of snowfall in the annual precipitation increases. It is found that ratio of snowfall to the annual precipitation varies roughly linearly with altitude (Fig. 2). Snowfall starts at about 1,300 m in this section of Himalayas. At an elevation of about 3,000 m solid and liquid precipitation are equal. Snow contribution further increases as the elevation increases and reaches to about 75% at an elevation of 4,325 m. The elevation where all the precipitation falls in the form of solid precipi-

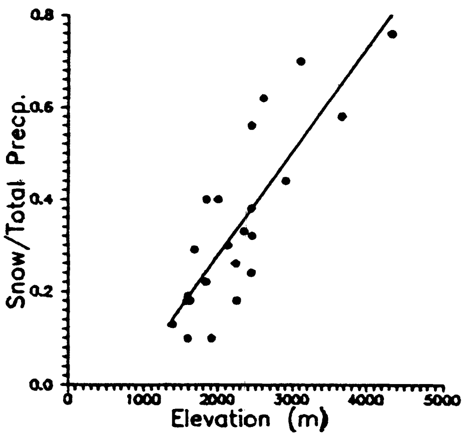


Fig. 2.
Variation in snowfall contribution to total precipitation with altitude in Himalayas.

tation could not be determined because data for locations beyond 4,325 m is not available. However, one can expect that above 6,000 m elevation, whatever precipitation occurs may be falling as snow only.

b) Rainfall Distribution

There is a variation in the amount of rainfall received at the same elevation in the different ranges of Himalayas. Orientation of the particular range further modifies the rainfall. Therefore, grouping of rainfall stations with respect to ranges and aspect is considered most important before carrying out such studies in the mountainous regions. Grouping of stations has been done on basis of aspect of mountain range. The list of stations for each range and aspect considered for study is given in Appendix-I.

The study area covers outer, middle and greater Himalayas, facilitating study of rainfall and snowfall distribution separately for each range and comparison of results for various ranges of Himalayas. A detailed discussion of the results follows.

i) *Outer Himalayas* – The rainfall analysis for this section of Himalayas is based on the limited number of rainfall stations on the windward and leeward side. The data were available only for two and three stations on the leeward and windward sides, respectively. On the other ranges, data for a number of stations were available on both sides of mountains. The results for different seasons and annual rainfall for windward and leeward sides are shown in Figs. 3(a)-(e). It is observed that rainfall linearly varies with elevation in this range of Himalaya during winter, pre-monsoon and post-monsoon seasons for both sides of mountains. However, magnitude of variation is different on both sides. In the monsoon season on the windward side first rainfall increases with elevation up to an altitude of about 600 m and then decreases. Second order polynomial fitted well with rainfall distribution on the windward side. On the other hand, rainfall on leeward side varied linearly with elevation.

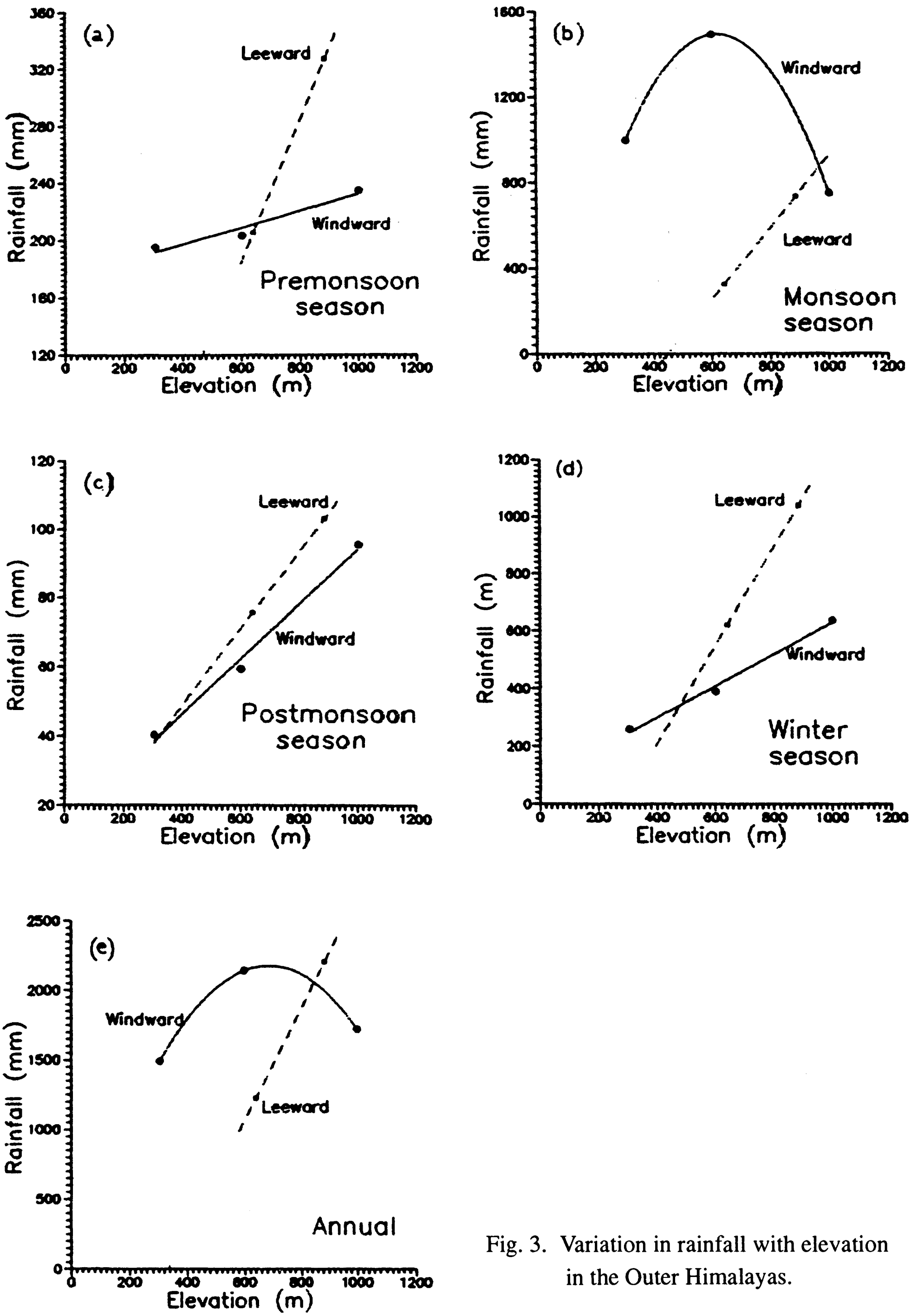


Fig. 3. Variation in rainfall with elevation in the Outer Himalayas.

Results indicated that maximum rainfall is received on the leeward side in these three seasons, except monsoon season. In the monsoon season it is on the windward side of the mountains. Such behaviour can be expected in the outer Himalayas in particular not only because of their relatively lower elevation, but also their location with respect to the monsoon currents. In the winter, pre-monsoon, and post-monsoon rainfall there is a possibility of spill over effects in rainfall while this effect is not found in the monsoon season. In the three seasons, the prevailing weather conditions are different than the monsoon season. The moisture content in the air is less than in the monsoon season. In this situation clouds precipitate at relatively higher elevation. And as clouds become mature to precipitate, the mountain barrier effect on the windward side is bypassed which results in heavy amount of rainfall on the upper part of leeward sides. It is seen that this phenomenon is very dominant in the winter and pre-monsoon in particular. A significant drop in rainfall from the upper station to lower station on the leeward side may be due to lower moisture content in the clouds after precipitating heavily on the top. The situation in the monsoon season is different than the other three seasons. In monsoon, the moisture content in the atmosphere and clouds are in saturated conditions and clouds become mature at relatively lower elevation. It results in high rainfall on the windward side before they cross the mountain barrier height. Consequently, rainfall increases up to a certain height and thereafter it decreases. Maximum rainfall is experienced in this season at about 600 m altitude on the windward side. It is to be noted that pre-monsoon and post-monsoon rainfall is caused by locally formed cloud systems whereas winter and monsoon rainfall is caused by moving moist air systems.

Spill over effect on rainfall is dominant in the three seasons out of four seasons of a year. Therefore, this effect is also reflected in the annual distribution of rainfall. However, trend of annual rainfall is guided by the monsoon rainfall. On the annual basis, maximum rainfall is observed on the leeward side at an elevation of about 900 m due to spill over effect in three seasons (pre-monsoon, post-monsoon and winter), whereas on the windward side it is around 600 m.

In order to have qualitative information on whether number of rainy days, or intensity of rain or combination of both is responsible for the rainfall variation with elevation, an analysis of annual rainfall and number of rainy days has been made for the outer Himalayas. For this purpose, average number of annual rainy days are computed for each station on windward and leeward sides of these mountains. An average annual value of intensity in terms of rainfall per rainy day is obtained from average annual rainy days and rainfall. The ratios of rainfall and rainy days for all the stations located on windward and leeward sides with respect to a rainfall station located at lowest height on the windward side are depicted in Figs. 4(a) and (b). Average intensity for the same is shown in Fig 4(c). It was seen from the results that average number of rainy days at maximum annual rainfall receiving station on the windward side was less than the leeward station of highest rainfall. But rainfall intensity was higher in comparison to the leeward side station. This shows that in-

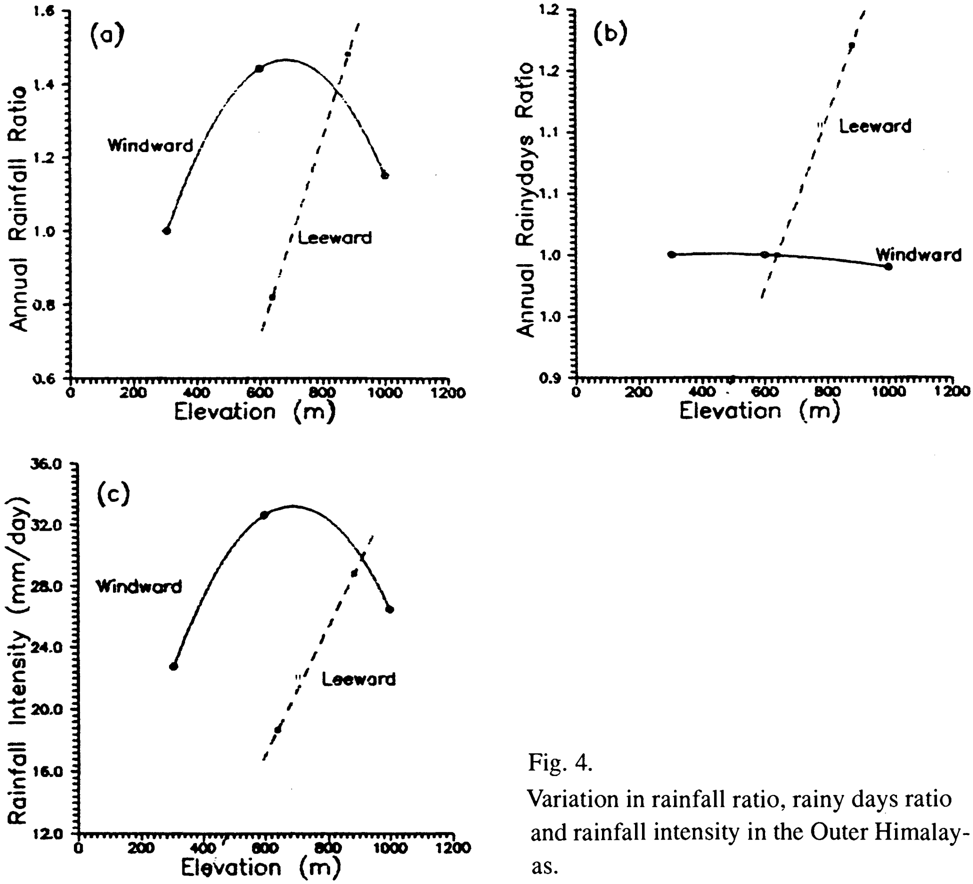


Fig. 4.
Variation in rainfall ratio, rainy days ratio and rainfall intensity in the Outer Himalayas.

crease in rainfall on the windward side is because of higher intensity of rain, whereas on the leeward side it is due to higher number of rainy days with lesser rain intensity.

To compare average seasonal rainfall and their contribution in the annual rainfall at both sides, an average rainfall is computed by taking average of all stations on each side. The values of seasonal and annual rainfall and their contribution in annual rainfall is given in Table 1. It is found that out of four seasons maximum rainfall on the windward side of the outer Himalayas is received in the monsoon season (60.4%) whereas on the leeward side it is in the winter season (48.4%). However, rainfall on the leeward side in the monsoon season is also substantial. As such there is not much change in the average number of rainy days, rainfall intensity and annual rainfall on both sides (Tables 1 and 2).

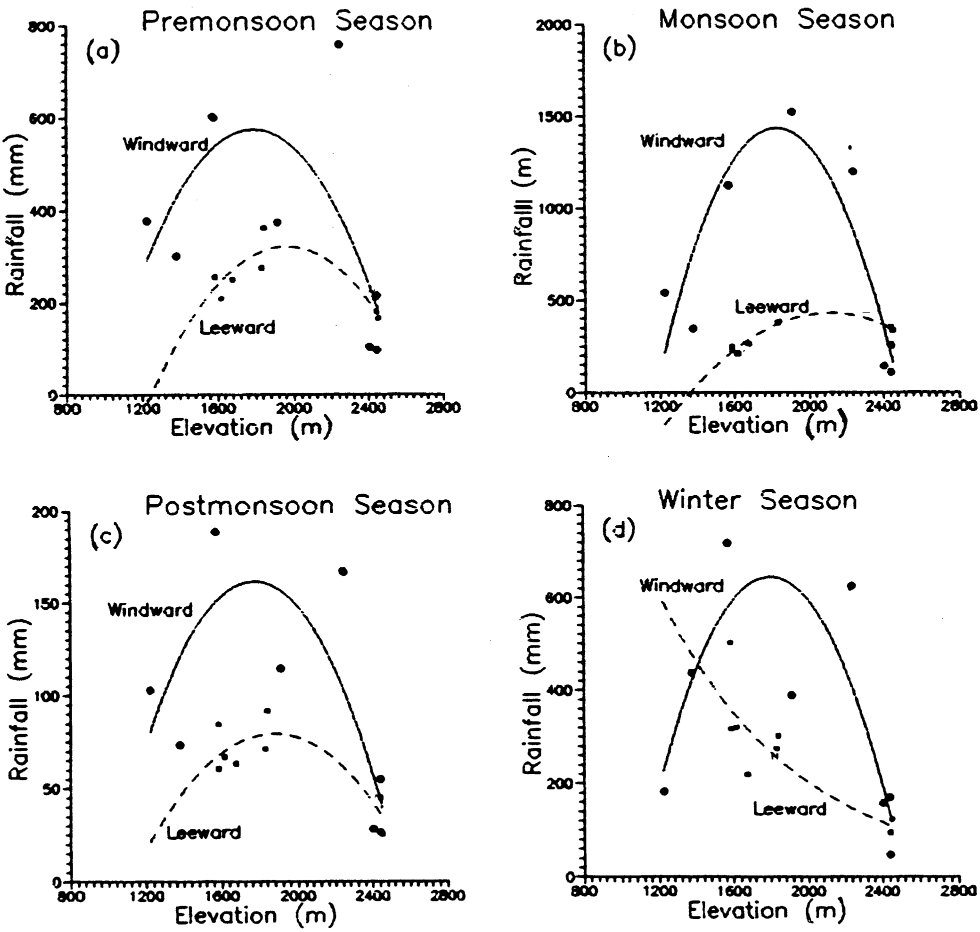
ii) *Middle Himalayas* – Rainfall distribution with elevation for the middle Himalayas is shown in Figs. 5(a)-(e). Availability of rainfall data in this range of Himalayas

Table 1 – Seasonal distribution of average rainfall in different ranges of Himalayas. The figures in brackets indicate percentage contribution of each season in the annual rainfall

Range	Aspect	Rainfall (mm)				
		Winter	pre-monsoon	monsoon	post-monsoon	Annual
outer Himalayas	Windward (South)	429 (24.1%)	211 (11.8%)	1,077 (60.4%)	65 (3.6%)	1,782
	Leeward (North)	830 (48.4%)	266 (15.5%)	528 (30.8%)	90 (5.2%)	1,714
	Average	630 (36.0%)	239 (13.7%)	803 (45.9%)	78 (4.5%)	1,748
middle Himalayas	Windward (South)	341 (23.6%)	354 (24.5%)	653 (45.3%)	94 (6.5%)	1,442
	Leeward (North)	270 (30.8%)	244 (27.8%)	299 (34.1%)	64 (7.3%)	877
	Average	306 (26.4%)	299 (25.8%)	476 (41.0%)	79 (6.8%)	1,160
greater Himalayas	Windward (South)	62 (14.3%)	177 (40.8%)	163 (35.6%)	32 (7.4)	434
Mean		333 (29.9%)	238 (21.4%)	481 (43.2%)	63 (5.7%)	1,114

Table 2 – Average annual rainy days, rainfall intensities, snowy days and snowfall intensities for different ranges of Himalayas

Range	Aspect	Rainy days	rainfall intensity (mm/rainy day)	snowy days	snowfall intensity (mm/snowy day)
outer Himalayas	Windward (South)	65	27	-	-
	Leeward (North)	71	24	-	-
	Average	68	25	-	-
middle Himalayas	Windward (South)	57	23	10	44
	Leeward (North)	60	15	13	25
	Average	59	19	12	35
greater Himalayas	Windward (South)	36	10	30	12



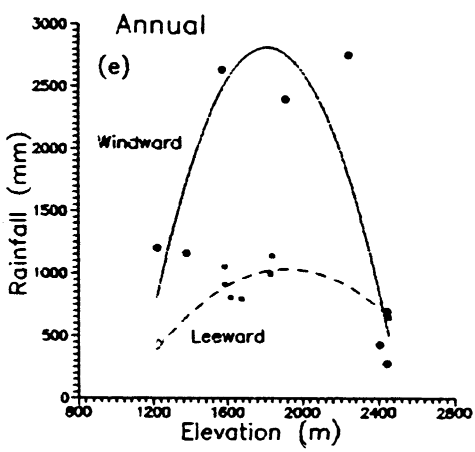


Fig. 5. Variation in rainfall with elevation in Middle Himalayas.

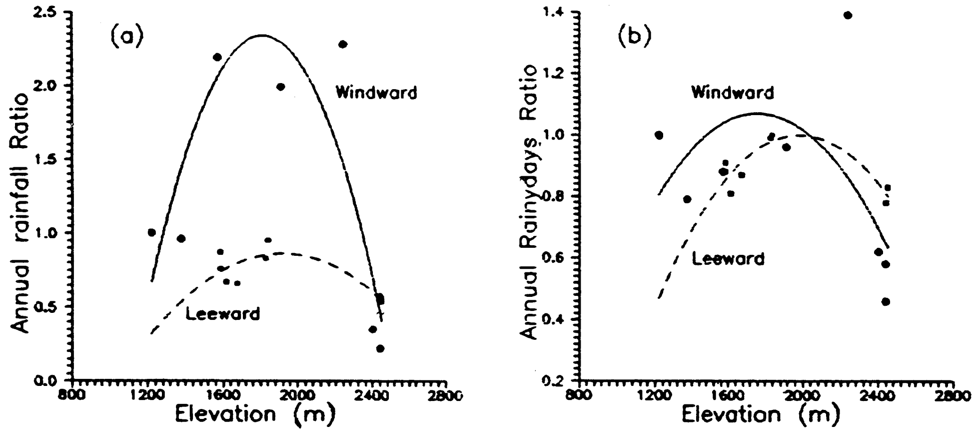
is better than for the outer Himalayas. Data of sixteen stations were available on the windward and leeward side of this range of Himalayas in this basin. It is seen that rainfall distribution on the windward side has similar trend for all the four seasons in this Himalayan range. It increases with elevation up to a certain altitude and thereafter decreases with elevation. In all the cases maximum rainfall is occurring somewhere between 1,600 and 2,200 m. The lower rainfall beyond the elevation of maximum rainfall can be explained by the availability of lower moisture content in the clouds. Once the clouds have precipitated on the windward producing maximum rainfall, they are still forced to rise along the slopes of mountain barrier. Because of lower moisture content available within the clouds at this stage, rainfall is significantly reduced. Second order polynomial was fitted for both sides in this range of Himalayas.

Rainfall distribution with elevation on the leeward shows trend similar to windward side with lower magnitude, except for the winter season. It is interesting to note that maximum rainfall on the leeward side also has maxima at about same elevation range as on the windward side. This feature is more evident in the pre-monsoon and post-moonsoon seasons. It can be explained on the basis of cloud formation and their movement. In the pre-monsoon and post-monsoon seasons clouds are locally formed due to convection mechanism on both windward and leeward sides. Moreover, their movement is restricted to the respective sides of the mountain, whereas in the monsoon and winter seasons moist air crosses windward side and reach leeward side. The higher magnitude of rainfall on the windward side of the middle Himalayas in all the seasons can be explained as follows:

In the monsoon and winter seasons moist airmass first faces the windward side and gives significant amount of rainfall on this side. In the pre-monsoon and post-monsoon seasons higher convective activity causing higher number of clouds (higher rainfall) is expected on windward side (south slope) because south slope receives more solar radiation in comparison to the leeward (north slope). It is evident that once maxima of rainfall is produced on either side of mountain, it reduces significantly after that event.

Variability in rainfall on the windward side is found to be relatively higher in the winter, pre-monsoon and post-monsoon seasons when compared with monsoon season. Different cloud formations mechanism in the different seasons may be responsible for it. A well established continuous weather system in the monsoon season could have reduced variability significantly. Variability on the leeward side is always less than on the windward slopes.

The variation in the average annual rainfall and rainy days with respect to a station at the lowest elevation on the windward side of the middle Himalayas are shown in Figs. 6(a)-(b) and annual average rainfall intensity per rainy day is also illustrated in Fig 6(c). It can be noticed that ratios of annual maximum rainfall on the windward side with respect to a rainfall station located at lowest elevation on the same side is found to be more than 2 and this ratio with respect to same station on



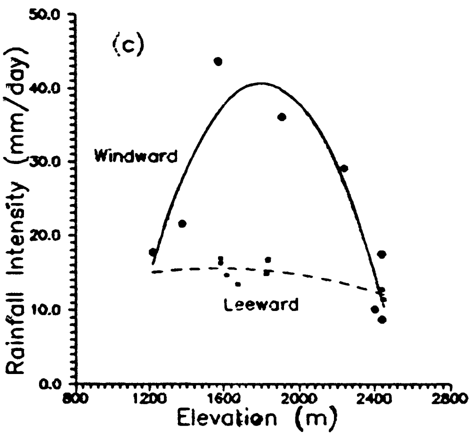


Fig. 6.
Variation in rainfall ratio, rainy days ratio and rainfall intensity with elevation in the Middle Himalayas.

the leeward side reduces to unity. This confirms that variations in rainfall on the windward side are more significant by topography than on the leeward side. Moreover these Figures also elucidate that rainfall intensity and the number of average rainy days first increase with elevation and then decrease. Rainfall intensity changes more significantly in comparison to number of rainy days on the windward side whereas reverse is found true on the leeward side. It can be concluded that higher intensity of rainfall plays a more important role than number of rainy days in increasing rainfall on the windward side. Number of rainy days are more responsible in comparison to rainfall intensity to enhance the rainfall on the leeward side in this section of Himalaya.

Average of all stations on each side of middle Himalayas shows that monsoon rainfall dominates on both the windward and leeward sides (Table 1). Monsoon rainfall represents about 34% and 45% of the annual rainfall on the leeward side and windward side, respectively. However, rainfall during winter and pre-monsoon seasons is also significant on both sides. Average annual rainfall intensity is also higher

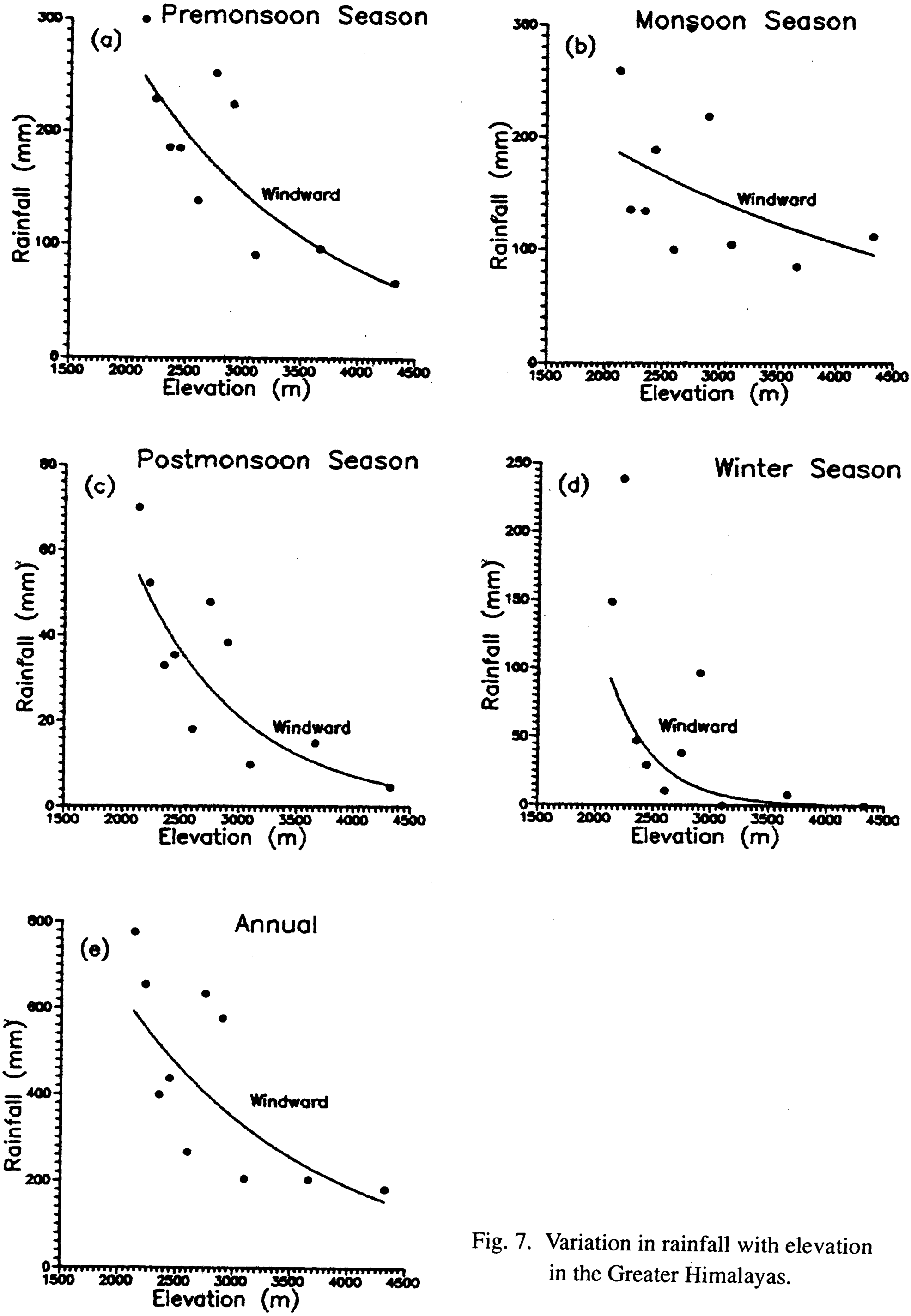


Fig. 7. Variation in rainfall with elevation in the Greater Himalayas.

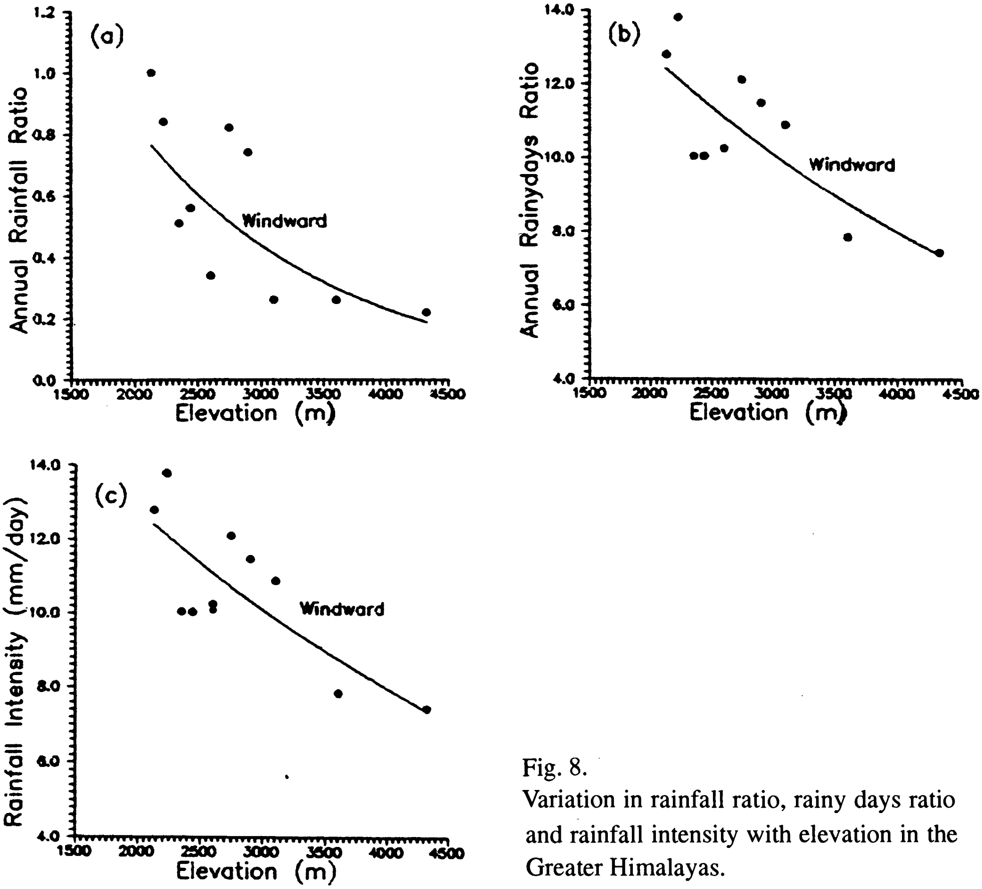


Fig. 8.
Variation in rainfall ratio, rainy days ratio and rainfall intensity with elevation in the Greater Himalayas.

on the windward side. Annual rainfall on the windward side in the middle Himalayas was found to be more than one and half times that of rainfall observed on the leeward side. It shows that orographic effect on rainfall is more pronounced in the middle Himalayas in comparison to the outer Himalayas.

iii) *Greater Himalayas* – Trends of rainfall distribution in the greater Himalayas are exhibited in Figs. 7(a)-(e). Patterns of rainfall distribution in this section of Himalayas were found to be different from those observed for outer and middle Himalayas. In all the four seasons rainfall decreases exponentially with elevation. The annual rainfall also has shown the same exponentially decreasing behaviour with altitude. Such trends can be expected at such high elevations because of much less moisture content in the clouds by the time they reach this Himalayan range. In the winter season rainfall decreases with relatively faster rate as compared to the other three seasons and becomes negligible around 4,000 m. The basic cause for this type of trend in rainfall in the winter season may be colder temperature at higher elevations in comparison to other seasons which results in solid precipitation. In the pre-monsoon and post-monsoon seasons most of the clouds are locally formed and precipitate which results in gradual decrease in rainfall with elevation. It can be noticed that rainfall magnitude is not much changed in monsoon season while compared with pre-monsoon season, indicating that monsoon rainfall is not very significant in this section of Himalaya.

Analysis of annual average intensity, rainy days and annual rainfall ratios with elevation has also been made for this part of Himalayas (Figs. 8(a)-(c)). It is apparent that both lower rainfall intensity and less number of rainy days are responsible for decrease of rainfall with elevation in the greater Himalayas. Average of all stations in each season on the windward side is given in Table 1. It is observed that in the greater Himalayas, pre-monsoon rainfall (40.7%) dominates on the windward side.

The rainfall data for the leeward side was not available. Therefore, rainfall distribution on this side could not be studied. However, little rainfall is expected in this region in the monsoon season because most of the moisture from the clouds is precipitated before they reach this part of Himalaya. Consequently, a cold desert type of climate in the trans-Himalayas is experienced. However, there is possibility of some rainfall from locally formed clouds in the pre-monsoon, monsoon and post-monsoon seasons.

c) Comparison of Rainfall in Different Ranges of Himalayas

A comparison of the average figures of annual rainfall all over a mountain range *i.e.* average of windward side and leeward side indicated that annual rainfall decreases from south to north (Table 1). It is highest in the outer Himalayas and lowest in the greater Himalayas. In the middle Himalayas annual rainfall lies in between that of outer and greater Himalayas. It can be observed that annual rainfall in the outer and middle Himalayas is about four times and three times in comparison to the greater Himalayas, assuming that there is no significant rainfall on the leeward side of greater Himalayas. Outer and middle Himalayas show moderate conditions of rainfall (1,000-2,000 mm) whereas greater Himalayas receive less rainfall. In general average monsoon rainfall is dominant in the outer and middle Himalayas and contributes more than 40% to the annual rainfall. Winter rainfall contribution is next to monsoon rainfall. In the greater Himalayas pre-monsoon rainfall contributes much to the annual rainfall and monsoon rainfall is next to it. Rainfall during post-monsoon season is always lowest over all the ranges of Himalayas.

d) Snowfall Distribution

i) *Middle Himalayas* – Because most of the snowfall is restricted to winter season only, snowfall distribution has not been studied season wise. The distribution of annual snowfall with altitude for middle Himalayas on the windward and leeward sides is shown in Fig. 9(a). It was observed that unlike rainfall, snowfall linearly increases with elevation on the windward side of the middle Himalayas. On the lee-

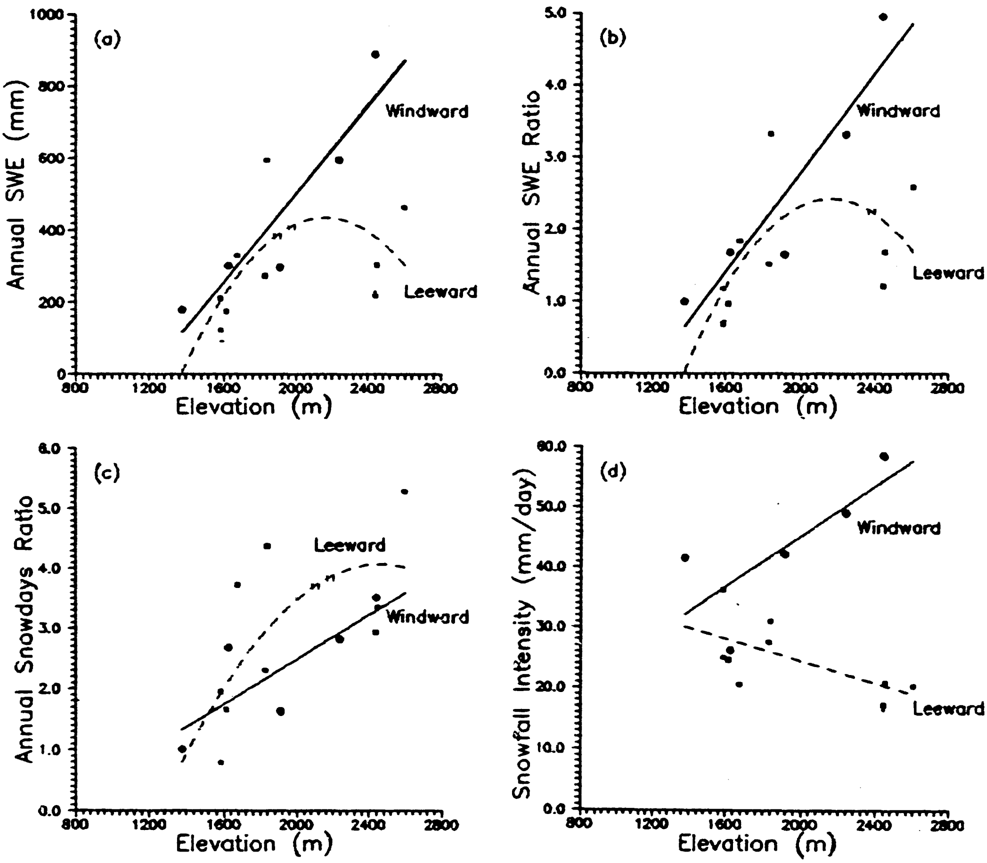


Fig. 9. Variation of snowfall water equivalent (SWE), its ratio, snow days ratio and snow intensity with elevation in the Middle Himalayas.

ward side it first increases and then decreases. The available data indicated that maximum snowfall is received on the windward side at about 2,500 m elevation in the middle Himalayas whereas on the leeward side it was found at relatively lower elevation of about 1,800 m. The substantial amount of snowfall on the upper part of leeward side also is expected due to linear increase in snowfall on the windward side. The clouds contain sufficient moisture when they approach leeward side even after precipitating on the windward side.

When snowfall on windward and leeward sides was compared with snowfall at the valley station on the windward side, it was found that on the upper part of windward side, snowfall is about 5 times higher than the valley station (Fig. 9(b)). On the leeward side the highest point value was about 3 times higher when compared with same station. For further details, investigations were extended to find out average annual snowy days and snowfall intensity per snowy day on both sides of middle

Himalayas. Variation in snowdays on both sides with respect to base station is shown in Figs. 9(c)-(d). It was observed that variation in number of snowy days on the leeward side was more pronounced than on the windward side. Results indicated that on the windward side both snowdays and snowfall intensity increase linearly with elevation. On the leeward side snowfall intensity decreases as elevation increases, but in general snowy days increase with elevation. At the same time it was also noticed from these figures that variation in the number of snowy days with elevation on the leeward side is more pronounced than on the windward side, while the reverse is true for the snowfall intensity. It could, therefore, be concluded that significant increase in snowfall with elevation on the windward side is because of higher snowfall intensity while lower intensity on the leeward is responsible for the lower snowfall variation on the leeward side.

The average annual snowfall values for all stations on the windward and leeward sides of the middle Himalayas are computed to be 452 and 277 mm respectively which constitute 24% of the annual total precipitation on both sides (Table 3). It shows that snowfall on the windward side is more than one and half times greater than on the leeward side in this range of Himalayas. On average 10 and 13 snowy days were experienced on the windward and leeward sides, respectively, but intensity was computed to be 44 and 25 mm/snowy day (Table 2). It shows that more or less snowfall intensity on the windward side is about one and half times greater than on the leeward side.

Table 3 – Contribution of rainfall and snowfall in the annual total precipitation

Range	Aspect	Precipitation (mm)		
		rainfall	snowfall	total precipitation
outer Himalayas	Windward (South)	1,783 (100%)	-	1,783
	Leeward (North)	1,715 (100%)	-	1,715
	Average	1,749 (100%)	-	1,749
middle Himalayas	Windward (South)	1,441 (76.1%)	452 (23.9%)	1,893
	Leeward (North)	877 (76.0%)	277 (24.0%)	1,154
	Average	1,159 (76.1%)	364.5 (23.9%)	1,523.5
greater Himalayas	Windward (South)	433 (55.4%)	348* (44.6%)	781*

* These values are supposed to be higher because there would be more snowfall at higher elevations on the windward side of greater Himalayas for which data is not available.

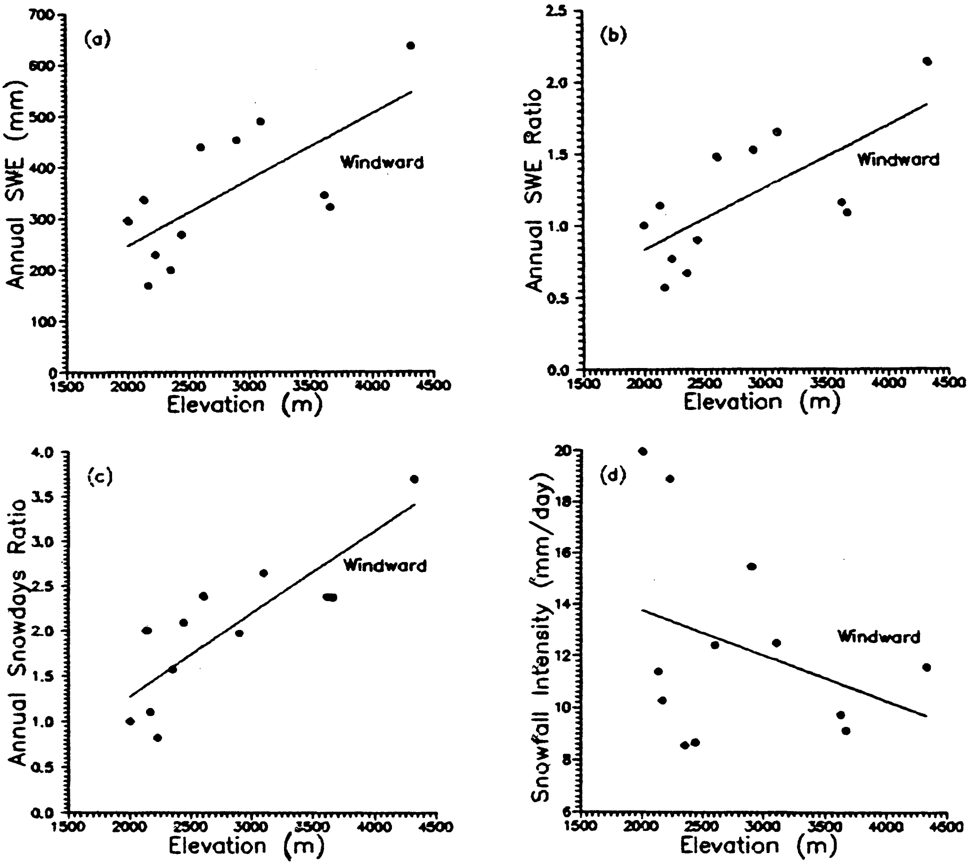


Fig. 10. Variation of snowfall water equivalent (SWE), its ratio, snow days ratio and snow intensity with elevation in the Greater Himalayas.

ii) *Greater Himalayas* – With the available data on snowfall on the windward side of the greater Himalayas, efforts have been made to study the distribution of snowfall with elevation. It was found that in this range also snowfall increases approximately linearly with elevation (Fig. 10(a)). The trend of snowfall could not be studied on the leeward side or on the windward side beyond 4,325 m due to nonavailability of data. Using the available data on the windward side the average of all stations for annual snowfall was estimated to be 348 mm, which is 44.6% of the total annual precipitation. However, it is expected to be more because of the likely higher snowfall at higher elevation (Table 3).

Analysis of variation of snowfall ratio with respect to a station located at lowest elevation in the valley on windward side, it was found that snowfall is nearly about 4 times at an elevation of 4,325 m (Fig. 10(b)). The number of snowy days also increases linearly with altitude in this range, but no systematic trend of snowfall intensity has been observed (Figs. 10(c) and (d)). It could be broadly said that snowfall intensity decreases as the elevation increases in this part of Himalayas. This shows that higher number of snowy days are responsible for increase of snowfall with altitude. The average number of snowy days was computed to be 30 days and snowfall intensity was found to be of the order of 12 mm/per snowy day. The average annual snowfall was estimated to be 348 mm (Table 2).

e) Comparison of Snowfall Distribution in Middle and Greater Himalayas

Average annual snowfall was found to be higher in the middle Himalayas in comparison to the greater Himalayas (Table 3). Further, average snowfall intensity is very high on the windward and leeward sides of middle Himalayas in comparison to the greater Himalayas. It is about four times on the windward side and two times on the leeward side of the middle Himalayas (Table 2). But average annual number of snowy days were computed to be three times in the greater Himalayas in comparison to both sides of middle Himalayas. Maximum snowfall was observed in the months of January/February over the middle and in March over greater Himalayas, respectively. Like rainfall, snowfall is also significantly influenced by orography in the middle Himalayas.

Conclusions

In the present study attempts have been made to determine the effect of orography on the precipitation distribution in the Chenab basin located in the western Himalayas. Because precipitation in the western Himalayas is caused by different weather systems in different seasons of a year and varies greatly from range to range because of highly rugged topography of the Himalayan mountains, therefore, the study is carried out for different ranges Himalayas. Different trends of rainfall and snowfall distribution with elevation led to carry out such studies separately for snowfall and rainfall distribution for each range. Grouping of stations was done with respect to particular range and aspect. The following conclusions are drawn from this study:

a) Rainfall Distribution

1) Distribution of seasonal and annual rainfall has shown that rainfall increases linearly with elevation in the outer Himalayas on both windward and leeward sides, except in monsoon season. In the monsoon season, rainfall increases with elevation up to a certain height and then starts decreasing. Maximum rainfall is observed at about 600 m on the windward side during monsoon season.
2) Spill over effect is noticed in the outer Himalayas during winter, pre-monsoon and post-monsoon seasons.
3) Rainfall follows a similar distribution with elevation on both windward and leeward sides *i.e.* first it increases with elevation and then starts decreasing. The

rainfall distribution fitted well with second order polynomials. The region of maximum rainfall on windward and leeward sides was found to be between 1,600 and 2,200 m.

4) Increase in rainfall intensities with elevation is found to be responsible for higher amounts of rainfall on the windward side of the middle Himalayas while more number of rainy days at higher elevation on the leeward side contributed to higher rainfall in the middle Himalayas.
5) On an average, maximum annual rainfall (1,749 mm) is observed in the outer Himalayas, whereas minimum (433 mm) is observed in the greater Himalayas. In the middle Himalayas it is observed to be 1,159 mm. These figures of rainfall indicate that moderate rainfall (1,000-2,000 mm) is experienced in the outer and middle Himalayas, whereas less rainfall is experienced in the greater Himalayas.
6) In general, monsoon rainfall is found to be dominant in the outer and middle Himalayas. It has been noted that monsoon rainfall contributes about 46% and 41% to the annual rainfall of outer and middle Himalayas, respectively. In the greater Himalayas pre-monsoon rainfall contribution to the annual rainfall was found to be maximum (41%) in the annual rainfall. Post-monsoon rainfall contribution was always least all over the Himalayan ranges. Generally, maximum rainfall is observed in the month of July over outer Himalayas, in March and July over middle Himalayas and in May over the greater Himalayas.
7) Rainfall decreases exponentially with elevation in the greater Himalayas and becomes negligible at elevations beyond 4,000 m. Lower rainfall intensity and lesser number of rainy days are found to be responsible for lesser rain in this section of Himalayas.
8) The role of orography in the middle Himalayas is found to be very pronounced for both rainfall and snowfall in comparison to other ranges of Himalayas.

b) Snowfall Distribution

9) Snowfall increases linearly with elevation on the windward side of middle Himalayas, whereas on the leeward side it followed the trend of rainfall *i.e.* first increases with elevation and then decreases.
10) Maximum snowfall is observed at about 2,500 m elevation on the windward and at 1,800 on the leeward side of middle Himalayas.
11) Higher snowfall intensities are found to be responsible for higher amount of snowfall on the windward side in the middle Himalayas. Lower snowfall on the leeward side is caused by the lower snowfall intensity.
12) Snowfall increases linearly with elevation in the greater Himalayas.
13) On average, greater Himalayas experience lower snowfall in comparison to the middle Himalayas. It is found that average number of snowy days increases with elevation, while the intensity decreases.
14) Mostly maximum snowfall is experienced in the months of January/February in the middle Himalayas and in March in the greater Himalayas.

15) At an elevation of about 3,000 m, solid and liquid precipitation equally contribute in annual precipitation. It shows that below 3,000 m rainfall dominates and above 3,000 m snowfall dominates in the annual precipitation.

Acknowledgements

Authors are very much thankful to Ministry of Water Resources, Govt. of India for permitting to publish the paper.Thanks are also due to Northern Circle, Central Water Commission, for making available data. Help extended by Indus Commissioner, Ministry of Water Resources, Govt. of India, in getting data is also acknowledged.

References

Barry, G. B. (1992) *Mountain Weather & Climate*, 2nd Edition, Routledge, New York.

Burns, J. I. (1953) Small-scale topographic effects on precipitation distribution in San Dimas Experimental forest, *Trans. Amer. Geophys. Un., Vol. 34*, pp. 761-768.

Caine, N. (1975) An elevational control of peak snowpack variability, *Wat. Res. Bull., Vol. 11*, pp. 613-621.

Dhar, O. N., and Rakhecha, P. R. (1981) The effect of elevation on monsoon rainfall distribution in the Central Himalayas, Proc. International Symposium on Monsoon Dynamics, Cambridge University Press, pp. 253-260.

Duckstein, L., Fogel, M. M., and Thames, J. L. (1972) Elevation effects on rainfall: A stochastic model, *Journal of Hydrology, Vol. 18*, pp. 21-35.

Engman, E. T., and Hershfield, D. M. (1969) Precipitation climatology of the Sleepers river watershed near Danville, Vermount Paper ARS, pp. 41-148, USDA, Agr. Res.

Fitzharris, B. B. (1975) Snow accumulation and deposition on a west coast midlatitude mountain. Ph. D. Thesis, Dept of Geography, University of British Columbia, Canada.

Førland, E. J. (1979) Precipitation and topography (in Norwegian with English summary), *Klima, No. 2*, pp. 3-24.

Golding, D. L. (1968) Snow measurement in Marmot basin, Proc. National Workshop Seminar on Snow Hydrology, Fredericton, N. B., February, 1968.

Hamon, W. R. (1971) Reynolds Creek, Idaho Agr. Res. Precipitation Facilities and Related Studies, USDA ARS, pp. 41-176.

Hanson, C. L. (1982) Distribution and stochastic generation of annual and monthly precipitation on mountainous watershed in southwest Idaho, *Water Resour. Bull., Vol. 18*, pp. 875-883.

Hendrick, R. L., DeAngelis, R. J., and Dingman, S. L. (1978) The Role of elevation in determining spatial distribution of precipitation, snow and water input at Mt. Mansfield, Vermount, Proc. Workshop on Modelling of Snowcover and Runoff, US Army Cold Region Research and Engineering Lab.

Higuchi, K., Ageta, Y., Yasunari, T., and Inoue, J. (1982) Characteristics of precipitation during monsoon season in high mountain areas of the Nepal Himalayas, Hydrological Aspects of Alpine and High Mountain Areas, *IAHS Publication No. 138*, pp. 21-30.

Hill, S. A. (1881) The meteorology of North-West Himalaya, Ind. Met. Mem. I(VI), pp. 377-429.

Howell, W. E. (1949) On the climatic description of physiographic regions, *Annals of the Ass. Am. Geogr., Vol. 39,1*, pp. 13.

Kanestorm, I. (1987) Distribution of Heavy precipitation in Northern Norway and effect of orography, Proc. Nordic Symposium on Climatological Extremes in the Mountains, Dept. of Physical Geography, Uppsala University, Rapport Nr. 65, pp. 53-67.

Linsley, R. K., Kohler, M. A., and Paulhas, J. R. H. (1949) *Applied Hydrology*, McGraw-Hill, New York.

Loijens, H. S. (1972) Snow distribution in an alpine watershed of the Rocky Mountains, Canada, Proc. WMO Symposium on Distribution of Precipitation in Mountainous Areas, Vol. II, pp. 175-183, 31 st July-5th Aug., Geilo, Norway.

Loukas, A., and Quick, M. C. (1993) Rain distribution in a mountainous watershed, *Nordic Hydrology, Vol. 24*, pp. 225-242.

Martinec, J. (1987) Importance and effects of seasonal snow cover, In: B. E. Goodison, R. G. Barry, and J. Dozier (eds.), Large Scale Effects of Seasonal Snow Cover, *IAHS Publ. No. 166*, pp. 107-120.

Niemczynowicz, J. (1989) Altitude effect on summer precipitation measured in Swedish mountains, Proc. Seventh Northern Research Basins Symposium, May 25-June 1, Llulissat, Greenland.

Obedkoff, W. (1970) A study of the grid square method for estimating mean annual runoff, MASc. Thesis, University of British Columbia, Canada.

Ohmura, A. (1991) New precipitation and accumulation maps for Greenland, *J. Glacio., Vol. 37*, pp. 140-148.

Peck, E. L., and Brown, M. J. (1962) An approach to the development of isohyetal maps for mountainous areas, *J. Geophys. Res. Vol. 67*, pp. 681-694.

Rhea, J. O., and Grant, L. O. (1974) Topographic influences on snowfall patterns in mountainous terrain, In; Advanced Concepts and Techniques in the Study of Snow and Ice Resources, pp. 182-192, Washington, D. C., National Academy of Science.

Rumley, G. B. (1965) An investigation of the distribution of rainfall with elevation for selected stations in Ecuador, M. S. Thesis, Texas A & M University, USA.

Schermerhorn V. P. (1967) Topography and annual precipitation, *Water Resources Research, Vol. 3*, pp. 707-711.

Solomon, S. I., Denouvillies, J. P., Chart, E. J., Wolley, J. A., and Cadou, C. (1968) The use of a square grid system for computer estimation of precipitation, *Trans. Am. Geophys. Un., Vol. 49*, pp. 285-290.

Spreen, W. C. (1947) Determination of the effect of topography on precipitation, *Trans. Am. Geophys. Un., Vol. 28*, pp. 285-290.

Storr, D., and Ferguson, H. L. (1972) The distribution of precipitation in some mountainous Canadian watersheds, Proc. WMO Symposium on Distribution of Precipitation in Mountainous Areas, Vol. II, pp. 241-263, 31st July-5th Aug., Geilo, Norway.

Sugden, D. E. (1977) Reconstruction of the morphology, dynamics and thermal characteristics of the Laurentide ice sheet at its maximum, *Arct. Alps. Res., Vol. 9*, pp. 21-47.

Witmer, U., Filliger, P., Kunz, S., and Kung, P. (1986) Erfassung, bearbeitung and kartieren von schneedaten in der Schweiz. Geogr. Bernensia G25.

Appendix I

List of stations used for analysis

Windward side (South)	Elevation (m)	Snow (S)/ rain (R)	Leeward side (North)	Elevation (m)	Snow (S)/ rain (R)
a) Foot hills and outer Himalayas					
1. Akhnoor	305	R	4. Dhamkund	640	R
2. Paoni	600	R	5. Damni	885	R
3. Gainta	1,000	R			
b) Middle Himalayas					
6. Gulabgarh	1,220	R	15. Palmar	1,585	R&S
7. Rot	1,375	R&S	16. Ohli	1,585	R&S
8. Kati	1,570	R	17. Kistwar	1,615	R&S
9. Banihal	1,625	S	18. Sirsi	1,675	R&S
10. Nandan	1,910	R&S	19. Bhadarwah	1,830	R&S
11. Sain	2,240	R&S	20. Chingaon	1,840	R&S
12. Gohala	2,400	R	21. Dusadudha	2,440	R&S
13. Mohu	2,440	R&S	22. Devigol	2,450	R&S
14. Thana	2,440	R	23. Bunnencha	2,600	S
c) Greater Himalayas					
24. Sohal	2,000	S			
25. Tillar	2,130	R&S			
26. Yurdu	2,165	S			
27. Arthal	2,225	R&S			
28. Sarkund	2,350	R&S			
29. Inshan	2,440	R&S			
30. Udaipur	2,600	R&S			
31. Hawal	2,745	R			
32. Mau	2,900	R&S			
33. Tandi	3,100	R&S			
34. Koksar	3,615	S			
35. Rikiniwas	3,660	R&S			
36. Matsal	4,325	R&S			

First received: 22 February, 1994
Revised version received: 19 October, 1994
Accepted: 21 December, 1994

Address:
National Institute of Hydrology,
Jal Vigyan Bhawan,
Roorkee-247 667 (U.P.),
India.