TR(BR)-107

Effect of Orography on Precipitation Distribution in the Chenab Basin

National Institute of Hydrology
Jalvigyan Bhawan
Roorkee
1993-94

Preface

There is strong demand for better estimation of precipitation in the mountainous areas mainly for various hydrological studies such as streamflow forecasting, design flood and snowmelt contribution in the rivers in the snowfed rivers etc. Precipitation phenomenon differ greatly from place in the mountainous area because of highly rugged topography. It is important, therefore to study the distribution of precipitation in the different parts of the Himalayas for both phases of precipitation namely snowfall and rainfall. In the present report, rainfall and snowfall distribution with altitude have been studied for three ranges of Himalayas in the Chenab basin,namely outer, middle and greater Himalayas. Good network and availability of sufficient data made possible to carry out this study. Efforts have been made to explain the precipitation distribution in the respective range of Himalayas. An analysis to find out seasonal precipitation contribution in the annual precipitation is also made. Moreover, how ratio of solid and liquid precipitation varies with altitude is also investigated. A review of rainfall and snowfall distribution over the Himalayas in other mountainous parts of the world is also made.

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Abstract

Precipitation distribution with elevation has been studied in the Chenab basin located in the western Himalayan region. This basin comprises parts of outer, middle and greater Himalayan ranges and results could therefore be compared for different ranges of Himalayas. Because precipitation experienced in different seasons is derived from different weather systems which are influenced by different ranges of Himalayas differently. Grouping of stations with respect to the particular range and aspect has been done before making precipitation analysis. Analysis of the rainfall and snowfall distribution were carried out separately for each range and season. 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. Rainfall analysis was made using rainfall data of 31 stations considering 17 years of daily rainfall data. To study snowfall distribution, snowfall data of 26 stations have been used for the same period as for rainfall.

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 the leeward side during winter, pre-monsoon and post-monsoon seasons in the outer Himalayas. For these three seasons rainfall increases linearly with elevation, but in the monsoon season rainfall on the windward side initially increases reaching to its maximum at about 600m and thereafter it decreases. Annual rainfall trends are guided by monsoon season rainfall and show similar pattern of distribution with elevation. Second order polynomials fitted well for rainfall distribution of monsoon and annual rainfall.

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. Snowfall has shown more significant variation with elevation in comparison to rainfall. Rainfall follows similar type of distribution with elevation on both windward and leeward sides i.e. first it increases with elevation and then starts decreasing and distribution of rainfall fitted well with second order polynomials on both sides. The region of maximum rainfall on windward and leeward sides was found to be between 1600 and 2200 m. Snowfall distribution has shown a trend of linear increasing with elevation on the windward side whereas on the leeward side it followed the trend of rainfall in the

middle Himalayas i.e. initially increases with elevation and then decreases. In this range maximum snowfall was found at about 2500m on the windward and at 1800 m on the leeward side. An increase in rainfall and snowfall intensities was found responsible for higher amount of rainfall and snowfall on the windward side in the middle Himalayan range.

In the greater Himalayan range it was found that rainfall decreases exponentially with elevation and snowfall increases linearly. Rainfall becomes negligible at elevations beyond 4000m on the windward side of great Himalayan range. Also, greater Himalayas experience lower snowfall in comparison to the middle Himalayas. Average number of snowfall days increases with elevation, but the intensity decreases.

Outer and middle Himalayas experience moderate rainfall whereas greater Himalayan range receives less rainfall. In the outer and middle Himalayas, average of all stations on a particular range indicates that monsoon rainfall exhibits maximum contribution, more than 40%, in annual rainfall followed by winter rainfall which is more than 26%. In the greater Himalayas, premonsoon rainfall was found to be relatively more prominent than the monsoon rainfall. Post-monsoon rainfall contribution was in general negligible over all 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.Maximum snowfall is generally experienced in the months of January and February in the Middle and in March in the greater Himalayas.

1.0 Introduction

Precipitation provides the basic input for hydrological studies, however, it varies greatly in space and time from one mountain range to another. The hydrological processes can not be properly represented until distribution of precipitation is known. The gradients in amount and intensity of precipitation depend upon several factors such as topography, geography, strength of moisture current, its moisture content, orientation of the mountain range with respect to the prevailing wind direction.The ambient temperature determines types of precipitation namely rain, snow or both types of precipitation. Either a deficiency of water vapour or the non-occurrence of major weather disturbances, or both, are mainly responsible for lower precipitation.

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 good rainfall on the windward side of the mountains. If basin relief is very high, there may not be continuous rise; beyond a particular altitude the precipitation may actually decrease with height. The variation in precipitation with altitude is limited by mean height of clouds and decrease of water vapour with altitude. Thus, precipitationin mountains can decrease with altitude above certain level. Information on variation of precipitation with elevation for a particular watershed would be very much 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 of these regions so that utilization of the available water resources is carefully and judiciously planned.

35% of the geographical area in India is mountainous and 58% of this is accounted for by the mighty Himalaya. Moreover, the mountain zone of perpetual snow has given rise to a number of rivers. The role of this control structure in the climatology is well pronounced in the indian subcontinent. 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 this region. In context to India in particular, detailed studies to assess the orography effect on precipitation in the Himalayan region were not done. The main reason for the limited number of studies has been lack of information on precipitation at high elevations because of inaccessibility and other difficulties. Now precipitation (snowfall and rainfall) data base for few basins has improved because of good network in the lower, middle and upper part of the basins. The Chenab basin which has been taken up for the present study is one of those catchments which have a very good network even at high elevations. This has helped in undertaking a systematic scientific study to understand the nature of precipitation distribution in the western Himalayas.

2.0 Review of Orographic Effect on Precipitation Distribution

The influence of mountain barriers on precipitation distribution has been attracting the attention of scientists since long.As recognised by Salter (1918) from analysis of British data, the effect of altitude on the vertical distribution of precipitation in mountainous areas is highly variable in different geographical locations. It was pointed out that the relative relief of topographical obstacle need not be great in order to influence the air flow or the occurrence of climatic elements such as precipitation. Even 'micro relief' of 50 m or less can affect precipitation distribution (Bergeron,1960). The effects of small differences in relief may be much more greater than that had been supposed (Thornthwaite,1961 ; Bergeron,1965).

To establish relationship between precipitation and topography is considered an interesting problem to the hydrologists to account for variation in precipitation in the mountainous basins. Several studies are carried out on distribution of rainfall and snowfall with elevation in the different parts of the world. Because rainfall and snowfall have shown different patterns of variation with elevation, the review has accordingly been presented separately for rainfall and snowfall.

2.1 Rainfall distribution

The distribution of rainfall with elevation in the Sierra Nevada mountains in the USA has shown that rainfall increases up to a height of 1500m in these mountains (Linsley et al., 1949), whereas in the Andes mountains in the Ecuador two zones of maximum rainfall along the western and eastern slopes at elevation of 1000m and 1400 m respectively are found (Rumley, 1965).

Based on rainfall events, Murphy and Shamach (1966) carried out a comparative study of the concurrent rainfall made during storms at Juneau, Alaska, USA, both at sea level station, Juneau city and a nearby mountain station, Mount Juneau (3400 ft). The two stations 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. Based on the analysis of the limited samples of storms it was 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 at the city of Juneau which shows very high increase in rainfall with elevation. However further trend can not be inferred from these results because only two stations were considered in this study.

Duckstein et al. (1972) carried out a study on elevation effects on rainfall using an event based stochastic model of thunderstorm rainfall and empirical data. For this purpose data of summer rainfall which is essentially caused by the airmass convective storms occurring in July, August and September are considered. The distribution of number of events per season is assumed to be a Poisson variate whereas distribution of point rainfall depth has been considered as geometric. The summation of random number of random variables has been used to represent seasonal point precipitation. The mean total seasonal rainfall increases as a quadratic polynomial with elevation, but linear approximation was also found quite satisfactory. 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, USA. It was found that mean numbers of events per season increases considerably with elevation while mean amount of rainfall per event increases moderately with elevation. Engman and Hershfield (1969) reported that average number of days and hours with precipitation increases with elevation in both summer and winter in northeastern Vermount, USA.

2.2 Snowfall 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 explain most of the variations(Scermerhorn, 1967)

Distribution of winter precipitation has also been a topic of special interest in the Rocky Mountains. Rhea and Grant (1974) found that 80% of the variance of water content of snow in Colorado and Utah can be accounted for in terms of two parameters:

the directionally adjusted slope which potential precipitation bearing air currents must across for a distance of 200 km upwind; 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 2400 m. Variability, on the other hand,decreases with increasing elevation.

In the winter season (October-May), Hendrick et al (1978) reported a three-fold increase in the hours of precipitation between 400 and 1200 m elevation at Mt Mansfield, Vermount. Hamon (1971) concluded that winter precipitation increased more than four times at the 7000 ft elevation in comparison to that observed at the 4000 ft elevation in the southwestern Idaho. 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 proved best when the stations were grouped into downwind and upwind sites. It was indicated that winter precipitation will also follow the same distribution, because a high percentage of annual precipitation falls during winters.

Various high level stations and observatories in the Alps indicate that amount of precipitation increases with elevation to the highest level of 3000-3500 m (Barry, 1992). In the Swiss Alps , snow depth (water equivalent) appear to be maximal around 2700 m altitude, and may decrease slightly above (Martinec, 1987). Witmer et al (1986) found mean gradient of total new snowfall below 1100 m altitude varies from 80 mm/100m in south-western Alps to 730 mm/100m in northern slopes of Alps.

Golding(1968) found a linear relationship between snow water equivalents and elevation. A mean rate of increase for snow water equivalent for 4 years was reported of the order of 873 mm/km between 1950 m and 2225 m. Using a stepwise linear regression analysis in the Canadian Rocky Mountains covering a range of elevation from 1500 to 2800 m, Loijens (1972) has shown that between 81-87% of variance of snow water equivalent is associated with physiographic variables namely elevation and slope.

One of the major studies has been carried out by Storr and Ferguson(1972) in five 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 is considerably higher than that for rainfall. Several regression models for mean annual and monthly precipitation were developed. From the preliminary models, it was concluded that elevation and barrier distance provide highest correlation with precipitation. An examination of variation of precipitation with these two parameters suggested that a second power relationship provided the better fit. The use of elevation and barrier distance in the second power as predictor of precipitation in mountainous areas were also suggested in similar studies by Solomon et al (1968) and Obedkoff (1970).

For the polar regions, data on the altitudinal effect on precipitation relate primarily to snow accumulation records on Greenland and Antarctic ice sheets. These have been summarised by Sudgen(1977) noting that accumulation in Antartica and north Greenland increases to about 1500-1600 m altitude and thereafter decreases. In south-east Greenland and eastern Antarctic the maximum snow occurs at about 700 m. Using precipitation and accumulation data for Greenland, Ohmura(1991) shows the existence in western Greenland of a zone of maximum occurring around 2500 m at 69°North and descending northward to about 1500 m at 76°North. In the eastern Greenland, the higher values are found along the coast.

3.0 Status of Snowfall and Rainfall Distribution Over Himalayas

The interest in such studies in Himalaya 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 1200 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 exist 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) rainfall-elevation profile show that the zones of maximum rainfall occur near the foothills and at an elevation of 2000m to 2400 m. Beyond this elevation, rainfall decreases continuously as elevation increases until the great Himalayan range is reached. Higuchi et al (1982) also 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 2800 m to 4500 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 were carried out to understand snow distribution. Studies in Langtang valley in Nepal between 3920 m and 5090 m show that snowfall from winter weather system increases with height in the winter season.

4.0 Problem Definition

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 adjacent watersheds. Significant variations may occur between physiographical precipitation models over relatively short distances in the mountainous areas (Peck and Brown,1962). Fitzharris(1975) also observed that improved precisions are possible when separate equations are developed for each zone. The same is applicable for the watersheds of the Himalaya 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 a 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. Because most of the snowfall is restricted to the winter season,there is no scope to study snowfall distribution season wise. 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 premonsoon and postmonsoon 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 studied for each season. The list of stations with respect to orientation in the three ranges is given in Appendix-I.

5.0 Study Area and Data Used

5.1 About Himalayas

The Himalayas are an extensive mountain system of 2400 km from Nanga Parbat (8126 m) in the west to Namcha Barua (7756 m) in the east in the shape of a convex with its convexity toward the south. The Himalaya further may be subdivided laterally into western, central and eastern Himalayas. The western Himalaya extends right from Nanga Parbat to Nanda Devi and is the origin of Indus and Ganga river. The central Himalayas stretches from Ghaghra and Gandak to Kosi river system and limited to Nepal Himalayas, whereas the eastern Himalaya ranges from east of Kosi to Namcha Barua in bend of Brahamputra river (Figure 1).

The Himalayas are not a single chain of mountains. It consists of three west to east running parallel ranges and between these ranges there are numerous narrow valleys. Three parallel ranges or geographical zones are described below:

(i) Outer Himalayas

This is the southernmost range of Himalayas and is known as Siwalik ranges also. Their average height varies from 900 to 1200 m asl and average width varies from 10 to 50 km. Attaining an altitude of about 600m they end abruptly inwards in steep escarpments and follow successive narrow parallel ridges, trending NW-SE and separated by valleys representing basins. The elevation of outer hills rarely exceeds 1200m.

(ii) Middle Himalayas

The ranges representing this part of Hiamalayas consists of higher mountains. These are a series of broken mountain ranges whose mean elevation varies from 2000 m to 3300 m asl. Their width varies from 60 to 80 km. These ranges have different names in the different sections of the Himalayas such as Lesser Himalayas or Pir Panjal ranges in the western Himalayas. The middle Himalaya lies between the outer Himalaya and the perpetual snow covered ranges of greater Himalaya. It is characterized by deeply cut valleys. The ridges extending in irregular direction appear to branch again and again.

(iii) Greater Himalayas

This is the most northern range of the Himalayas. It is lofty, rugged chain reaching high above the perpetual snowline. The average height of this range is about 6000 m asl. In this great Himalayan range as many as 13 peaks exceed 6000m elevation.

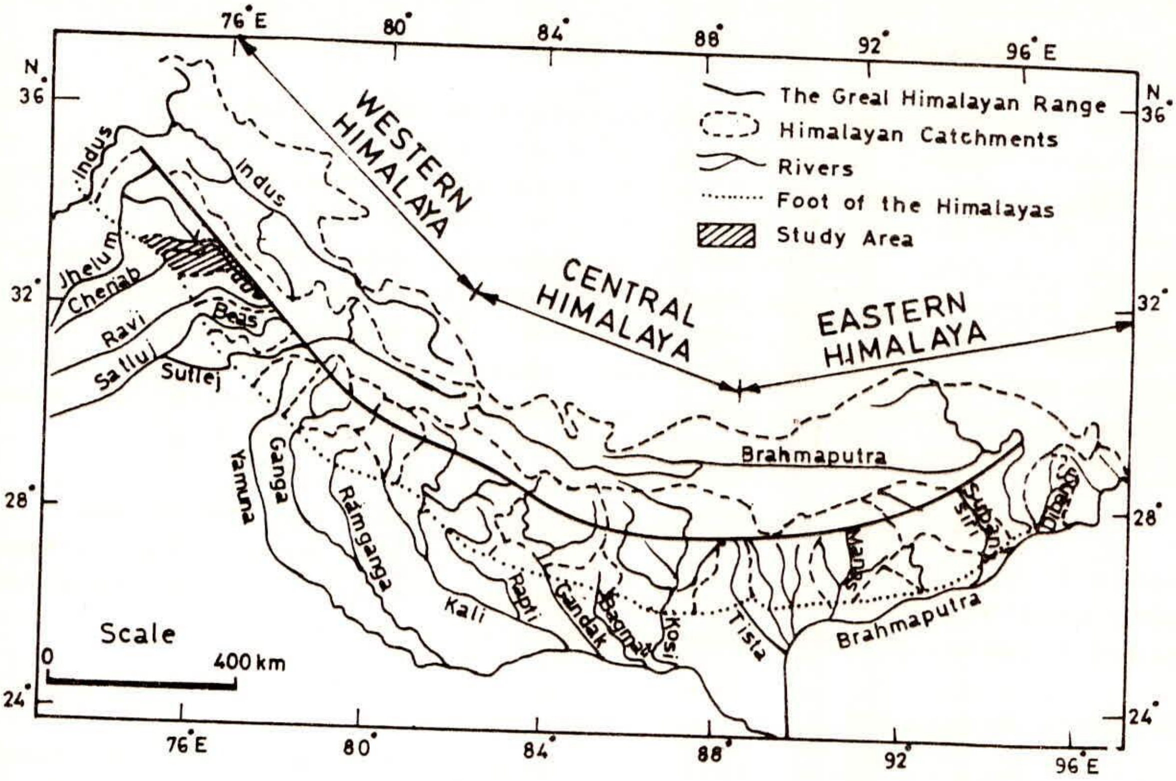

Fig 1 : Different sections of Himalayas and catchments of the Himalayan rivers.

A still large number of peaks range from 4500 m to 6000 m. Beyond the main ranges of Himalaya, there is a continual series of somewhat lower Trans Himalayan zone (average altitude varying between 5000 m and 6000m) adjoining the Tibetan plateau.

5.2 Himalayan climate

The great contrast in the geographical relief results in variety of climate in the Himalayas. Such regions are characterized by numerous small climatic differences over short horizontal distances. Principal controls producing such differences are those of altitude, local relief and mountain barrier effect. The strongest systematic dependence of climate on physiography is its relation to elevation (Howell, 1949), but the actual distribution of elements is greatly determined by the patterns of landscape and other physiographical contrasts in slopes, valleys etc creating climatic differences over short distances.

The most important factors controlling the weather and climate in the Himalayas are altitude and aspect. Largely due to variations in altitude, the climate varies from hot and moist tropical climate in lower valleys, to cool temperate climate at about 2000 m and tends toward polar as the altitude increases beyond 2000 m. Altitude controls not only temperature but rainfall also. The second factor controlling the climate is aspect. Usually the south facing slopes are more sunny and also get more rain. Further, in each individual range the snowline is higheron souther aspect as these slopes have more sunshine. Also, the snow line in the eastern Himalayas is higher than in the western Himalayas.

5.3 Precipitation characteristics of the region

Knowledge of precipitation distribution during individual months, seasons and the year is of vital importance both for planning water resources projects and agricultural operation in a given basin/region. The precipitation distribution over this basin in months, season and year have 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.

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

The source of precipitation and its distribution in each of the season is described in the following section.

Winter Season

The precipitation during this season is caused by extratropical weather system of mid latitude region originating from Caspian sea and moving eastward. They approach India from the west through Iran, Afghanistan and Pakistan. With the setting of the winter season these disturbances have the tendency to move along lower latitudes. Ordinarily these disturbances remain at high latitudes and do not influence the Himalayas. But, as the season advances they come lower and lower and by the end of December they cover more or less whole Himalaya. After the close of season they recede to their original position beyond the Himalayan mountains. Normal tracks of these disturbances during the month of October and January are shown in Figure 2. The tracks of the disturbances lie over continental areas , far removed from the sea, they carry a small amount of moisture with result that precipitation caused by them is small.

The precipitation during this season is generally in the form of snow in the greater Himalayas , snow and rain in the middle Himalayas, and only rain over the outer Himalayas and the adjoining north Indian plains. Precipitation occurs at intervals throughout the winter season. It is found that average frequency of occurrences of these disturbances is about 3 to 5 each month and reduces as the season advances.

The higher precipitation in the western Himalayas during these months is the combined effect of the nearly east-west configuration of the Himalayas and eastward movement of the winter weather system. The precipitation associated with this weather system decreases considerably as they move eastwards along the Himalaya because of increasing distance from the source of moisture. These weather systems cause snowfall at higher elevations.

Pre-monsoon Season

Generally this seasons lasts for about a period of 3 months from April to June and is considered as transit period between winter and southwest monsoon. Light to moderate rain is essentially caused by air mass convective storms. Convection increases as the season advances because of increasing trend of temperature in the Himalayan region.

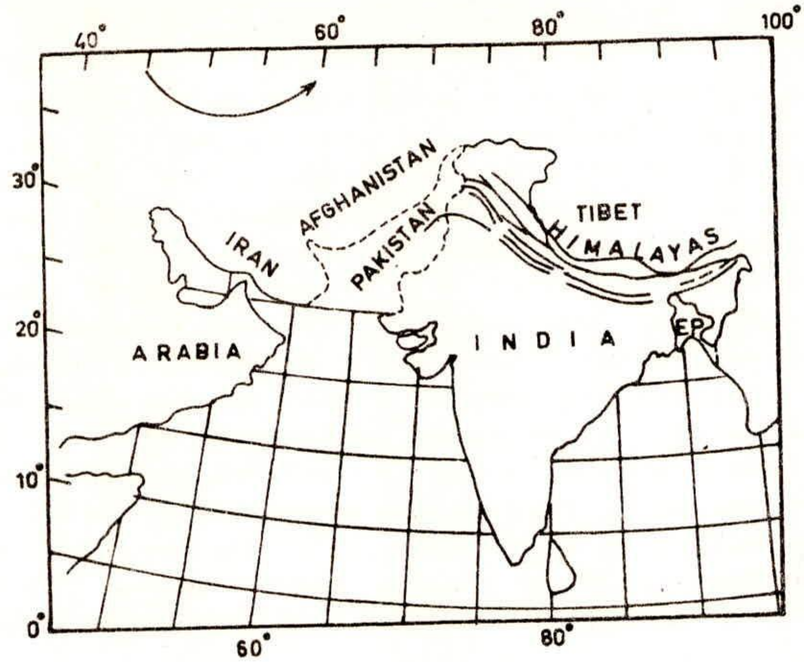

Fig.2(a) Normal track of western disturbance in October

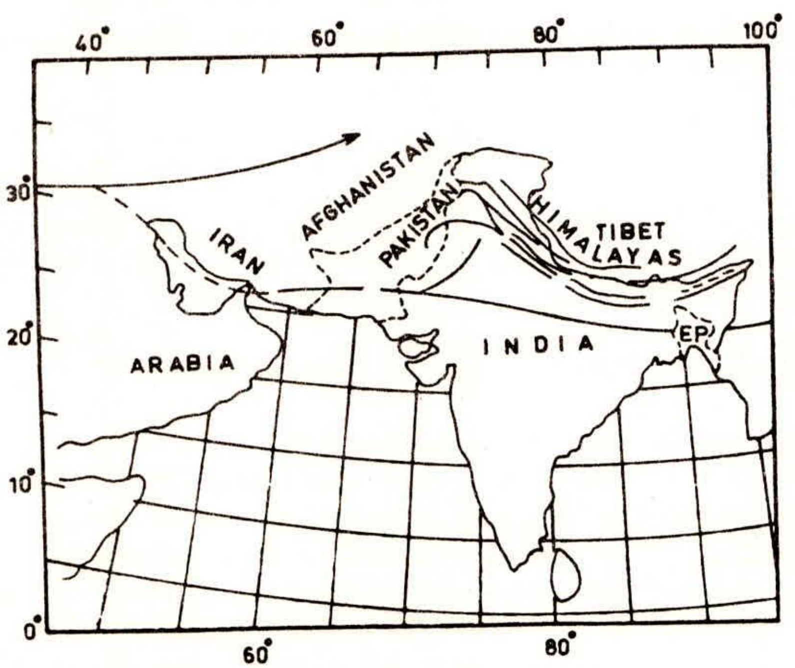

Fig. 2(b) Normal track of western disturbance in January

Monsoon Season

Normally precipitation over the Himalayas is caused by the moist air currents from Bay of Bengal in this season. Sometimes, in association with certain weather situations both branches of monsoon (i.e., the Bay of Bengal and Arabian sea) arrive simultaneously in this region heralding the onsetof monsoon. These currents after striking the Burma and eastern Himalayas are deflected westwards and travel along the Himalayas. Rainfall decreases westward because of increasing distance from the source of moisture i.e. Bay of Bengal or Arabian Sea, which results in less amount of moisture content in the air currents. Consequently lesser precipitation is observed as one moves further and further to the west. This is the season of abundant rain and rivers are generally flooded. Snow and glaciers at very high altitudes continue melting during this season. The monsoon normally starts withdrawing from this region towards the end of September.

It was observed that while the monsoon currents give copious rainfall over the Indian plains, after they cross the Himalayan ranges and move over trans-Himalayan regions become practically dry as most of the moisture they initially carried is precipitated during their passage over the plains and mountain ranges of the Himalayas.

Post Monsoon

During this season clear autumn weather sets in and there is generally little rainfall. This is the driest season in the entire Himalaya as well as in the plain areas.

5.4 Hydrological characteristics of Chenab basin

The area for which this study is carried out lies in the basin of Chenab. The study area included the foothills and high mountains of Himalayas. The basin consists of a series of high and rugged mountains. The contribution of snowmelt is quite significant in this river because of heavy snowfall from December to April. At the high altitudes the snow is experienced generally from October to May. A major part of annual precipitation, above 2000 m, falls during the winters in the form of snow. Due to large differences in seasonal temperature and great range of elevation variation in this region snowline changes its position considerably. The south-west monsoon causes rainfall in the lower part of catchment during the period July to September. The study area is shown in Figure 3.

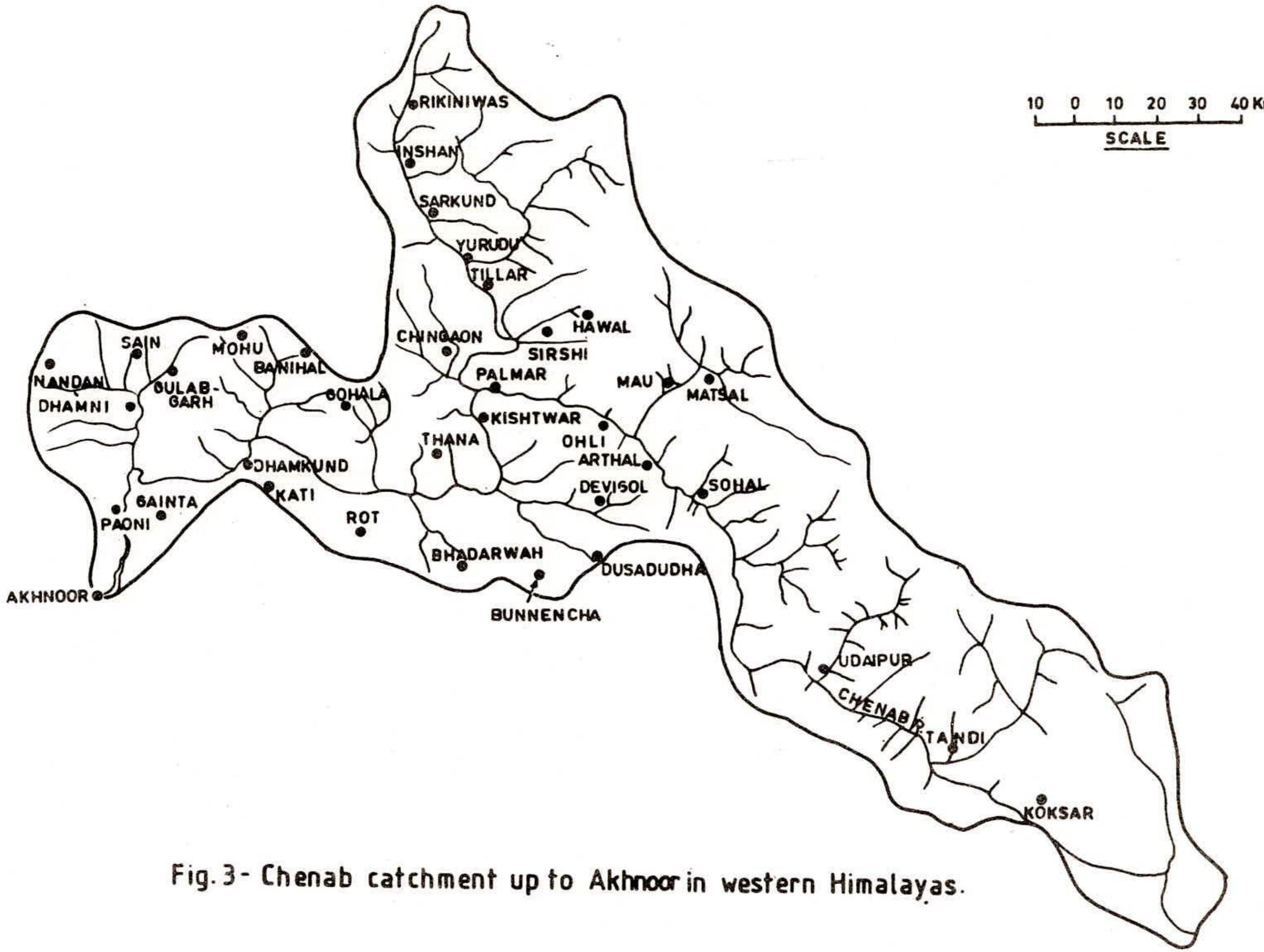

Fig. 3 - Chenab catchment up to Akhnoor in western Himalayas.

Temporal variability in discharge is another outstanding feature of the Himalayan rivers. The flow can be distributed in well marked four seasons. In the winter season flow is basically from surface flow due to seasonal rains and contribution from sub-surface flow and ground water in the outer and middle Himalayas. In the premonsoon season, snowmelt and glacier produce high flows in the mid or late summer. Sometimes, rainfall also contributes to the flows in this season. During monsoon season, the flow is augmented by monsoon rains to produce higher discharges and occasional peak floods. In the post monsoon season, flow is believed to be from the glaciers and occasional rain events in the basin.. Flooding in these areas results from excessive or heavy rainfall. Sometimes combination of rainfall and excessive snowmelt also cause floods.

5.5 Data Used

To study the rain distribution with altitude daily rainfall data of 31 stations located at different elevations is used. The snow distribution was carried out using daily snowfall data of 26 stations. For both rain and snow, data of 17 years (1974-1990) was considered. Data for one station,however, was available for 11 years period. Details of the stations used for this analysis are given in Appendix-I. Mean monthly, seasonal and annual values were 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. Data for snowfall and rainfall have been recorded separately at each station. A period from October-September is considered in terms of annual analysis so that complete snow cycle is covered. Generally snowfall starts in or after October at higher reaches in the basin.

6.0 Results and Discussions

6.1 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 (Figure 4). Snowfall starts at about 1300 m in this section of Himalayas. At an elevation of about 3000m solid and liquid precipitation are equal. Snow contribution further increases as the elevation increases and reaches to about 75% at an elevation of 4325 m. The elevation where all the precipitation falls in the form of solid precipitation could not be determined because data for locations beyond 4325 m is not available. However, one can expect that above 6000 m elevation, whatever precipitation occurs may be falling as snow only.

6.2 Rainfall distribution

There is variation in the amount of rainfall received at 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 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 on the results follows.

(a) 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 Figure 5(a)-(e). It is observed that rainfall linearly varies with elevation in this range of Himalaya during winter, premonsoon and

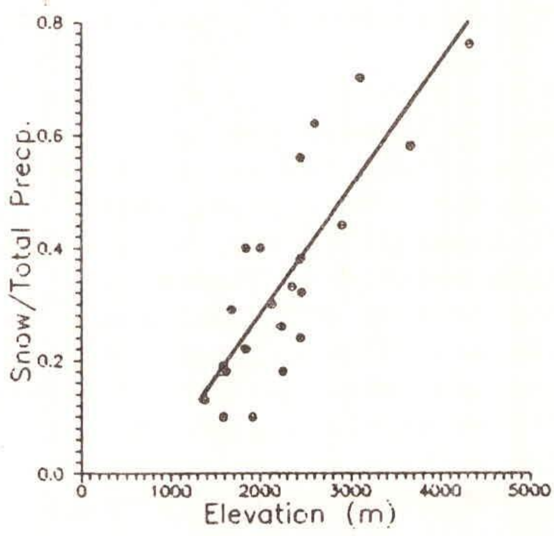

Figure 4 : Variation in snowfall contribution to total precipitation with altitude in Himalayas

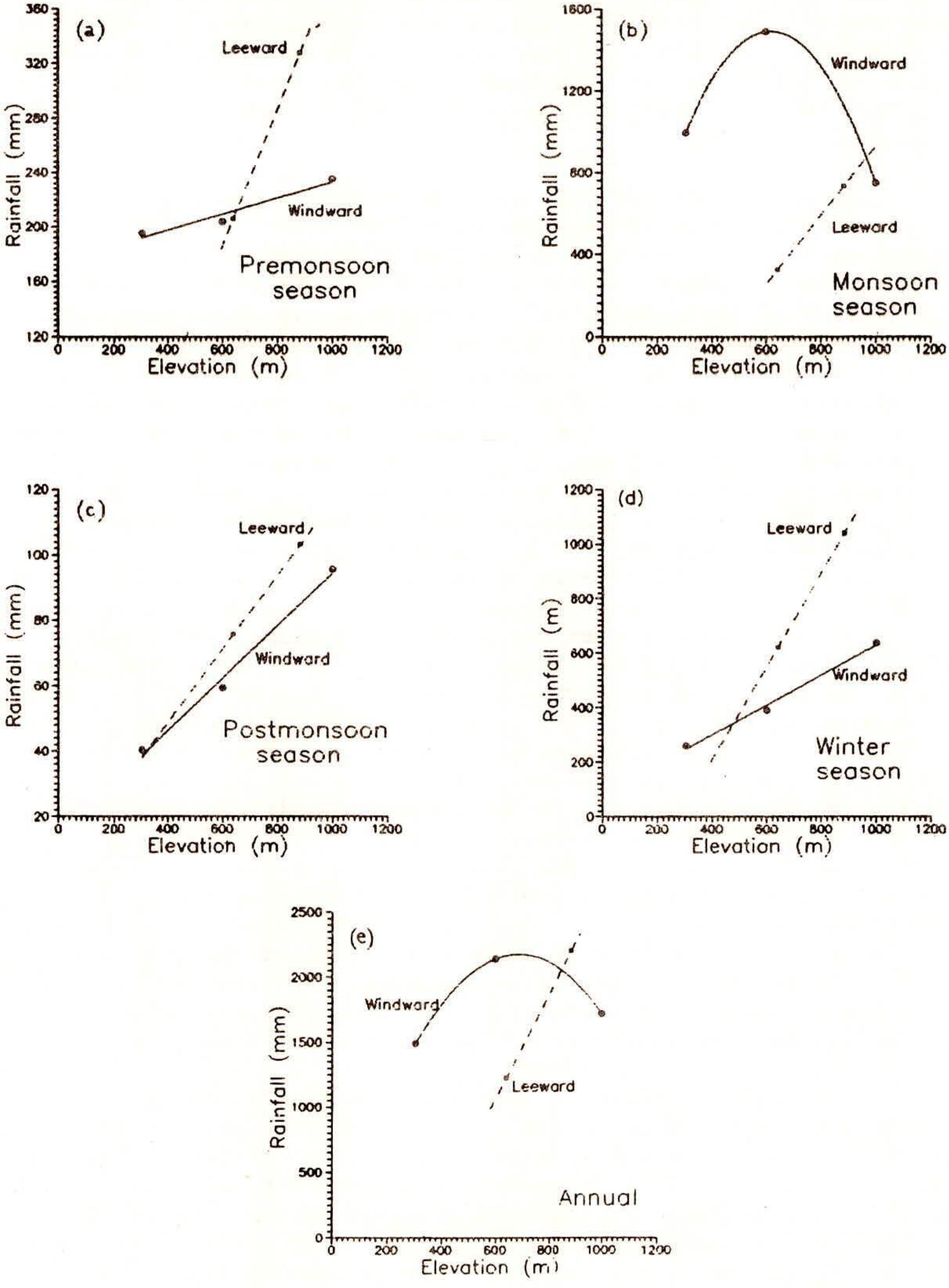

Figure 5 : Variation in rainfall with elevation in the Outer Himalayas

postmonsoon 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 600m 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.

Results indicate 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, premonsoon, and postmonsoon rainfall there is 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 premonsoon 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 premonsoon and post monsoon rainfall is caused by locally formed cloud systems whereas winter and monsoon rainfall is caused by moving moist air system.

Spill over effect on rainfall is dominant in the three seasons out of four season 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 (premonsoon, postmonsoon 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 Figure 6(a) and (b). Average intensity for the same is shown in Figure 6(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 increase 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 (Table 1&2).

(b) Middle Himalayas

Rainfall distribution with elevation for the middle Himalayas is shown in Figure 7(a)-(e). Availability of rainfall data in this range of Himalayas is better than for the outer Himalayas. Data of sixteen stations were available on the windward and leeward side of this range of Himalaya in this basin. It was 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 1600 and 2200 m. The lower rainfall

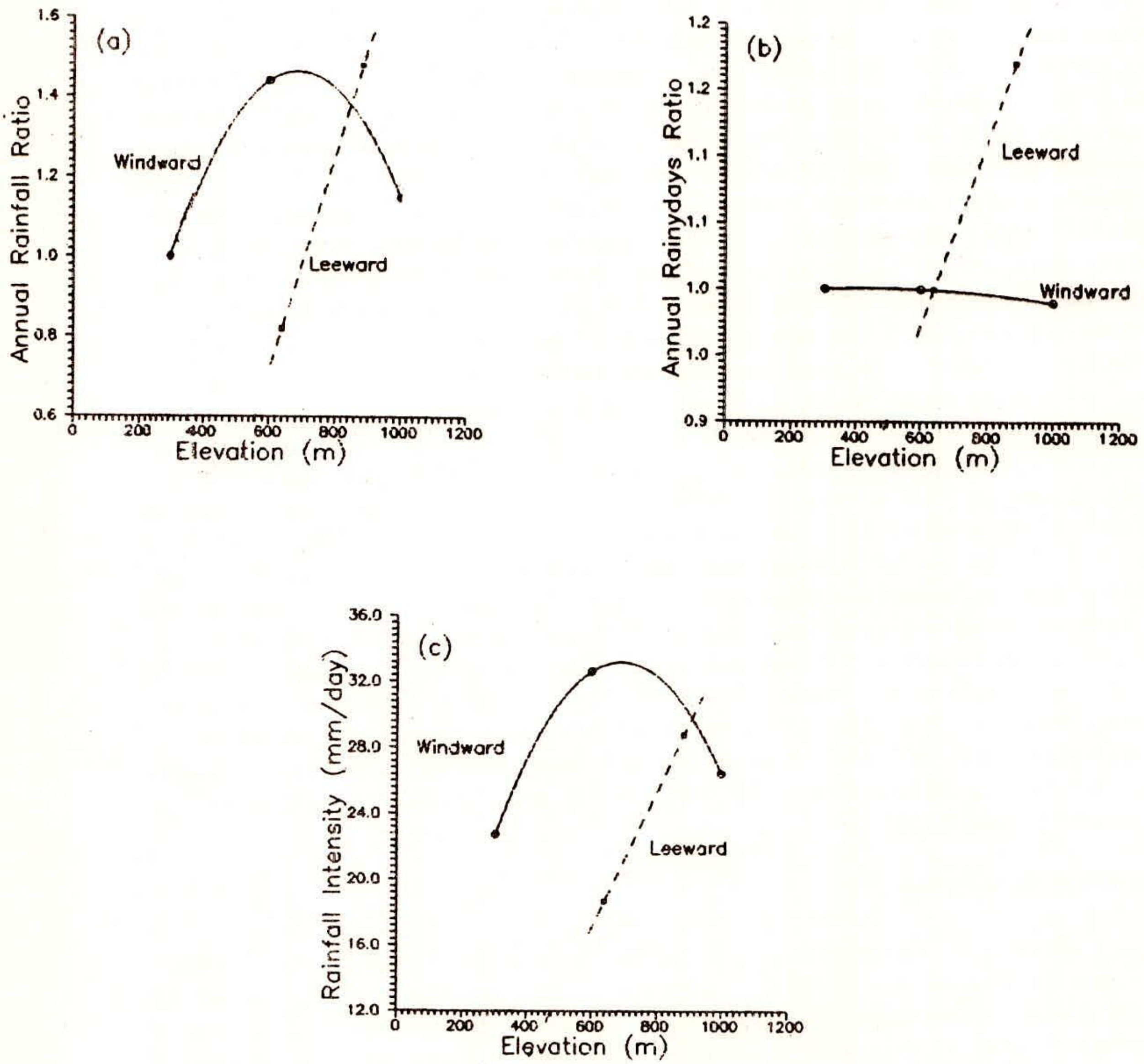

Figure 6 : Variation in rainfall ratio, rainydays ratio and rainfall intensity in the Outer Himalayas

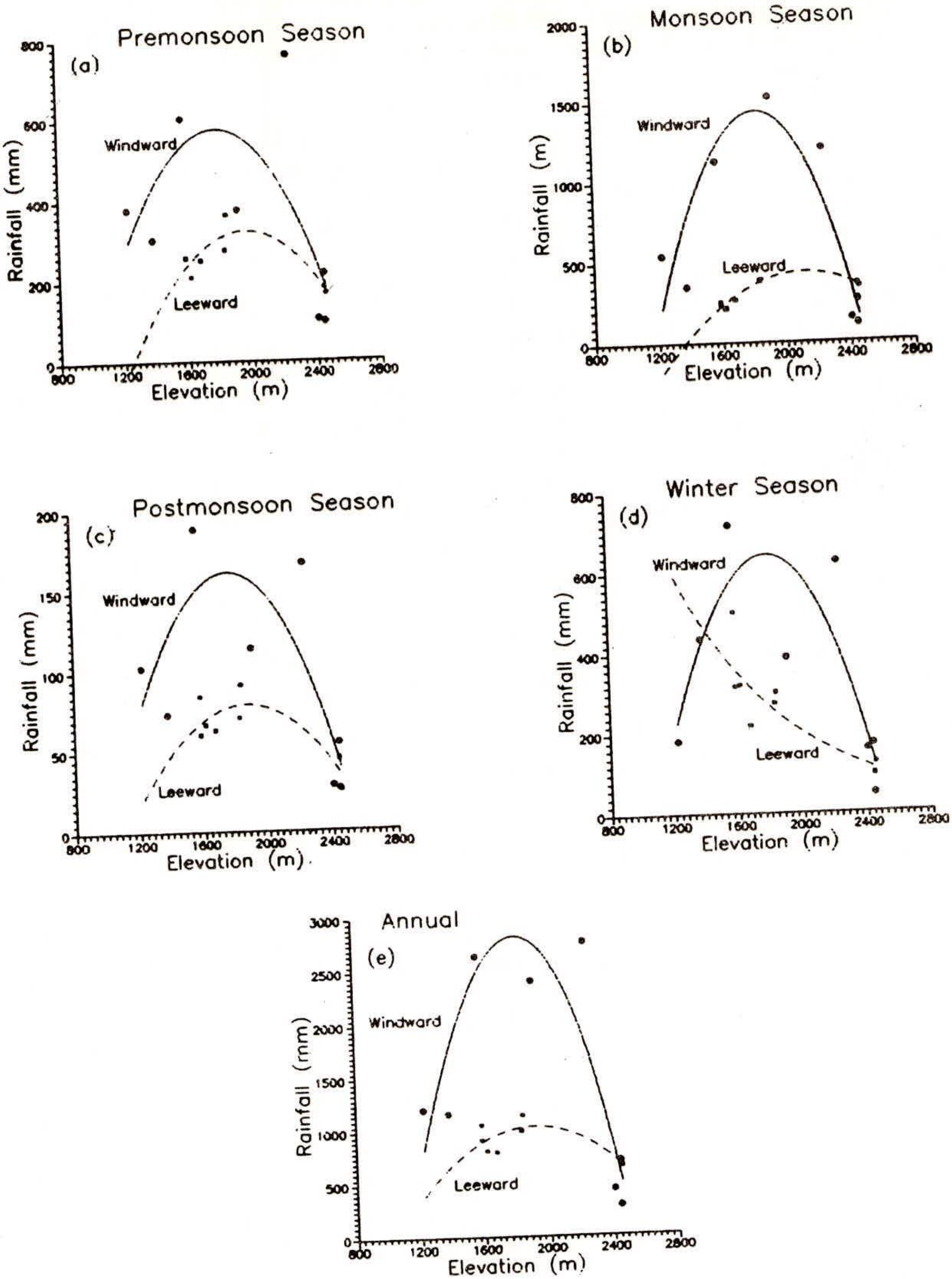

Figure 7 : Variation in rainfall with elevation in Middle Himalayas

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)	429.1 (24.1%)	211.4 (11.9%)	1077.0 (60.4%)	65.1 (3.7%)	1782.5
	Leeward (North)	830.7 (48.4%)	266.9 (15.6%)	528.3 (30.8%)	89.5 (5.2%)	1715.4
	Average	629.9 (36.0%)	239.2 (13.7%)	802.7 (45.9%)	77.3 (4.4%)	1748.9
middle Himalayas	Windward (South)	340.8 (23.7%)	353.5 (24.5%)	652.5 (45.3%)	94.3 (6.5%)	1441.2
	Leeward (North)	269.5 (30.7%)	244.1 (27.8%)	299.4 (34.2%)	63.6 (7.3%)	876.6
	Average	305.2 (26.3%)	298.8 (25.8%)	475.9 (41.1%)	78.9 (6.8%)	1158.9
greater Himalayas	Windward (South)	61.7 (14.2%)	176.6 (40.7%)	162.9 (35.7%)	32.4 (7.5%)	433.7
Mean		332.3 (29.8%)	238.2 (21.4%)	480.5 (43.1%)	62.9 (5.6%)	1113.8

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	27.3	-	-
	Leeward (North)	71	23.7	-	-
	Average	68	25.5	-	-
middle Himalayas	Windward (South)	57	23.0	10	44.0
	Leeward (North)	60	14.5	13	25.0
	Average	59	18.7	12	34.5
greater Himalayas	Windward (South)	36	9.8	30	12.4

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 slope of mountains 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 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 premonsson and postmonsoon seasons. It can be explained on the basis of cloud formation and their movement. In the premonsoon 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 side 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 premonsoon and postmosoon 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 relatively more in the winter, premonsoon and postmonsoon seasons when compared with monsoon season. Different cloud formation 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 leeward side is always less than on windward slopes.

The variation in the average annual rainfall and rainy days with respect to a station at the lowest elevation in the windward side of the Middle Himalayas are shown in Figures 8(a)-(b) and annual average rainfall intensity per rainy day is also illustrated in Figure 8(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

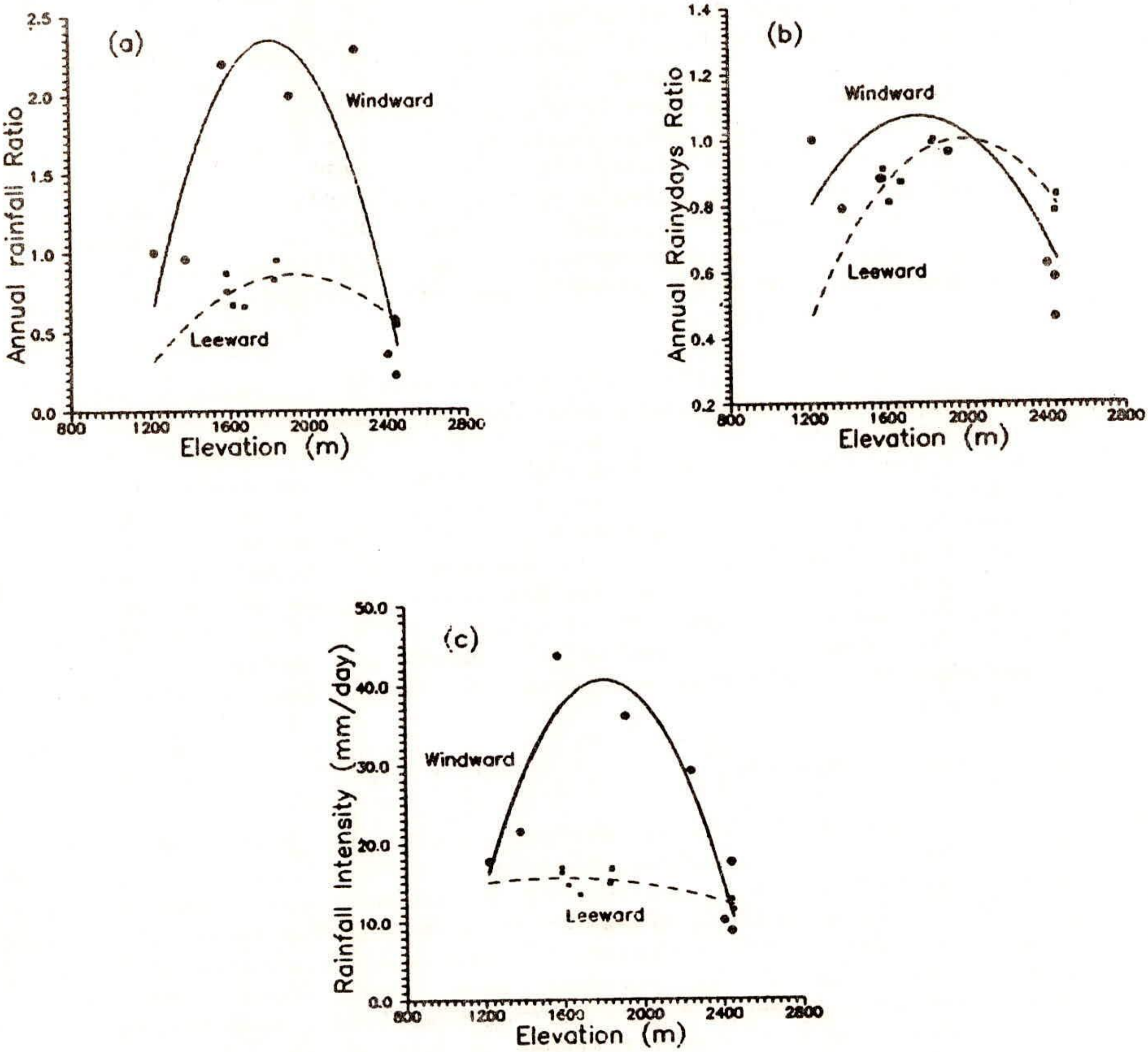

Figure 8 : Variation in rainfall ratio, rainydays ratio and rainfall intensity with elevation in the Middle Himalayas

found to be more than 2 and this ratio with respect to same station on 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 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 premonsoon seasons is also significant on both sides. Average annual rainfall intensity is also higher 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 are more pronounced in the middle Himalayas in comparison to the outer Himalayas.

(c) Greater Himalayas

Trends of rainfall distribution in the Greater Himalayas are exhibited in Figures 9(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 very less moisture content in the clouds by the time they reach in this Himalayan range. In the winter season rainfall decreases with relatively faster rate in comparison to the other three seasons and becomes negligible around 4000 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 premonsoon and postmonsoon seasons most of the clouds are locally formed and precipitate which results in gradual decrease in rainfall with elevation. It can be

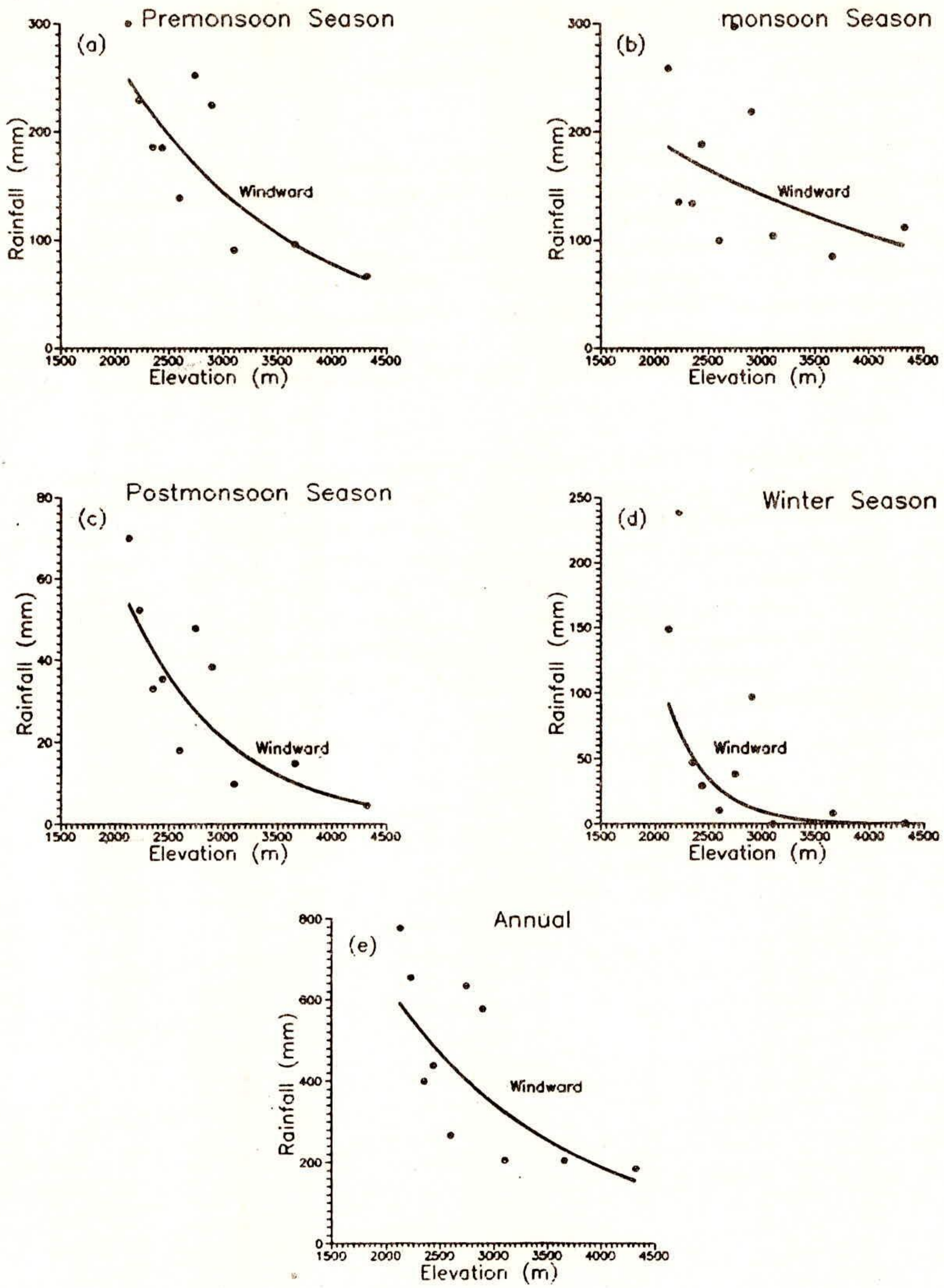

Figure 9 : Variation in rainfall with elevation in the Greater Himalayas

noticed that rainfall magnitude is not much changed in monsoon season while compared with premonsoon 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 (Figure 10(a)-(c)). It is apparent that both lower rainfall intensity and less number of rainy days are responsible fordecrease 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, premonsoon rainfall (40.7%) dominates on the wind ward 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 in 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 premonsoon, monsoon and postmonsoon seasons.

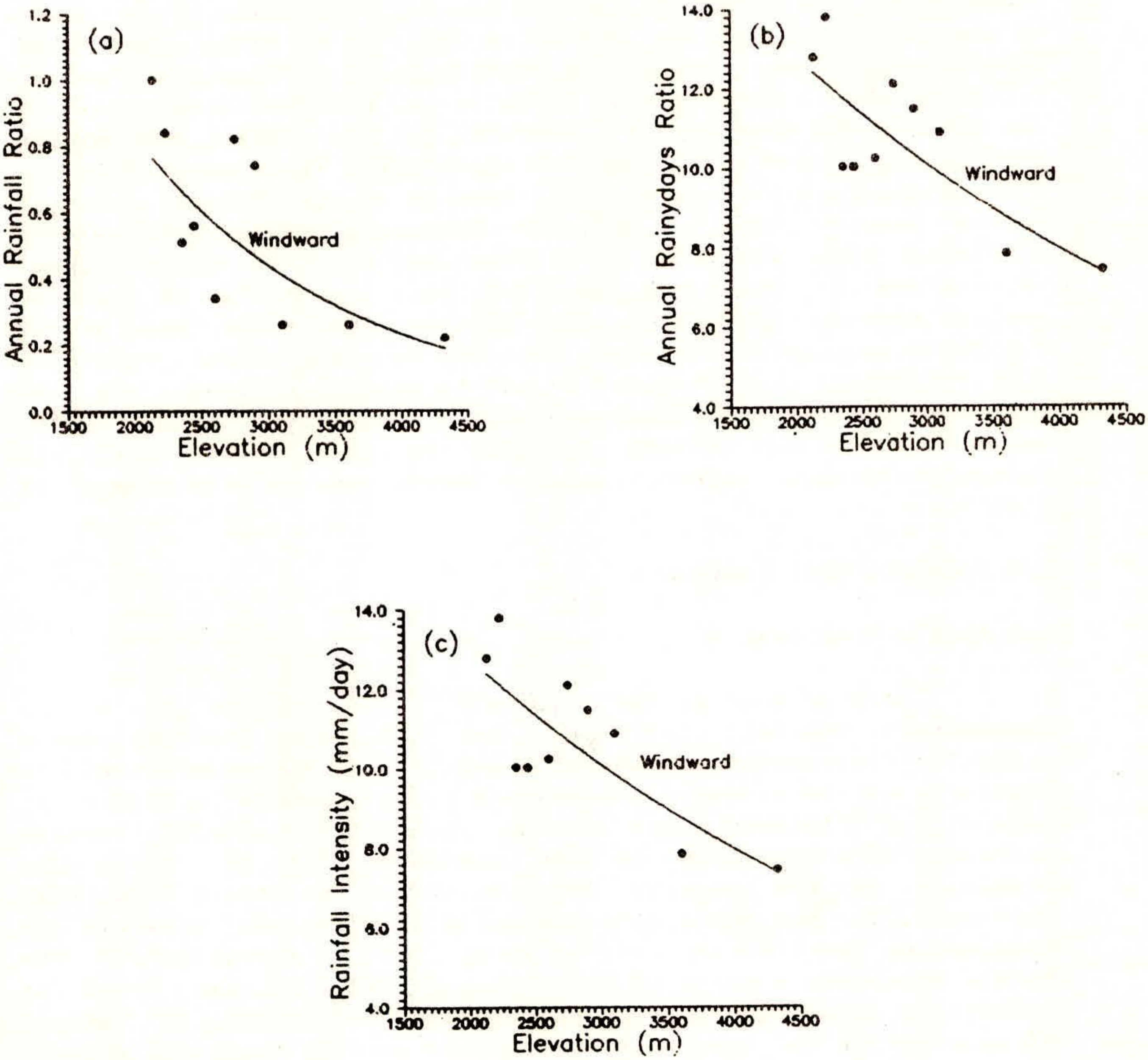

Figure 10: Variation in rainfall ratio, rainydays ratio and rainfall intensity with elevation in the Greater Himalayas

6.3 Comparison of rainfall in different ranges of Himalaya

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 (1000-2000mm) whereas greater Himalayas receives 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 premonsoon rainfall contributes much to the annual rainfall and monsoon rainfall is next to it. Rainfall during postmonsoon season is always lowest over all the ranges of Himalayas.

6.4 Snowfall distribution

(a) 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 altitudefor middle Himalayas on the windward and leeward sides is shown in Figures 11 (a). It was observed that unlike rainfall, snowfall linearly increases with elevation on the windward side of the middle Himalayas. On the leeward side it first increases and then decreases. The available data indicated that maximum snowfall is received on the windward side at about 2500 m elevation in the Middle Himayayas whereas on the leeward side it was found at relatively lower elevation of about 1800m. The substantial amount of snowfall on the upper part of leeward also is expected due to linearly 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 in the windward side, it was found that on the upper part of windward snowfall is about 5 times higher than the valley station (Figure 11(b)). On the leeward side the highest point value was about 3 times higher when compared

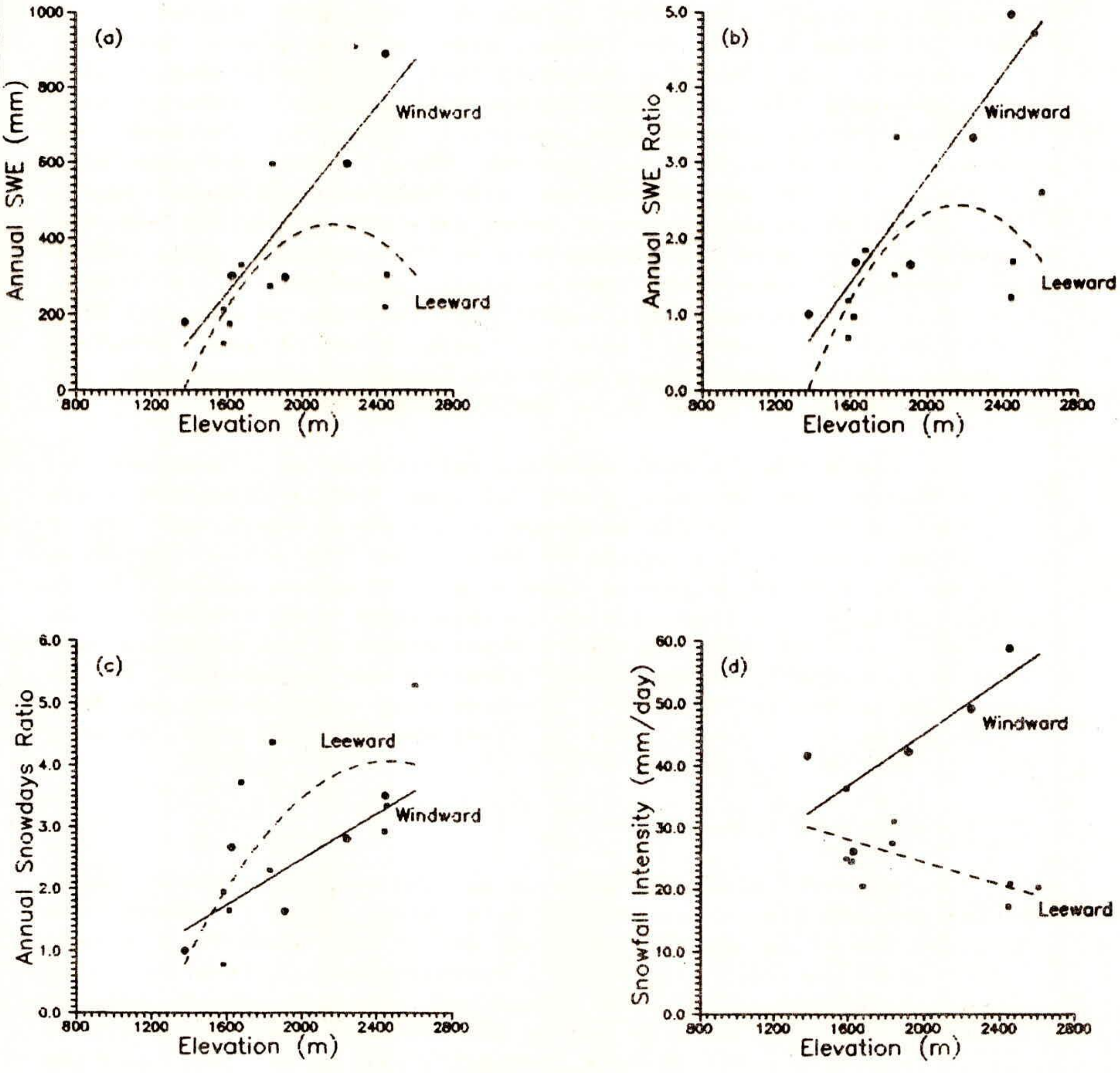

Figure 11 : Variation of snowfall water equivalent (SWE), its ratio, snowdays ratio and snow intensity with elevation in the Middle Himalayas

with same station. For further details, investigations were extended to find out average annual snowy days and snowfall intensity per snowy days on both sides of middle Himalayas. Variation in snowdays on both sides with respect to base station is shown in Figure 11(c)&(d). It was observed that variation in number of snowy days on the leeward side was more pronounced than 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.

(b) 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 (Figure 12 (a). The trend of snowfall could not be studied on the leeward side and on the windward side beyond 4325 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

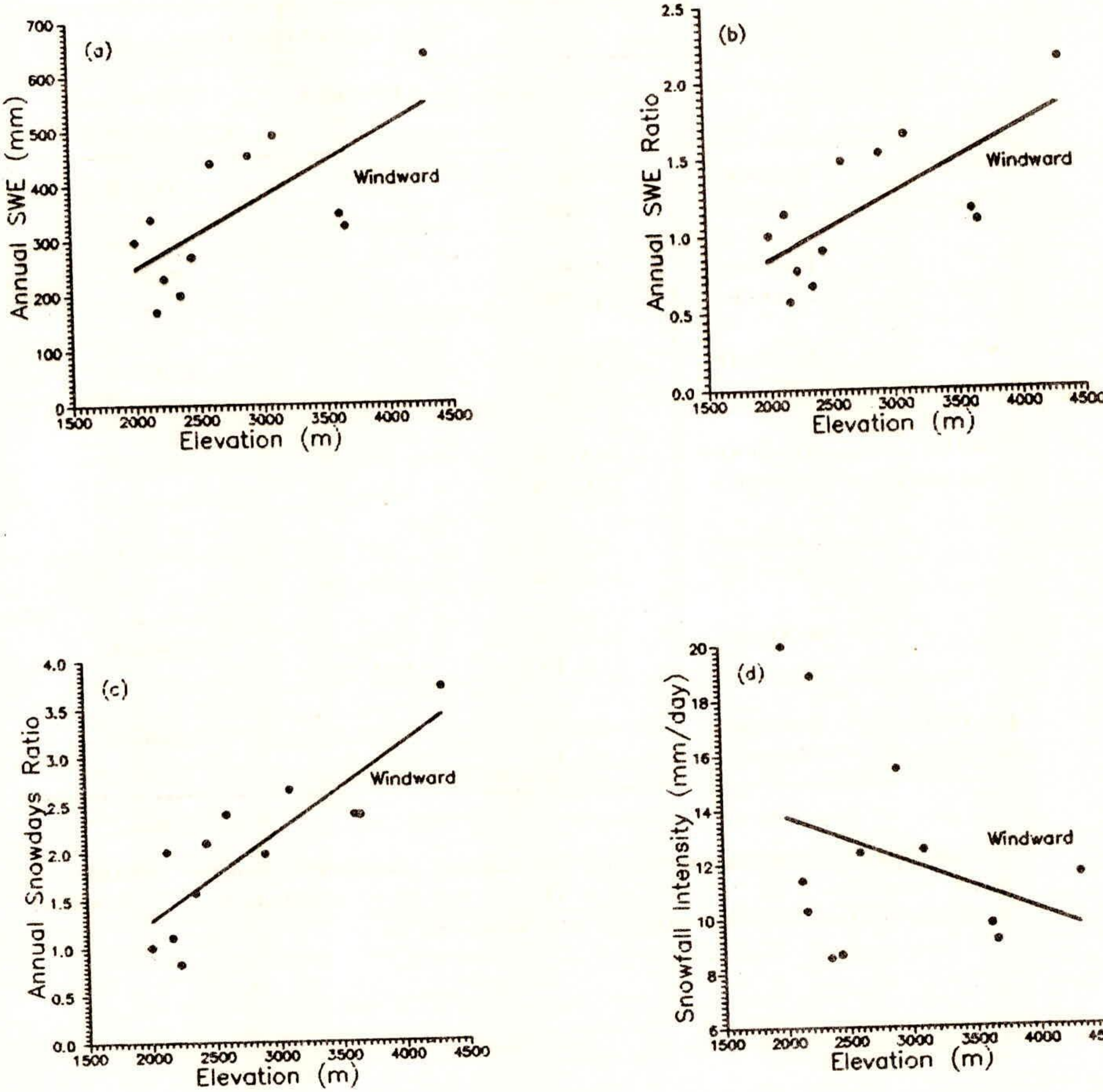

Figure 12 : Variation in snowfall water equivalent (SWE), its ratio, snowdays ratio and snow intensity with elevation in the Greater Himalayas

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

Range	Aspect	Precipitation (mm)		
		rainfall	snowfall	total precipitation
outer Himalayas	Windward (South)	1782.5 (100%)	-	1782.5
	Leeward (North)	1715.4 (100%)	-	1715.4
	Average	1748.9 (100%)		- 1748.9
middle Himalayas	Windward (South)	1441.2 (76.1%)	451.9 (23.9%)	1893.1
	Leeward (North)	876.6 (76.0%)	277.0 (24.0%)	1153.6
	Average	1158.9 (76.0%)	366.5 (24.0%)	1525.4
greater Himalayas	Windward (South)	432.5 (55.4%)	348.0^{+} (44.6%)	780.5^{+}

$^{+}$These values are supposed to be higher because there would be more snowfall at higher elevations on the windward of Greater Himalayas for which data is not available.

side, it was found that snowfall is nearly about 4 times at an elevation of 4325 m (Figure 12 (b)). The number of snowy days also increase linearly with altitude in this range, but no systematic trend of snowfall intensity has been observed (Figure 12(c)&(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).

6.5 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 time in the greater Himalayas in comparison to the 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.

7.0 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 place to place because of highly rugged topography of the Himalayan mountains. Therefore, effect of orography on precipitation distribution in the different sections of Himalayas is studies. Different trends of rainfall and snowfall distribution with elevation led to carry out such studies separately for snowfall and rainfall distribution. Grouping of stations was done with respect to particular range and aspect of Himalaya. The following conclusions are drawn from this study:

(a) Rainfall distribution

1. Distribution of seasonal and annual rainfall show 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 600m on the windward side during monsoon season.

2. Spill over effect is noticed in the outer Himalayas during winter, premonsoon and postmonsoon seasons.

3. Rainfall follows similar distribution with elevation on both windward and leeward sides i.e. first it increases with elevation and then starts decreasing. The rainfall pattern has been fitted well with second order polynomials. The region of maximum rainfall on windward and leeward sides was found to be between 1600 and 2200 m.

4. Increase in rainfall intensities with elevation was found 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 (1749 mm) was observed in the outer Himalayas whereas minimum (433 mm) was observed in the greater Himalayas. In the middle Himalayas it was observed to be 1159 mm. These figures of rainfall indicated that moderate rainfall (1000-2000mm) is experienced in the outer and middle Himalayas whereas less rainfall in received in the greater Himalayas.

6. In general, monsoon rainfall was found to be dominant in the outer and middle Himalayas. It was noted that monsoon rainfall contributes about 46% and 41% to the annual rainfall of outer and middle Himalayas, respectively. In the greater Himalayas premonsoon 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 was 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 Hiamalayas and becomes negligible at elevations beyond4000m. Lower rainfall intensity and lesser number of rainy days give lesser rain in this section of Himalayas.

8. The role of orography in the middle Himalayas was found to be very pronounced for both rainfall and snowfall in comparison to other ranges.

(b) Snowfall distribution

9. It was found that 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 was found to be at about 2500 m elevation on the windward and at 1800m on the leeward side of middle Himalayas.

11. Higher snowfall intensities were found to be responsible for higher amount of snowfall on the windward side in the middle Himalayas. Lower snowfall on the leeward side was found to be due to 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 was 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. It has been found that at an elevation of about 3000m, solid and liquid precipitation are 50% of annual precipitation.

Acknowledgements

Authors are very much thankful to Northern Circle, Central Water Commission for providing data for this study. Support extended by Indus Commissioner, Ministry of water Resources, Govt. of India is also acknowledged in making available required data. Authors are thankful to Shri Om Prakash, Research Assistant for helping in data preparation on computer.

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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	1000	R			
(b) Middle Himalayas					
6. Gulabgarh	1220	R	15. Palmar	1585	R&S
7. Rot	1375	R&S	16. Ohli	1585	R&S
8. Kati	1570	R	17. Kistwar	1615	R&S
9. Banihal	1625	S	18. Sirsi	1675	R&S
10. Nandan	1910	R&S	19. Bhadarwah	1830	R&S
11. Sain	2240	R&S	20. Chingaon	1840	R&S
12. Gohala	2400	R	21. Dusadudha	2440	R&S
13. Mohu	2440	R&S	22. Devigol	2450	R&S
14. Thana	2440	R	23. Bunnencha	2600	S
(c) Greater Himalayas					
24. Sohal	2000	S			
25. Tillar	2130	R&S			
26. Yurdu	2165	S			
27. Arthal	2225	R&S			
28. Sarkund	2350	R&S			
29. Inshan	2440	R&S			
30. Udaipur	2600	R&S			
31. Hawal	2745	R			
32. Mau	2900	R&S			
33. Tandi	3100	R&S			
34. Koksar	3615	S			
35. Rikiniwas	3660	R&S			
36. Matsal	4325	R&S			

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