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Two principal precipitation regimes in Himalayas and their influence on tree distribution

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Abstract: Based on data collected from 90 meteorological stations distributed in Indian Himalayas, two precipitation regimes has been identified: (i) Monsoonal Precipitation Regime (MPR), in which annual precipitation is high, generally from about 1500 mm to over 3000 mm, and 60–80% of which occurs during the monsoon months; and (ii) Non-monsoonal Precipitation Regime (NMPR), in which annual precipitation is generally below 1000 mm, and the contribution of monsoon months to annual precipitation is less than 50%. While MPR in the characteristic precipitation regime of the areas in south of the main Himalayan ranges, MPR generally occurs in areas north of the main Himalayan ranges or in southern slopes shielded from the monsoon thrust by high mountain ranges. Because of a stronger influence of westerlies in NMPR, winter and spring precipitations exceed the monsoon precipitation. Thus the two precipitation regimes differ, not only in the amount of annual precipitation, but also in its seasonal distribution. Temperature lapse rate is lower during monsoon season (e.g. in Nepal, 0.46°C/ 100 m altitude during the monsoon, compared to 0.49°C–0.64°C/ 100 m during other seasons), that is why the upper altitudinal limit of temperatures, warm enough to support tree growth, is relatively higher in MPR. The nature of precipitation regime influences the distribution of trees. Distribution of certain tree species, such as *Pinus wallichiana* and *Cedrus deodara* is particularly linked to NMPR, while some widely occurring Himalayan species, like *Pinus roxburghii* and *Quercus leucotrichophora* tend to avoid NMPR.

Key words: Himalayas, lapse rate, monsoonal and non-monsoonal precipitation, temperature, timberline, tree distribution.

Introduction

Understanding the changes in the amount of water and its seasonal availability in different regions of Himalayas is of critical importance not only to the people who live in mountains, but also for nearly one-fourth of global population living in the 10 connected river basins (Immerzeel *et al.* 2010; Revenga *et al.* 2003) where population density in some areas exceeds 1000 km^{-2}. Because of the sparse distribution of meteorological stations, particularly in higher mountain ranges, spatial and temporal distribution of precipitation in Himalayas is poorly documented. For example, contrary to the earlier understanding that precipitation in Himalayas decreases with elevation (Muller 1982), recent observations from Nepal show no sign of decrease in precipitation even beyond 3000 m (Immerzeel *et al.* 2014). The recent analyses of the difference in the responses of Himalayan glaciers to

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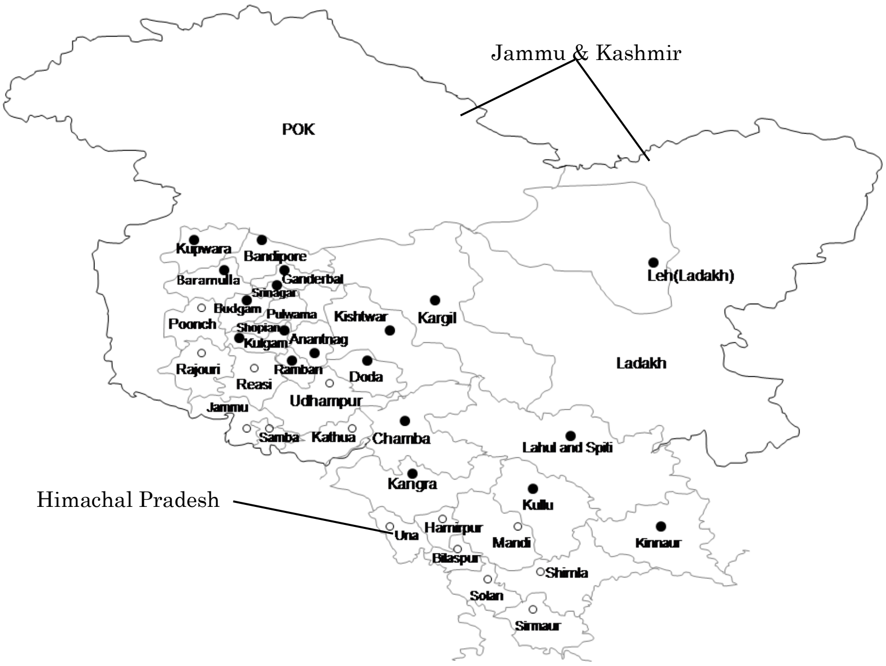
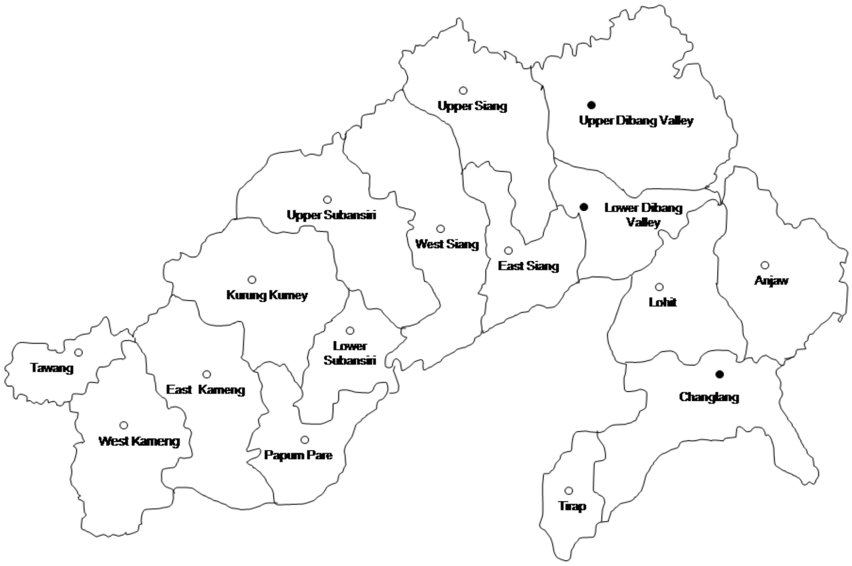
Western Himalayan States
Jammu & Kashmir 33.77° N, 76.7° E
Himachal Pradesh 31.10° N, 77.17° E



● Non-monsoonal Precipitation Regimes (NMPR)
○ Monsoonal Precipitation Regimes (MPR)

Eastern Himalayan State

Arunachal Pradesh 28.21°N, 94.72° E



● Non-monsoonal Precipitation Regimes (NMPR)
○ Monsoonal Precipitation Regimes (MPR)

Fig. 1. Map showing MPR and NMPR meteorological stations in the Western Himalayan states (Jammu and Kashmir and Himachal Pradesh) and Eastern Himalayan state (Arunachal Pradesh) of India.

climate warming have drawn attention to the relative roles of the monsoon and westerlies in precipitation and glacier dynamics. While the shrinkage of glaciers in monsoon dominated Himalayan regions is common, in Karakorum where the westerlies influence is conspicuous, glaciers have expanded (Immerzeel *et al.* 2010; Yao *et al.* 2012).

Much of the Himalayas are under the influence of monsoon with about 70%–80% of the annual precipitation occurring during the typical monsoon months, from June to September (Bookhagen & Burbank 2010). However, in several areas, particularly in the north of the main Himalayan ranges, westerlies, the upper tropospheric waves with source in the Mediterranean sea and the Atlantic ocean, exert a considerable influence on the seasonal pattern of precipitation (Brookhagen & Burbank 2010; Burbank *et al.* 2012; Mènègoz *et al.* 2013).

While much of the outer Himalayan ranges, directly exposed to monsoon thrust, receive up to 3000–4000 mm annual precipitation, the valleys in the North of the Main Himalayan Ranges (MHR) are dry receiving generally <500 mm precipitation. The precipitation of the areas in the north of MHR is characterized by the low amounts precipitation, the difference in seasonal distribution receiving only cursory attention. Researchers have pointed out that such areas getting more winter and spring precipitation due to the westerlies (Benn & Owen 1998; Bhutiyani *et al.* 2010, Burbank *et al.* 2012), but overall modification of the seasonal and spatial distribution of precipitation due to them at a regional level has drawn little attention. Moreover, how the difference in precipitation is reflected in the distribution of forest trees and other species has received only passing references in studies on Himalayan vegetation (Champion & Seth 1968; Miehe *et al.* 2015; Stainton 1972).

Here is an attempt to consolidate available information to compare the precipitation patterns between the areas that differ in exposure to monsoon, and the influence of difference in precipitation on vegetation, particularly tree distribution. The specific questions that we address are the following: (i) Do the Himalayan valleys, away from monsoon thrust consistently differ from those exposed to monsoon thrust in seasonality and amount of precipitation? (ii) How does the distribution of major forest forming tree species differ in relation to the two types of precipitation regime, the one dominated by monsoon and the other by westerlies? and (iii) analyzing the implication of difference in precipitation regime to temperature lapse rate and hence to the treeline altitude is a secondary objective. The seasonal distribution of precipitation is of critical importance to the annual plant growth cycle, particularly seed shedding, seed germination and establishment of seedlings, hence the geographical distribution of species, and altitudes of timberline formation.

Methods

Our analysis of precipitation is based on data of Indian Meteorological Department (IMD) on Indian Himalayan region. As for tree species distribution, we have extracted information largely from research articles, books on vegetation and flora, Ph.D. theses and the records of state forest departments. We could get precipitation data for 91 stations, distributed as following: Jammu and Kashmir (J&K) 22 stations, Himachal Pradesh (HP) 12 stations, Uttarakhand (UK) 13 stations, Arunachal Pradesh (AP) 16 stations, Mizoram 9 stations, Nagaland 11 stations, Sikkim 4 stations, Tripura 4 stations, Manipur 9 stations, Meghalaya 7 stations (Fig.1). The density of meteorological stations is very sparse, and they are mostly limited to <1000 m (40 stations) and 1000–2000 m (41 stations) altitudinal belts.

We classified meteorological stations into two broad precipitation regimes on the basis of percentage of annual precipitation during typical Indian monsoon months, from June to September: the first regime with 60% and more of annual precipitation during typical monsoon months, referred to as monsoonal precipitation regime (MPR); and the second regime with less than 50% of annual precipitation during monsoon months, referred to as non-monsoonal precipitation regime (NMPR). While monsoon is the dominant precipitation source for the first regime, the influence of westerlies is conspicuous in the second. Westerlies are extra-tropical storms originating in the Mediterranean and surrounding regions, that deposit precipitation during winters and pre-monsoon seasons; they are strong in the north western parts of Indian sub-continent and surroundings. The months of seasons recognized were as following: monsoon from June to September, autumn from October to November, winter from December to February and pre-monsoon from March to June.

The two meteorological stations, in which monsoon accounted for an intermediate percentage of annual precipitation, (50% and 55%) were not

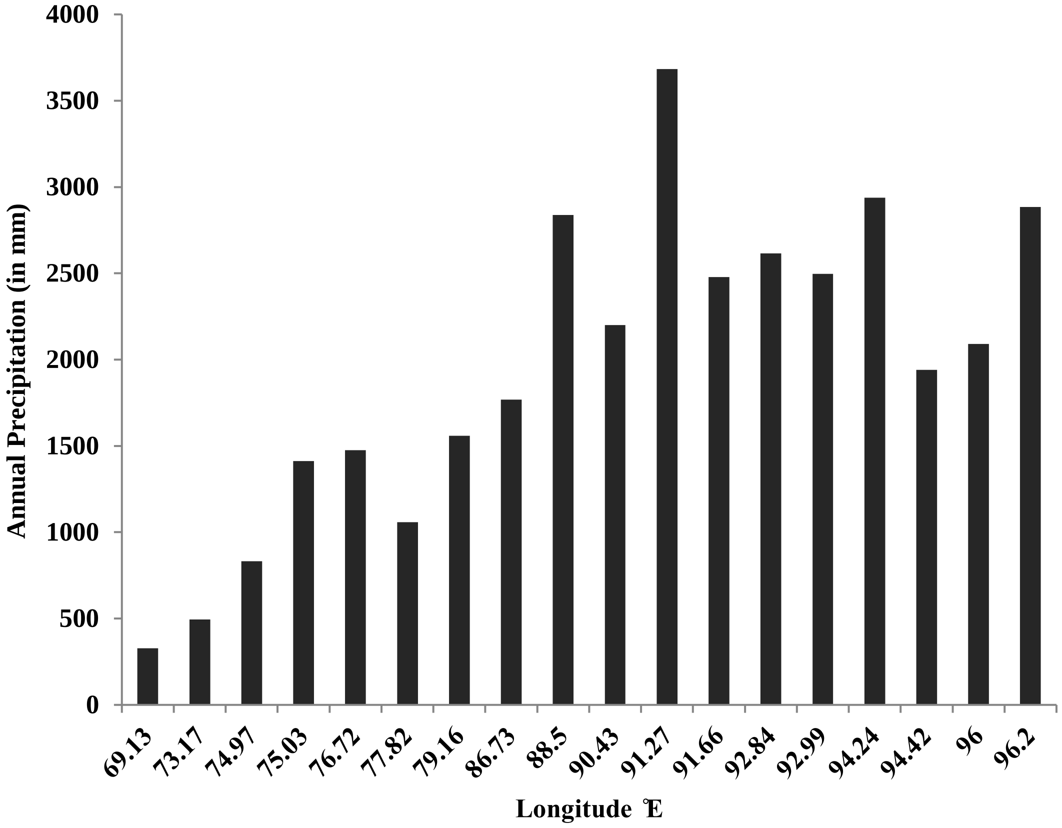


Fig. 2. Pattern of annual precipitation in relation to longitude along the Himalayan Arc (they were significantly positively correlated, r = 0.85; $P \leq 0.05$). The regions/states by longitudes (average) are; 69.13 = Afghanistan, 73.17 = Upper-Indus-Basin, 74.97 = Jammu & Kashmir non-monsoonal, 75.03 = Jammu & Kashmir monsoonal, 76.72 = Himachal Pradesh monsoonal, 77.82 = Himachal Pradesh non-monsoonal, 79.16 = Uttarakhand, 86.73 = Nepal, 88.5 = Sikkim, 90.43 = Bhutan, 91.27 = Meghalaya, 91.66 = Tripura, 92.84 = Mizoram, 92.99 = Manipur, 94.24 = Arunachal Pradesh monsoonal, 94.42 = Nagaland, 96 = Myanmar, 96.2 = Arunachal Pradesh non-monsoonal.

included in this categorization. The monsoonal type was further divided into two sub-categories: (1) monsoonal with moderately high annual precipitation (generally 1000–2000 mm/year) and dry pre-monsoon, and (2) monsoonal with heavy annual precipitation (generally above 2000 mm/year) and relatively moist pre-monsoon season, referred to as monsoonal I and monsoonal II respectively.

The significance of difference between the two precipitation regimes was tested at 5% level of significance using the independent samples t-test with the help of SPSS 20.0 software. Correlation between annual precipitation and longitude for 18 stations and correlation between monsoon precipitation and longitude for 13 stations was developed in Microsoft Excel.

To determine the evenness (even distribution) of precipitation distribution across from seasons, Levine's Response Breadth (in Singh & Singh 1992) was used as:

$$B=1/\Sigma P_i^2.$$

where; B= Levine's measure of breadth, P_i= Proportional amount of precipitation in seasons (winter, pre-monsoon, monsoon and autumn).

The main literature sources that we used to analyse tree species distribution in relation to precipitation regime were: Troup (1921), Osmaston

(1927), Schweinfurt (1957), Champion & Seth (1968), Freitag (1971), Stainton (1972), Polunin & Stainton (1984), Singh & Singh (1992), Dobremez (1976), Shrestha *et al.* (2000) and Miehe *et al.* (2015). For seed dispersal and seed germination timings of tree species the distribution of which is extended to NMPR information were collected from Troup (1921), Rao (1984) and Singh *et al.* (2016).

Results and discussion

Annual precipitation distribution in Himalayas

Annual precipitation across the Himalayan states increased from the west to east along the Himalayan Arc (from Afghanistan to Arunachal Pradesh) (r = 0.85; $P \leq 0.05$ between longitude and annual precipitation) (Fig. 2). The annual precipitation in Meghalaya state of India was roughly 10 fold greater than that in Afghanistan. This pattern is largely determined by the amount of monsoon precipitation (r = 0.92; $P \leq 0.05$ between annual precipitation and monsoon precipitation; and r = 0.69; $P \leq 0.05$ between monsoon precipitation and longitude). A similar increase in precipitation occurs from north to south in these mountains (Burbank *et al.* 2012).

Precipitation regimes

Among the states which had stations both with MPR and NMPR, Jammu and Kashmir (J&K) was primarily non-monsoonal (15 stations with NMPR and 7 stations with MPR), while HP (3 stations with NMPR and 9 stations with MPR) and AP (3 stations with NMPR and 13 stations with MPR) were primarily monsoonal (MPR) (Fig. 2). Inner areas, away from the direct monsoon thrust also occur in some remote areas of UK, but they do not have meteorological stations. The NMPR is generally associated with areas north of the high Main Himalayan Ranges (MHR), but it can also occur in areas south of the MHR, Srinagar valley of Kashmir, which is shielded from the monsoon influence by high Pir Panjal range, being a typical example. It may be pointed out that MPR sites, such as Jamson in Nepal with annual precipitation of only 295 mm can also be dry because of topographical peculiarities (Burbank *et al.* 2012).

The two precipitation regimes generally differ not only in the amount of precipitation, but also in the distribution of wet and dry periods (Table 1). The characteristic feature of the seasonal pattern of MPR is that 60–80% of annual rainfall occurs from June to September, leaving much of the rest of year conspicuously dry (Table 2). The pre-monsoon (from march to May) was driest in Uttarakhand (monsoonal I) among the Indian Himalayan states, while in eastern Himalayan states (monsoonal II) the three winter months were the driest, accounting for only 1.3–5.0% of annual rainfall. The annual precipitation in Indian eastern Himalaya and the eastern Nepal is generally high (generally up to > 4000 mm) for a seasonal climate. In the Eastern Himalayas, period from June to September, the typical monsoon months accounted for about 60–65% of annual precipitation.

The average amount of annual precipitation was significantly lower in NMPR than MPR in JK (t= 3.456; $P \leq 0.05$) and HP (t= 2.486; $P \leq 0.05$), but not in AP (t= 0.131; $P \geq 0.05$). The two precipitation regimes also differed significantly ($P \leq 0.05$) in seasonal distribution of precipitation (Table 3). As for AP, the increase in precipitation due to the westerlies almost compensated for the decrease in monsoon precipitation in NMPR of AP, resulting in similar amount of annual precipitation in the two regimes. In contrast, the strengthening of westerlies in NMPR in J&K and HP was not enough to compensate for the weakened monsoon, resulting in lower annual precipitation than in MPR in these two states.

In NMPR of J&K, pre-monsoon (36.9%) was the wettest season, in contrast to UK and other monsoonal western Himalayan regions where pre-monsoon drought is often the cause of tree water stress (Singh *et al.* 2006) and drought-induced fires (Singh *et al.* 2016). Levine's response breadth, a simple measure of evenness was significantly higher for NMPR than MPR, indicating relatively even distribution of precipitation across the seasons in NMPR (Fig. 3). NMPR is quiet common in Upper Indus Basin, Pakistan. Proportional distribution of annual precipitation across the seasons (based on 10 altitudinal belts of 500 m each between 500–4900 m) in the Indus valley indicates that winter precipitation (December, January, February) ranges between 20.74% and 29.62%, pre-monsoon (March, April, May) between 22.45% and 36.53%, monsoon (June, July, August) between 24.05% and 45.46% and autumn (September, October, November) between 9.6% and 11.6% (in this seasonal classification September was the part of pre-monsoon, Abbas *et al.* 2014). Data from 1900 to 2012 of a station (33.06 N, 64.82 E) from Afghanistan shows that typical monsoon months are rainless, about 94% of annual precipitation occurring during winter and pre-monsoon months

Table 1. Major categories of tree species distribution in relation to two precipitation regimes, Monsoonal Precipitation Regime (MPR) and Non-Monsoonal Precipitation Regime (NMPR) (based largely on Anonymous 2010; Champion & Seth 1968; Miehe *et al.* 2015; Singh & Singh 1992; Stainton 1972; Troup 1921).

Species	Place	Altitudinal (m) and Longitudinal (E) Ranges	Annual Precipitation (AP) and other characters
Entirely of NMPR			
Pinus gerardiana	Inner valleys, Nitipass in Garhwal to Chitral	1200–3500 m 79°E–71°E	AP, 250–270 mm
Juniperus macropoda	Nepal westwards	1515–4240 m 84°E	AP below 200 mm, mostly as snowfall
Juniperus recurva	Kumaun to Hengduan Shan, in Tibet to the east of Makalu	3000–4300 m 80°–-99°E	AP, 600–3500 mm
Juniperus Communis	From Afghanistan to Kumaun	1676–4268 m 72°E–79°E	AP less than 450 mm; snowfall considerable
Pistacia mutica	Eurasia from the Iranian Plateau to North Africa	1100–2300 m 99°E–25°E	AP, 300–500mm
Primarily of the NMPR but also of MPR			
Cedrus deodara	From Afghanistan, (Safed Koh) in the west to Nepal in the east (uncommon in Kumaun)	1800–2600 m 69°E–83°E	10% to 80% of AP as snowfall
Aesculus indica	Western Himalaya, Nepal westwards	1800–3100 m 69°E–82°E	Snowfall accounts for 50% (Jumla) to 90% (Nuristan) of AP
Pinus wallichiana	From Afghanistan to Bhutan	1800–4300 m 70°E–92°E	Snowfall accounts for 30% to 90% (NW parts) of AP
Picea smithiana	Between eastern Afghanistan to central Nepal	2100–3600 m 69°E–85°E	Snowfall accounts for 15% (Jumla, Nepal) to 85% (Nuristan) of AP
Fairly common in both MPR and NMPR			
Abies pindrow	From Safed Koh, Nuristan and Kulu (Himachal) to central Nepal	2000–3500 m 70°E–82°E	25% of AP as snowfall in Kulu
Betula utilis	From Afghanistan (Safed Koh) to Western China, including Bhutan	3030–4240 m 70°E–84°E	AP, 400–1700 mm; snowfall accounts from 25% (western Nepal) to 85% (Safed Koh) of AP
Cupressus torulosa	Between Chamba and the Thakkhola; the drought line ecotone; Dolpa, Suli Gad valley, Phoksundo Lake, Cha Lungpa	2500–3200 m 76°E–83°E	Precipitation ranges from 250 mm in inner valleys to >1000 mm in MPR areas; snowfall 10–55% of AP
Mostly NMPR			
Pinus roxburghii	Pakistan to Bhutan	500–2700 m 72°E–92°E	AP 500–2000 mm, monsoonal
Quercus leucotrichophora	Western Himalayan, extending eastwards to Nepal	1500-2700 m 74°E–83°E	AP, 1010–2410 mm, monsoonal
Quercus lamellosa	Eastern Himalayan from Nepal eastwards, Manipur, Darjeeling hills	1600–2800 m 83°E–102°E	AP, exceeds 3500 mm
Quercus semecarpifolia	Afghanistan to Bhutan and Manipur (absent from Sikkim)	2400–3400 m, occasionally up to 3700 m 72°E–94°E	AP, 1000–2000 mm; snowfall 10–30% of AP
Castanopsis spp.	China, Indochina to Indonesia, and also in Japan	1000–2900 m 83°E–100°E	AP, 1400–5000 mm
Rhododendron arboreum	Swat to Myanmar	1200–3200 m 72°E–98°E	AP, 850–2000 mm*

*But in Swat (Pakistan) half of precipitation as snow.

Table 2. A comparative account of Monsoonal Precipitation Regime (MPR) and Non-Monsoonal Precipitation Regime (NMPR) in Indian Himalayas. In the three states, Jammu & Kashmir (J & K), Himachal Pradesh (HP) and Arunachal Pradesh (AP) separate values for MPR and NMPR stations are available. Eastern Himalayan states other than AP have been grouped separately. Uttarakhand (UK) represents a western Himalayan state with no NMPR station. Values for the states are averages of several meteorological stations indicated in parentheses (n).

Parameter	States with both MPR and NMPR						States with only MPR	
	Jammu & Kashmir (Western)		Himachal Pradesh (Western)		Arunachal Pradesh (Eastern)		Uttarakhand (Western)	Eastern Himalayan states other than AP*
	MPR n=7	NMPR n=15	MPR n=9	NMPR n=3	MPR n=3	NMPR n=3	n=13	n=44
Annual precipitation (mm)	1413.2 ±135.8	831.5 ±99.2	1476.2 ±118.0	1057.7 ±120.0	2937.5 ±249.2	2883.5 ±330.2	1558.03 ±103.8	1940.7±113.3–2616.3±71.4
Percent of annual precipitation in different seasons**								
- in monsoon	68.9	28.9	73.7	38.7	63.4	43.3	78.6	60.5–70.9
- in pre-monsoon	12.2	36.9	10.4	29.2	23.8	36.8	9.0	16.4–70.9
- in autumn	3.4	8.9	3.7	6.0	7.1	9.2	4.5	7.1–11.4
- in winter	15.0	24.7	12.1	26.1	6.6	10.6	7.9	1.3–5.0
Levine's response breadth#	1.99	3.67	1.79	3.35	2.18	3.00	1.6	1.86–2.24

*Includes Mizoram, Nagaland, Sikkim, Tripura, Manipur and Meghalaya with n= 9,11,4,4,9 and 7 respectively.

**Winter includes December, January and February; Pre-monsoon includes March, April and May; Monsoon includes June, July, August and September; and Autumn includes October and November.

#Higher the value more the even precipitation distribution.

Table 3. Difference between two precipitation regimes, MPR (Monsoonal Precipitation Regimes) and NMPR (Non-monsoonal Precipitation Regimes) by season and state. All t-values are significant at 5% level.

State	t-values			
	Winter	Pre-monsoon	Monsoon	Autumn
Jammu & Kashmir	5.82	10.59	11.79	6.94
Himachal Pradesh	4.61	9.83	6.78	4.70
Arunachal Pradesh	4.05	9.54	8.76	6.98

(Climate Change knowledge Portal 2.0, The World Bank Group 2016). In brief, along the Himalayan Arc from east to west generally the monsoon precipitation decreases and overall seasonal pattern of precipitation gets more winter- and spring- oriented.

The greater proportional distribution of precipitation in non-monsoonal months (winter and spring months) western part of Himalayas as described above, is linked to the incursions of westerlies, which create a different seasonal pattern of precipitation. There are evidences to suggest that because of increase in the intensity of westerlies in recent decades, the glaciers in Karakoram region have increased in size, while glaciers of monsoon region generally have shown shrinkage (Yao *et al.* 2012). Thus, the degree of glacier shrinkage and the proportional distribution

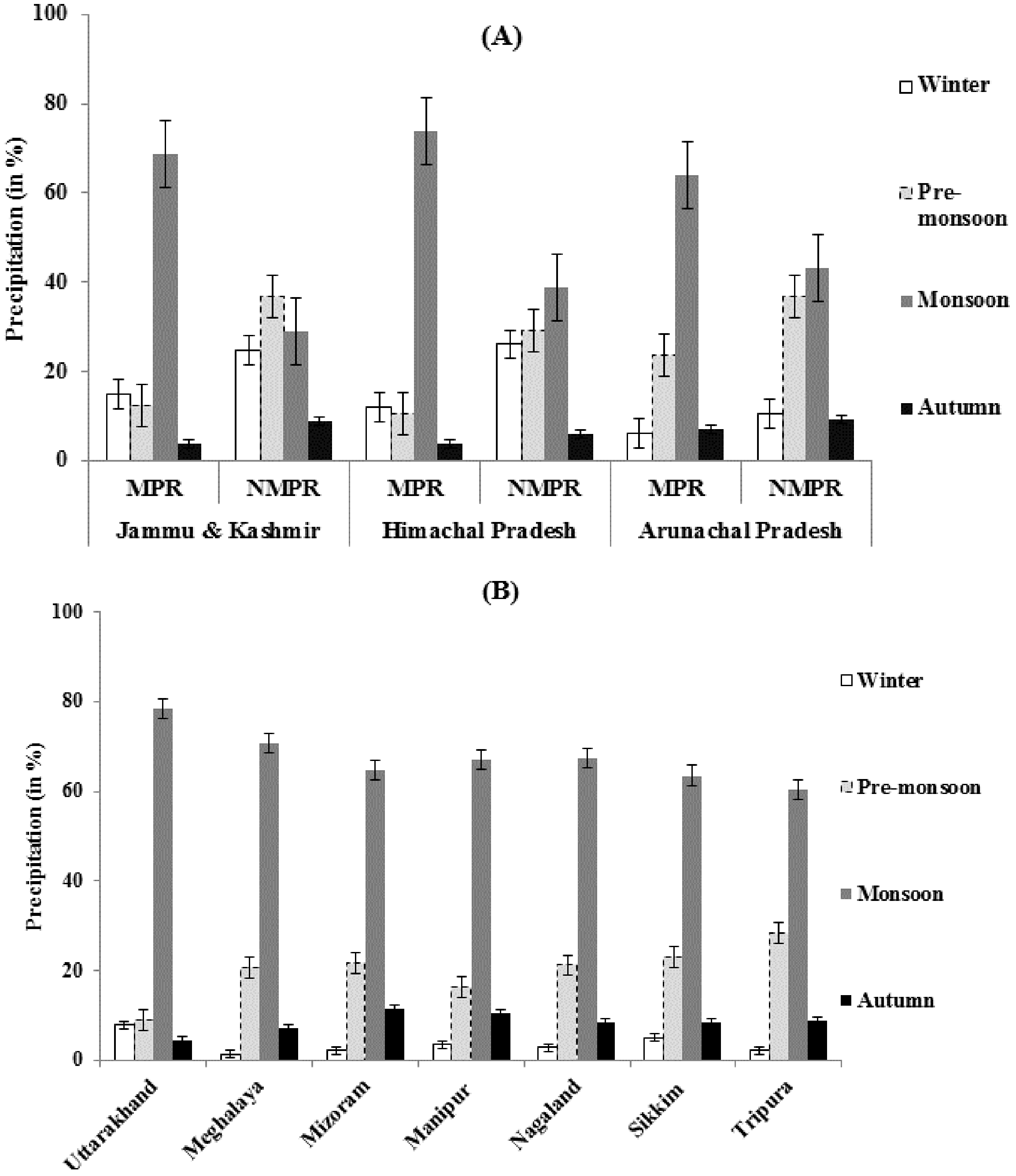


Fig. 3. Seasonal distribution of precipitation in MPR (Monsoonal Precipitation Regime) and NMPR (Non-monsoonal Precipitation Regime) in Indian Himalayas (A) states with both MPR and NMPR, and; (B) states with only MPR. Winter includes December to February; pre-monsoon includes March to June; monsoon includes June to September; and autumn October to November. Levine's breadth (higher the value more the evenness in seasonal distribution of precipitation) is 1.99 for MPR and 3.67 for NMPR in J&K; 1.79 for MPR and 3.35 for NMPR in HP; 2.18 for MPR and 3 for NMPR in AP; 1.6 for UK; 1.86 for Meghalaya; 2.14 for Mizoram; 1.86 for Manipur; 2 for Nagaland; 2.24 for Sikkim; and 2.24 for Tripura. Annual precipitation is as following: Jammu and Kashmir, 1413 mm for MPR (n=7) and 832 mm for NMPR (n=15); Himachal Pradesh, 1476 mm for MPR (n=9) and 1058 mm for NMPR (n=3); Arunachal Pradesh, 2938 mm for MPR (n=13) and 2884 mm for NMPR (n=3); Uttarakhand, 1558 mm for MPR (n=13); Meghalaya, 3683 mm for MPR (n=7); Mizoram, 2616 mm for MPR (n=9); Manipur, 2497 mm for MPR (n=9); Nagaland, 1941 mm for MPR (n=11); Sikkim, 2838 mm for MPR (n=4); and Tripura, 2479 mm for MPR (n=4) (in each case n is number of meteorological stations).

Table 4. Timing of seed dispersal and seed germination in common Himalayan tree species occurring in areas both with monsoon precipitation regime (MPR) and non-monsoon precipitation regimes (NMPR) (Source: Rakhuri *et al.* 1985; Rao 1984; Singh & Singh 1992; Singh *et al.* 2016; Thapliyal *et al.* 2005; Troup 1921).

Species with altitudinal range in parenthesis	Timing of seed dispersal	Timing of seed germination	Remarks
Pinus wallichiana (commonly 1820–3030 m); evergreen	September-early November; remain on ground during winter and spring	Begins in later half of June with the commencement of monsoon, germination continues throughout the monsoon in MPR	Rain 1000–1900 mm, snow cover protects seeds from being devoured by predators; but the role of snow melt water in seed germination not yet investigated
Cedrus deodara (commonly 1970–2575 m); evergreen	Early September and October; seeds remain on ground during winter	Germinate in spring with snow melt; seedlings can be seen below melting snow	Dependence on snow for germination high, particularly in non-monsoonal areas
Abies pindrow (2120–3330 m); evergreen	October-November; seeds remain on ground during winter and spring	May and early June	Heavy snow cover (snow+ rain=1140 mm–25400 mm)
Picea smithiana (2120–3330 m); evergreen	October-November; seeds remain on ground during winter and spring	From May-end/ June to July-August	Precipitation 1000–1800 mm, a lot as snow
Cupressus torulosa (1820–2730 m); evergreen	August – December; seeds remain on ground during winter and summer	In following July with the commencement of monsoon	Seeds sown artificially in November would germinate only next year, March-July
Juniperus macropoda (1800–4240 m); evergreen	September-October	Summer with snow melt	-
Juniperus wallichiana (2775–4545 m); evergreen	Fruit ripe September-October	Summer with snow melt	-
Aesculus indica (1500–2730 m); deciduous	October-November; seeds remain on ground as during winter	Following spring, April, snow-melt water is made available	Generally in ravines and depressions
Betula utilis (3030–4240 m); deciduous	August- October; seeds remain on ground during winter	April- May	Distributed up to China and Tibet, as timberline species.

of precipitation in monsoon are linked. Precipitation data from 1866 to 2006 in the western Himalaya indicate a decrease in monsoon precipitation and an increase in the westerlies (Bhutiyani *et al.* 2010).

Influence of monsoon regime on timberline

These differences between the two precipitation regimes have implications for tree growth. For example, a tree ring study on Himalayan birch (*Betula utilis*) in Nepal at sites with MPR indicates that tree ring width is negatively correlated with years with warm and dry pre-monsoon period, emphasizing that pre-monsoon moisture and temperature control its growth, and hence the timberline range shifts (Liang *et al.* 2014). Timberline is not moving up in spite of 4 °C increase in temperature during last 50 years in some parts of Nepal because of the negative effect of water stress intensified by warmer and drier pre-monsoon condition and depleting supply of snow melt water (Liang *et al.* 2014). If pre-monsoon moisture levels were the key factor in timberline ecosystems, then the growth of birch at sites with NMPR is likely to be less adversely affected because of the favourable pre-monsoon moisture condition.

The precipitation regime can influence the upper limit of treeline. In the eastern declivity of the Tibetan highlands (30°18´N/ 91°31´E) with MPR, treelines, generally consisting of *Juniperus tibetica* (Farjon 2005), are the highest (4900 m) in the northern hemisphere (Schickhoff 2005). Generally, treelines are higher in the monsoonal eastern and central Himalayas than in the non-monsoonal parts of western Himalayas. For example, in Nepal it occurs between 3700–4200 m (Schickhoff 2005), while in Kashmir its altitudinal range is between 2700–3500 m (Dar & Khuroo 2013). However, several factors such as latitudinal effect on temperature, grazing pressure and topography affect the altitudinal location of timberlines. The low temperature lapse rate during monsoon months is likely to raise tree line elevations. Studies based on observed data in Himalayas with MPR indicate that, temperature lapse rate is lower (0.46 °C/100 m) during monsoon season than during other seasons of a year (between 0.49 °C and 0.64 °C/100 m) (Immerzeel *et al.* 2014; Shiraiwa 1992). Because of the cooler temperatures at timberlines, plant growth starts late in the season and broadly overlaps with monsoon periods (Rikhari *et al.* 1993). The lower Temperature Lapse Rate (TLR) means higher upper elevation limit at which temperatures are warm enough for tree growth during monsoon season. This may partly explain why treelines are higher in strongly monsoonal areas of Himalayas, such as southern Tibet. In contrast, the westerlies deposit precipitation when plants are dormant (winter) or physiologically less geared to grow (pre-monsoon).

Tree species distribution and timings of seed dispersal and seed germination in relation to the precipitation regimes

The Himalayas being largely monsoonal, most of the tree species of the region occur in areas with MPR. Here our focus is on the tree species with more NMPR association. So, we have largely analysed the species which occur above 2000 m altitude, up to timberlines, generally with centres of populations in the western part of the East to West Himalayan Arc where the differentiation of areas with MPR and NMPR is more obvious from available data. In geological past, species distribution in Himalayas has been affected by several cycles of warm and humid and cold and dry phases (Vishnu-Mittre 1984). Generally, plants would have migrated towards higher mountain ranges during a warming phase and towards lower ranges during a cooling phase. Species movements would have also occurred along the East-to-West Arc during these phases. So species distribution in Himalayas is unlikely to be driven only by the species preferences to a precipitation regime. Then, anthropogenic pressure particularly grazing in sub-alpine and alpine belts of the western and central regions of the Himalayas also control altitudinal ranges of species. For example, because of high sheep grazing timberline in some areas of Garhwal, India comes down to 3200 m altitude (Rikhari *et al.* 1993).

Distribution of not many species is tied only to NMPR, and of those of which it is tied are generally from dry areas, such as *Pinus gerardiana,* and some *Juniperus* species among conifers (Table 1). *Pistacia mutica* seems to be a common angiosperm in the areas under NMPR. Among the important western Himalayan trees, *Cedrus deodara* (deodar) is largely an NMPR species (Table 1).

Pinus wallichiana (blue pine) which can go up to the timberline in some areas also performs well in NMPR, but not to the extent deodar does. In these areas, generally elevations are too high for *P. roxburghii*. *Picea smithiana* (Himalayan spruce) also occupies NMPR areas, though it generally prefers damp places. Seed germination and seedling growth of these conifers depend on snow melt water (Singh & Singh 1992).

Abies pindrow (lower altitude Himalayan silver fir) and the characteristic timberline deciduous species, *Betula utilis* (bhojpatra/birch) can occur in areas with NMPR. However, they are largely MPR species. In comparison *A. spectabilis* is more common in areas with NMPR. *Aesculus-Juglans-Acer* community generally occurs along water courses (Stainton 1972). *Cupressus torulosa* (Himalayan cypress) does well in both precipitation regimes, though it generally occurs in dry areas with annual precipitation, from 250 mm to 1000 mm. Snow fall occurs in sites that this cypress occupies, but does not stay for more than 2–3 days because of the steepness of the slopes. Its seed germination is synchronized with monsoon (Singh & Singh 1992). In fact, edaphic factors, like steep slopes, limestones and lack of soil seem to determine its distribution, in monsoonal areas.

Among the eastern Himalayan species, larch (*Larix* spp.) occupies non-monsoonal areas, even up to timberline. This deciduous conifer and the birch are prominent where new grounds are formed due to landslides and glacier retreats. Among the prominent Himalayan Oaks, only *Q. semecarpifolia* is able to penetrate somewhat into NMPR areas, but it is largely as MPR species.

Several other oaks (including widely distributed *Q. leucotrichophora*), *Castanopsis* spp., *Lithocarpus* spp., *Rhododendron arboreum* and most members of Lauraceae and Magnoliaceae are monsoonal in distribution. This category is also joined by *Pinus roxburghii* which, however, occurs in some of the driest areas of Himalayas. In most of these species seed germination and seedling growth are synchronized with monsoon season. Many of these have desiccation sensitive seeds. Perhaps, *Q. leucotrichophora* and *P. roxburghii* are strongly monsoonal, as they are absent from Kashmir valley, with a typical NMPR. It is speculated that oaks were driven out of Kashmir valley during a comparatively recent ice age and then could not come back, because of increased anthropogenic pressure (Stainton 1972).

Climate change is likely to affect the distribution and dominance of tree species through its impact on the precipitation regime. Strengthening of westerlies (Yao *et al.* 2012) is likely to make species like *Cedrus deodara* and *Juniperus* spp. more prominent. Furthermore, more incursions of westerlies in monsoonal region may reduce the severity of winter and spring droughts. The precipitation regimes affect species distribution through their influences on seed germination. Information is available on the timing of ripe seed dispersal and seed germination for 9 common tree species with distributional ranges that include NMPR (Table 4). In most of them seed dispersal occurs between September and December, with peak during autumn months, October and November. Generally, seeds remain on ground during winter months under snow cover, and germinate with snow melt during spring and summer. In *Pinus wallichiana*, however seeds wait for the commencement of the monsoon in MPR areas, but not much is known about NMPR areas. In other species the dependence of seed germination on monsoon is not explicit.

This seasonal pattern of what is different from that of several MPR- centered tree species which form extensive forests in Himalayas, like *Shorea robusta*, oaks, such as *Quercus floribunda* and *Q. semecarpifolia* and *Castanopsis* spp. in which both seed fall and seed germination are synchronized with the monsoon (Singh & Singh 1992). Seeds of these species show a tendency for vivipary and have short seed viability (1–3 weeks). In contrast species in which distribution extends to NMPR, seeds remain on ground over a long period and are subject to predation, when not under snow cover.

Conclusion

In this study, we have documented the existence of two precipitation regimes in the Himalayan region, largely on the basis of proportion of annual precipitation occurring during typical monsoon months, from June to September. They are driven by different atmospheric circulation patterns: MPR by the Indian summer monsoon and NMPR by the westerlies. The last century of climate change coincides with weakening of MPR and strengthening of NMPR, at least in some parts of Himalayas. The differences in the two precipitation regimes have implications to treeline dynamics, and tree species distribution. The summer monsoon-linked low temperature lapse rate might be one of the contributors to high treelines in central and eastern parts of Himalayas. The precipitation regimes described here provide a framework for investigating the factors accounting for differences in glacier melt, tree growth and treeline formation. Most of the Himalayan tree species are centred in areas with MPR, however, several species such as *Cedrus deodara* and *Juniperus* spp. favour NMPR, though their distributional ranges include both MPR and NMPR.

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