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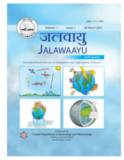

Research Article

Elevation Dependency of Precipitation over Southern Slope of Central Himalaya

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Abstract: Precipitation plays vital roles in the global water cycle, knowledge of the spatial and temporal variation of the precipitation is essential to understanding extreme environmental phenomena such as floods, landslides, and drought. In this paper, the integrated characteristics of precipitation during 1980–2016 over Nepal along with the seasonal elevation dependency of precipitation were examined for three different regions over the country using Multi-Source Weighted-Ensemble Precipitation (MSWEP) product. The spatial distribution of mean annual precipitation varies significantly with the highest (lowest) precipitation of ~5500 (~100) mm/year in the Arun valley (Manang and Mustang). The precipitation regime of the country is determined

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by the contribution of the monthly precipitation amount with distinct spatial gradients between the eastern and the western sides during pre-monsoon, post-monsoon, and winter seasons. On the contrary, the spatial distribution of monsoon precipitation tends to more heterogeneous with visible differences between the lowland, midland, and highlands as similar to the annual one. Further, elevation dependency of seasonal precipitation revealed that the winter and post-monsoon precipitation distribution in western and central are very similar, whereas post-monsoon precipitation was found slightly higher than winter season in the eastern region. The highest precipitation areas in eastern and central region are located between 2000-2500 m, which is between 500 and 1000 m in the western region of the country. Overall, the pre-monsoon, summer monsoon and annual precipitation increases gradually with elevation upto 2500 m and then decreases with increasing elevation, whereas winter and post-monsoon precipitation are almost identical to each elevation interval of 500 m.

1. Introduction

Complex climate, coupled with topographic variability makes regional water resource management challenging, especially in high-altitude areas (Viviroli and Weingartner, 2004). The challenges are further exacerbated by hydrological hazards such as floods and landslides, which depend on the precipitation amount. Further, precipitation duration, intensity and distribution are affected by climate change. The quality and availability of precipitation estimates have a consequential effect on hydro-meteorological and natural disaster studies (Viviroli et al., 2007; Viviroli et al., 2011). Thus, robust knowledge of precipitation is important for water systems management under a changing climate (Daly et al., 2017; Schneider et al., 2016).

The unique topography in the southern slope of Central Himalaya, Nepal, is dominated by the high-Himalaya and mountains (~80% of Nepal's total area), extending from east to west with an average length of ~885 km and width of 193 km. These high-Himalaya and mountains have significant impacts on precipitation distribution in the country. The distribution of monsoon precipitation is generally characterized by the initiation of convection over the Mt. Annapurna range, central region; whereas, winter rain is more pronounced over the western hills (Hamal et al., 2020b; Sharma et al., 2020b). In particular, precipitation requires continuous monitoring, as it is the most crucial component of the water cycle, especially in the context of climate change. Rain gauge-based observations from the Department of Hydrology and Meteorology (DHM), Government of Nepal provide the ground-based measurements of precipitation in Nepal, and these stations are non-uniformly distributed across the country (concentrated in the southern lowlands and scanty in high mountain areas) (Diodato et al., 2010; Barros and Lang, 2003). Such paucity of accurate observations mounts significant challenges to hydro-meteorological studies and comprehensive management of precipitation induced disaster. This further restrains the knowledge of precipitation patterns and distribution, especially in high-elevation areas (Islam et al., 2010). Thus, Accurate modeling and prediction of the precipitation variability over the country are crucial not only for forecasting but also for the management of water resources, which is especially important for the mountainous country(Anjum et al., 2019; Bhardwaj et al., 2017; Burton et al., 2018).

The high-resolution satellite-based and reanalysis precipitation products are potential alternatives of ground observations for evaluating precipitation, especially over remote areas, and rugged terrains, where stations are sparse (Chen et al., 2021; Hamal et al., 2020a; Hamal et al., 2020c; Sharma et al., 2020a; Sharma et al., 2020d). On the other hand, satellite reanalysis and gauge merged precipitation products such as Multi-Source Weighted-Ensemble Precipitation (MSWEP) is another alternative of gauge measurement with relatively higher accuracy of precipitation measurement (Beck et al., 2017a). However, all these measurements need validation and calibration before further applications (Tian and Peters-Lidard, 2010; Khairul et al., 2018).

Several previous studies analyzed the characteristics of precipitation over Nepal using satellite, reanalysis, and gauge observation. For example, Hamal et al. (2020a) evaluated seasonal precipitation trend and found the decreasing trend of monsoonal precipitation during 2000–2016. Similarly, Sharma et al. (2020c) analyzed the precipitation pattern over seven different provinces of Nepal and found decreasing precipitation trend over most parts of the country. The author also mentioned that high-intensity related to extremes are increasing over Nepal. Recent trend analysis of precipitation in the last two decade revealed that dry spells are increasing, while wet spells and extreme precipitation events are decreasing over the country (Shrestha et al., 2021). Furthermore, Subba et al. (2019) revealed that average annual precipitation over the eastern region of Nepal was decreasing at an alarming rate of−20 mm/year in the last two decades. Most of the above-mentioned studies either evaluated precipitation pattern using limited gauge observation or based on satellite and reanalysis data for a short period of time. Thus, in order to improve our understanding of precipitation pattern and its variation with elevation, this study aims to draw an up-to-date status of spatio-temporal precipitation pattern, and the elevation dependency of precipitation using MSWEP precipitation product during last four decades (1980–2016) over the southern slope of Central Himalaya, Nepal. Further, this study helps to understand the precipitation pattern from past to present and its variation with an elevation over the mountainous region.

2. Materials and Methods

2.1 Study Area

The study area, Nepal, is located on the southern slope of Central Himalaya (Figure 1). The country features unique topography, i.e., from flatlands in the south to summit of the world within the short width of the country. The precipitation distribution is primarily affected by the South Asian Summer Monsoon (SASM). Approximately 80% of the total precipitation in the country occurs during the summer season (June–September, JJAS), followed by pre-monsoon (March–May, MAM), post-monsoon (October-November, ON) and winter (December–February, DJF). The high-Himalaya and mountains act as a barrier to the monsoon transfer from south to northward. Thus, the climate of the country is characterized by a significant wet and dry contrast between the southern and northern slopes (trans-Himalayan areas), because of the orographic effect of high mountains. The precipitation amount is very high in summer and more vulnerability to extreme precipitation–related disasters (i.e., landslides and floods), especially over the mountainous areas of the country. The summer season is a hot and rainy period, whereas the winter season is cold and dry. Following the previous study (Chen et al., 2021; Sharma et al., 2020a), the study area is divided into three regions (i.e., western (western boundary to 83°E), central (from 83° to 85°E), and eastern region (from 85°E to eastern boundary) based on three major river basins and monsoonal climatology (Figure. 1).

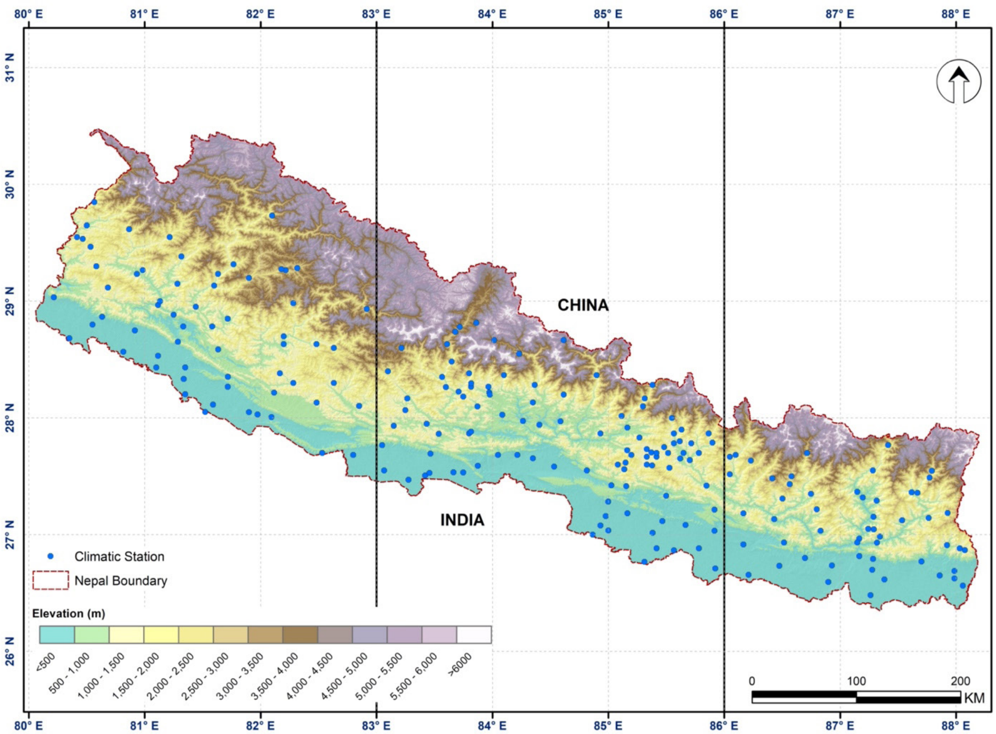

Figure 1. Study area Nepal with its elevation and geographic location of 220 meteorological stations for validation of MSWEP product. The study area was divided into three subregions: Western (80–82°E), Central (83–85°E) and Eastern (86–88°E). Color bar represents the elevation in a meter.

2.2. Data sets

MSWEP is a global precipitation product developed by Hylke Beck (Princeton University), with a 3-hourly temporal and 0.1° spatial resolution (Beck et al., 2019). Firstly, the long-term climatic records were temporally downscaled to a monthly timescale, then to a daily timescale and finally to a three-hourly timescale using weighted averages of precipitation anomalies obtained from gauges, satellite, and reanalysis datasets to yield the final research-quality MSWEP precipitation product. The first version (MSWEP V1) relied entirely on reanalysis and gauged data during the pre-TRMM era (before 2000; (Beck et al., 2017b)). For MSWEP V2, the reanalysis and gauge data during the pre-TRMM era with rainfall estimates based on infrared data from the GridSat B1 archive [0.07° resolution; (Knapp et al., 2011)] improved the precipitation estimates in convection-dominated regions. Specifically, MSWEP V2 takes advantages of satellite [CMORPH, Tropical Rainfall Measuring Mission (TRMM) Multi-satellite Precipitation Analysis (TMPA) 3B42RT, GridSat, and GSMaP], reanalysis [European Centre for Medium-Range Weather Forecasts (ECMWF) interim reanalysis, Japanese 55-year reanalysis]. In addition to satellites and reanalysis product, data from an extensive gauge observation network (76,747) was also assembled from various global and national databases. The final precipitation was estimated using a parsimonious CDF-matching approach (Beck et al., 2019; Beck et al., 2017b). For the current study, daily 10km MSWEP V2 data was used, which was downloaded from Princeton's web portal (http://hydrology.princeton.edu/data/hylkeb/MSWEP_V220).

2.3 Methodology and Data Validation

Firstly, 10 km gridded MSWEP precipitation product was extracted using a land mask of the study region. It is worth mentioning that any scaling (upscale or downscale) was not applied to the datasets. The mean monthly, seasonal, and annual precipitation datasets were obtained by averaging the daily precipitation at each grid during the study period to characterize seasonal and the annual timescale. Since MSWEP gridded precipitation product is indirect measurement; hence, the MSWEP product was validated with averaged precipitation series calculated from 220 rain gauge observations over Nepal (Figure 1), collected from the Department of Hydrology and Meteorology (DHM). To do this, we have compared the seasonal cycle and standardized interannual anomaly of precipitation from MSWEP against rain gauge observation over Nepal during the study period. MSWEP product showed a very similar seasonal cycle of precipitation as that of observation stations ($R>0.95$), although MSWEP slightly overestimated the precipitation amount, particularly during monsoon season (JJAS) (Figure. 2a). MSWEP product is generated using large scale global gauge network (including some of the selected DHM observations) (Beck et al., 2019); so it shows very similar characteristics of observed precipitation over Nepal. Furthermore, standardized anomaly time series for annual precipitation is calculated for MSWEP and observation stations (Figure 2b). Moreover, MSWEP product achieved a strong correlation ($R=0.85$, $p<0.05$) for the interannual anomaly, indicating that MSWEP product is a good alternative to the gauge observation in the mountainous country.

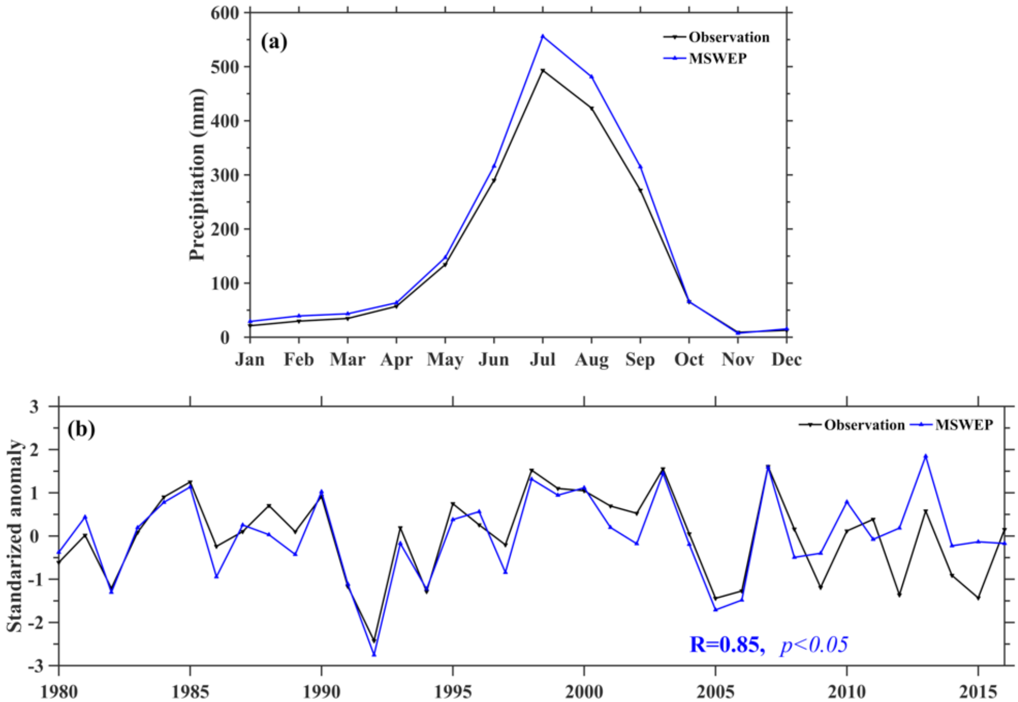

Figure 2. (a) The seasonal cycle of precipitation (mm/month) obtained from rain-gauge and MSWEP average during the study period over Nepal. (b) The time series of correlation between average annual precipitation anomaly (mm) obtained from the station (black line), and MSWEP (blue line) datasets from 1980 to 2016.

Further, the mean annual and seasonal precipitation at each grid was visualized for the spatial distribution of precipitation over the country. For the elevation dependency, 0.1° grid spacing topographic data (similar to MSWEP precipitation grid) from the National Geophysical Data Center (NGDC) was used to separate the precipitation distribution at different elevation levels. This dataset was divided into 13 elevation groups (at an elevation interval of 500 m from <500 m to >6000 m) to examine the precipitation characteristics in relation to elevation. The seasonal and annual precipitation and the number of grids are also calculated for each elevation groups. Additionally, to examine the regional and the seasonal elevation dependency, mean monthly regional precipitation were computed for three regions with longitudes of 80–82°E, 83–85°E and 86–88°E being grouped as the western, central, and eastern regions, respectively (Figure 1).

3. Results and Discussion

3.1 Spatio-temporal distribution of precipitation over Nepal

The spatial distribution of mean annual and seasonal precipitation across Nepal between 1980 and 2016 are presented in Figure 3. The climate regime of the study area is typically seasonal with some evident spatial differences. The highest precipitation is recorded in mid-elevation areas of the eastern region, because of the significant orographic effect on precipitation (Chen et al., 2021). The spatial distribution of mean annual precipitation varies significantly from ~100 to 5500 mm/year with highest (lowest) precipitation of ~5500 (~100) mm/year in the Arun valley (Manang and Mustang) (Figure 3a). It is also notable that MSWEP precipitation product captured the rain shadow areas in the high-elevation areas of the central region.

The summer precipitation still dominates both west and east regions and the mountains; however, winter precipitation is higher over the western mountains than the eastern mountains. The SASM starts from the eastern region and advances westwards, resulting in high precipitation in the eastern region than in central and western regions (Pokharel et al., 2019; Shrestha et al., 2000). On the contrary, winter precipitation in western Nepal is predominantly affected by the westerlies disturbance (Hamal et al., 2020b). The wet air mass transfer from the Bay of Bengal (BoB) initially reaches Nepal during the pre-monsoon season, with the highest precipitation of about 320 mm/month in the mid-elevation areas of the eastern region (Figure 3b). The widespread precipitation during the monsoon season dominates across the country, particularly the high-elevation areas of the eastern region and mid-elevation areas of central region (Figure 3c). Further, precipitation starts to decrease from the western region with the withdrawal of the monsoon from September (Figure 3d). Unlike other seasons, during the winter season, the effect of westerlies disturbance is more pronounced, especially over the western hills. As winter precipitation starts from the western region, its effect becomes weaker towards the east; thus, most of the eastern region is comparatively dry during winter (Figure 3e). Generally, the winter season is characterized by cold and snowfall, especially over the high mountainous region (Khadka et al., 2020). Moreover, the distinct spatial gradients are evident between the eastern and the western sides during pre-monsoon, post-monsoon, and winter seasons. On the contrary, monsoon season shows a more heterogeneous spatial distribution of precipitation with visible differences between the lowland, midland, and highlands as similar to the annual one.

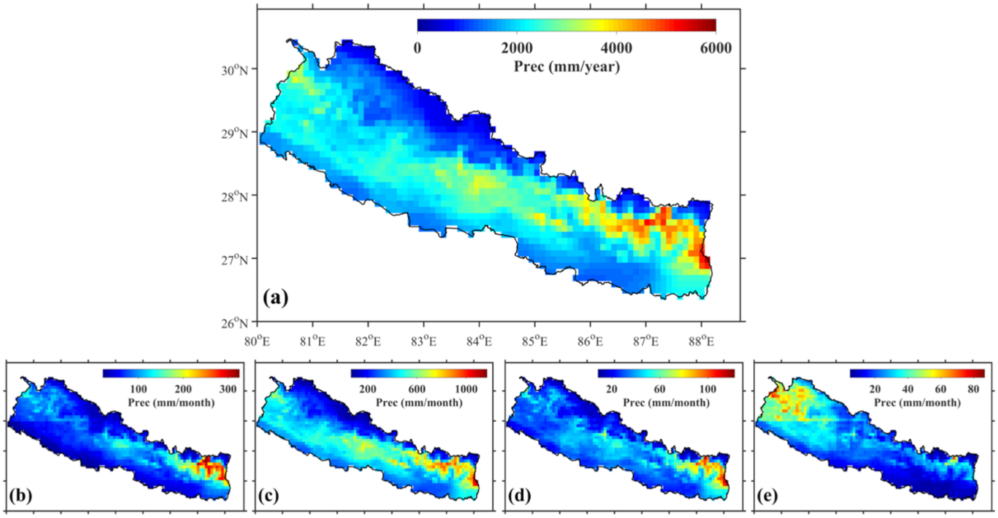

Figure 3. Spatial distribution of mean precipitation for (a) annual (b) pre-monsoon (MAM) (c) summer monsoon (JJAS) (d) post-monsoon (ON) and (e) winter precipitation (DJF) during 1980–2016.

The precipitation climate regime of a region is determined by the contribution of the monthly precipitation amount. Figure 4 shows the temporal distribution of mean monthly and annual precipitation distribution over the study area. The mean monthly precipitation cycle between 1980 and 2016 revealed that the precipitation sharply increased from April, with highest in July (~560 mm) due to control of the summer monsoon, while the lowest in November-December (~20 mm) (Figure 4a).

Generally, it is noted that May to November shows higher precipitation as compared to December to February (Figure 4b). This reflects the well-defined precipitation regime in Nepal: the wet season (May to November) and the dry season (December to February) constitute ~96% and 4% estimates, respectively (Figure 4b). Moreover, the precipitation in the country exhibits a dominance of the summer monsoon contribution to the annual precipitation (Figure 4a-b). These similar precipitation patterns have also been confirmed by several other studies using different data sets (Chen et al., 2021; Hamal et al., 2020b; Pokharel et al., 2019; Sharma et al., 2020b; Sharma et al., 2020c; Sharma et al., 2020d).

The interannual precipitation distribution over the study area from 1980 to 2016 is presented in Figure 4c. It shows the highest recorded annual precipitation across the country occurred in 2013 (~2350 mm), while the least in 1992 (1650 mm). The years 1982, 1986, 1989, 1992–1994, 1997, 2002, 2005–2006, 2008–2009, 2014–2016 was the comparatively dry years with precipitation less than mean precipitation (2094 mm) during the study period. The substantial precipitation deficit over India and Nepal is related to the El Niño years and the warming of the Indian Ocean. Moreover, the dry conditions observed over the South Asian countries is due to the temperature contrast between Indian land surface and the Tropical Indian Ocean (Devika and Pillai, 2020).

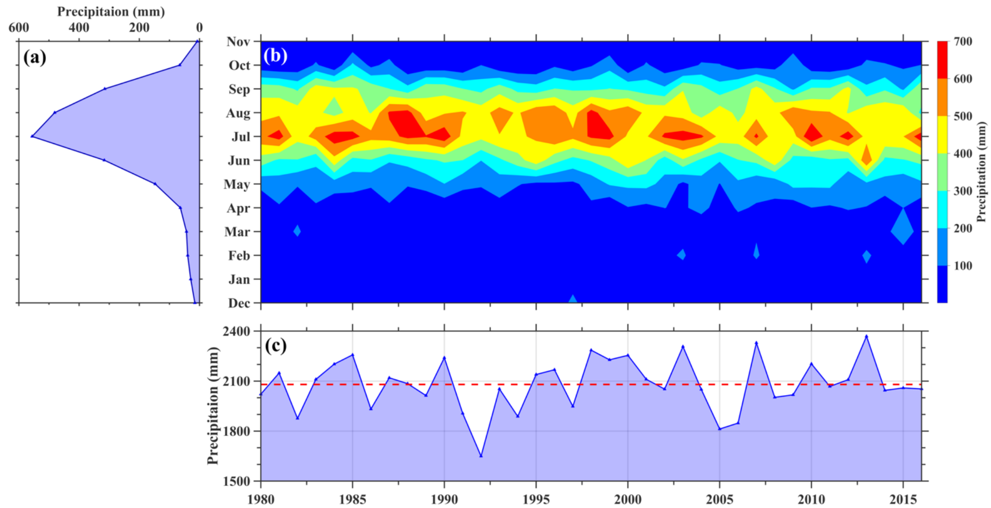

Figure 4. (a) mean monthly precipitation cycle, (b) monthly precipitation at each year, and (c) interannual precipitation distribution between 1980 and 2016 averaged over the study period.

3.2 Elevation dependency of precipitation

A steep slope and unique topography characterize the southern slope of central Himalaya, and it is challenging to monitor precipitation, especially in a mountainous region. It is evident that topography strongly affects the distribution of precipitation across Nepal (Figure 3a). Thus, grid-based seasonal and annual elevation-dependent precipitation characteristics over the three regions (western region, central region, and eastern region) and the whole country from MSWEP were investigated (Figure 5). The winter and post-monsoon precipitation distribution in western and central were similar, whereas post-monsoon precipitation was found slightly higher than winter season in the eastern region (Figure 5a-c). As SASM starts from the eastern region, the precipitation in the pre-monsoon and monsoon season varies significantly in all three regions –highest in the eastern region followed by central and western regions (Figure 5b-c). The summer monsoon season contributes ~80% to annual precipitation, elevation dependency of annual precipitation pattern is identical to monsoon season for all-region. The high precipitation zones are located at mid-elevation areas of eastern and central region (Figure 3a), highest precipitation is found between 2000-2500 m. In the eastern region, monsoon precipitation increases with increasing elevation up to 2000 m then decrease further, with the highest precipitation about 26 mm/day between 2000 and 3000 m elevation. In the central region, monsoon precipitation initially increases up to 1000 m then decrease and again increases up to 2500 m and decreases sharply with increasing elevation afterwards. The highest monsoonal precipitation ~20 mm/day is observed between 2000 m and 2500 m. On the contrary, in the western region precipitation increases up to 1000 m and gradually decreases until 2000 m and decreases sharply with increasing elevation. The highest monsoonal precipitation ~15 mm/day is observed at the low-elevation areas of the western region (500–1000 m).

Further, the elevation dependency pattern of pre-monsoon and monsoon season in each region is very similar; however, they differ significantly in precipitation amount. The MSWEP precipitation grid of 10 km (coarse resolution compared to an abrupt change in elevation) did not show the high-mountains located at the western and central regions (only show precipitation grid below 6000 m) have influenced the precipitation distribution pattern in higher elevation areas. However, five grids are located in the eastern region showing precipitation above 6000 m. The highest number of grids in all regions is located between 1000 and 1500 m elevation zones in all regions.

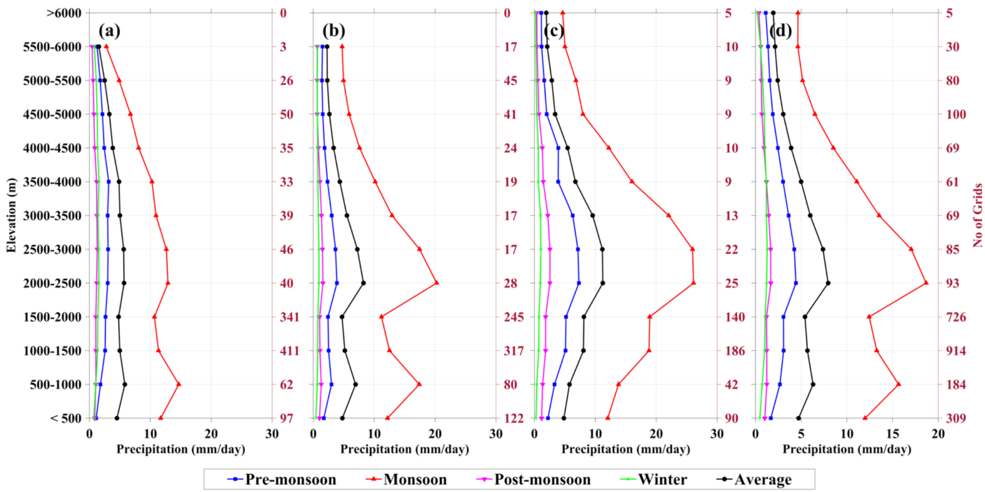

Figure 5. Mean annual and seasonal elevation dependency of precipitation for (a) western (80-82° E), (b) central (83-85° E), (c) eastern (86-88° E), and (d) the whole country during the study period.

Further, seasonal and annual elevation dependency averaged over the study region is presented in Figure 5d. The pre-monsoon, precipitation initially increases with increasing elevation up to 2500 m and decreases with increasing elevation, whereas winter precipitation is almost identical to each elevation groups. Post-monsoon characteristics are almost similar to winter precipitation with slightly higher precipitation between 1500 m and 3500 m. The precipitation gradually increases with increasing elevation up to 2500 m and decreases rapidly (red line, Figure 5d). The highest precipitation (approximately 18 mm/day) occurs in the range 2000–2500 m during the summer monsoon. These patterns are similar to the results revealed by the previous study conducted in central Nepal using TRMM radar (Shrestha et al., 2012). Differently, a few studies found the highest precipitation at an elevation between 1500–2000 m over the country (Kansakar et al., 2004; Chen et al., 2013; Sharma et al., 2020a). Most of these studies were based on point-scale measurement (or gridded data extracted on station location), and these measurements may not represent the spatial relevancy as gridded precipitation product. However, some study revealed that 10 km gridded product smooth out the land surface and may suffer from overestimation/underestimation of observed precipitation over the mountainous country (Zhou et al., 2019; Zhou et al., 2021). Moreover, the local weather conditions and nature of the topography also influence the precipitation capturing capacity of MSWEP precipitation product.

4. Conclusions

In this study, the characteristics of precipitation during 1980–2016 over Nepal along with the seasonal elevation dependency of precipitation were examined using MSWEP precipitation product. The climate regime of the study area is typically seasonal with some evident spatial differences. The highest precipitation occurs at mid-elevation areas of eastern and central regions. The heterogeneous distribution of precipitation during the monsoon season is almost identical to annual precipitation over the country. Further, the effect of the westerly disturbances becomes weaker towards the east, whereas the effect of pre-monsoon and summer monsoon is more pronounced over the eastern and central region.

The elevation dependency of seasonal precipitation shows that the winter and post-monsoon precipitation distribution in western and central are very similar, whereas post-monsoon precipitation was found slightly higher than winter season in the eastern region. As the high precipitation zones are located at mid-elevation areas of the eastern and central region, highest precipitation was found between 2000-2500 m over the eastern and central region. In contrast, the highest precipitation in the western region was located between 500 and 1000 m elevation. Overall, the pre-monsoon, summer monsoon and annual precipitation increase with increasing elevation up to 2500 m and then decreases with increasing elevation, whereas winter and post-monsoon precipitation are almost identical to each elevation interval of 500 m. Overall, our findings will be helpful to understand the seasonal precipitation regime and elevation dependency pattern over the southern slope of central Himalaya, Nepal.

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Conflicts of Interest: The authors declare no conflict of interest.

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