

Observed and Predicted Precipitation Changes in Pakistan Using Ground Observations, Satellite Data and Model Projections with Special Focus on Winter and Pre-Monsoon Precipitation

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Abstract

This study utilizes ground, satellite and model data to investigate the observed and future precipitation changes in Pakistan. Pakistan Meteorological Department's (PMD) monthly precipitation data set along with Tropical Rainfall Measuring Mission (TRMM) monthly dataset TRMM_3B43 (0.25°x0.25° resolution) have been used to evaluate rainfall trends over the climatic zones of Pakistan through Man-Kendall test and Sen's slope estimator for the time period 1978-2018. Community Climate System Model (CCSM4) projections have been employed to explore the projected changes in precipitation till 2099. Furthermore, TRMM and CCSM4 projections have been correlated and validated using Root Mean Square Error (RMSE) and Mean Bias Error (MBE). There is a good correlation between TRMM and PMD ground observation at all stations of the country for all seasons, with correlation coefficient values ranging from 0.89 (November) to 0.97 (July and August). The study shows a decreasing trend in winter precipitation in all zones of the country with a significant decrease over western mountains i.e. zone C of the country. During 2008-2018, a sharp decrease in winter precipitation is observed as compared to the baseline value of 1978-2007 in all climatic zones. There seems to be a shift in precipitation from winter towards pre-monsoon season as pre-monsoon precipitation in last 11 years increased in all zones except Zone C. Coherently, there is a decrease in area affected by winter precipitation and an increase in area for pre-monsoon precipitation. Future precipitation estimates from CCSM4 model for RCP 4.5 and RCP 8.5 over-estimate precipitation in most parts of the country for the first 9 observed years (2010-2018) and predict a rise in precipitation by 2099 which is more pronounced in the northern and western Pakistan while a decrease is predicted for the plains of the country, which might have negative consequences for agriculture.

Highlights

- Decline in winter whereas an increase in pre-monsoon precipitation is observed over the region.
- Coherently, there is a decline in area affected by winter precipitation and an increase in area impacted by pre-monsoon precipitation.
- TRMM satellite data monthly product TRMM_3B43 has good correlation with ground stations observations and can be a promising substitute for regions with limited gauge stations.
- CCSM4 model projections for RCP 4.5 and RCP 8.5 over-estimate precipitation in most zones of Pakistan for the first 9 years.

1. Introduction:

Precipitation is a natural meteorological phenomenon and is a vital component of water cycle as well as energy balance of the earth; it also contributes a significant part in the development of global and regional climate (Kumar et al., 2017; Zhang et al., 2016; Rahman et al., 2012). Precipitation has a considerable spatial and temporal variability which renders studying and modelling rainfall as one of the most complicated phenomenon; thus highlighting the importance of precise precipitation measurement inputs for accurate hydrologic forecasts (Kumar et al., 2017). Accurate estimates of precipitation with good resolution, both spatial and temporal, are of utmost importance various hydrometeorological and water resource management applications like study of crop yields, extreme weather events, flood prediction and monsoon climate variability, particularly in data-scarce areas and regions where there is a strong struggle to utilise sparse hydrological resources (Rahman et al., 2012; Zhang et al., 2016a; Cao, Zhang and Wang, 2018). Reliable statistics of rainfall also have a vital part in model initialization, data assimilation and model verification for numerical weather prediction (Prakash et al., 2015).

The three main data sources of precipitation are point measurements from rain gauge based on ground stations, radar weather observations and remotely sensed satellite-based precipitation estimates (Kumar et al., 1992). Among these, the most accurate source of rainfall measurement are the ground-based rain gauges, but these stations are often scarce or unequally dispersed due to geographical, climatic, financial or other limiting factors. Hence they are not representative for

various locations, especially in the developing countries with less number of weather stations. Similarly, coverage of weather radar-based estimates for rainfall is also not dense and representative in many parts of the globe. Therefore, satellite-based precipitation estimates present numerous benefits over weather radar and ground-based observation, for example long time and continuous coverage, easy data acquisition, suitable temporal and spatial resolutions and less disruptions due to variability in climate and terrain of the area (Kumar et al., 1992; Zhao et al., 2017).

As an attempt to increase precision of satellite based precipitation measurements, Tropical Rainfall Measuring Mission (TRMM) was launched by NASA and Japan Aerospace Exploration Agency in 1997, along with precipitation radar (PR) and TRMM microwave imager (TMI) (Kummerow et al. 1998). Following the launch of TRMM, microwave-based precipitation retrieval techniques progressed immensely, succeeded by launch of numerous high-resolution multi-satellite products of precipitation and a wealth of data has been obtained since then (Semire et al., 2012). However, multi-satellite precipitation products are also impacted by random and systematic errors which can vary with season and location, occasionally limiting their usage at both regional and global level (Xu, Niu and Shen, 2014; Liu, 2015; Prakash et al., 2015).

Rapidly changing climate puts an important influence on precipitation in various parts of the world, as rainfall patterns are affected by changing climatic parameters like greenhouse gases and temperature, which ultimately may manifest in extreme events of either flooding or drought (Cubasch, Voss and Mikolajewicz, 2000; Xie et al., 2013; Intergovernmental Panel on Climate Change, 2014; Roxy et al., 2015; Adnan et al., 2017; Mobeen et al., 2017; Safdar et al., 2019). Pakistan, in lieu of being located in South Asia is projected to be one of the most vulnerable and worst hit counties by the dire consequences of climate change, reasons being the geographical features and reliance on agriculture and natural resources for livelihoods (Islam, Sultan and Afroz, 2009). Water distribution and consumption predominantly relies on monsoonal rainfall, but the natural rain is unevenly distributed in time and space resulting in floods due to erratic rainfall in one region while drought in another region of the country (Hussain, Nabi and Wu, 2021).

In India, the largest country of South Asia, almost one-third of total annual precipitation falls in winter (December, January and February) through east-ward moving extra-tropical winds system called 'western disturbances' (Dimri et al., 2016) whereas summer monsoon rainfall system, the most important rainfall system which affects Indian sub-continent from June to September, is a component of global circulation system which also assists in regulating the temperature of Earth (Safdar et al., 2019). Similarly, annual precipitation received in Pakistan can also be divided into two main seasons, monsoon precipitation in summer months and winter precipitation, extending from December to February (Salma, Rehman and Shah, 2012). Various studies over South Asia and Pakistan have reported that rainfall in monsoon has declined after 1970s (Ashfaq et al., 2009; Annamalai et al., 2012; Loo, Billa and Singh, 2015; Roxy et al., 2015; Ali et al., 2019; Safdar et al., 2019) whereas winter-spring precipitation needs to be investigated for any patterns and trends.

Winter rainfall is important for the Indian sub-continent because the projection of inflow of water in summer for rivers like Indus is directly linked with the volume of winter precipitation in Himalayas Karakoram Kindukush (HKH) region. Hence, precipitation measurements and forecasts are crucial for winter and successive spring season for agricultural practices in the Indus plains which are predominantly dependent on irrigation as well as in rain fed northern and northwestern fruit growing regions of Pakistan where winter and spring rain has a critical impact (Ahmad et al., 2015). Any noticeable variation in water supply from these northern upstream reservoirs along with below average downstream rainfall results in damages to the food security and huge losses for Pakistan's economy (Akhtar and Athar 2019).

In this study, we investigate the seasonal precipitation variability over Pakistan, using three precipitation products from three different sources: gridded station data from Pakistan Meteorological Department (PMD), satellite-derived data from Tropical Rainfall Measuring Mission (TRM) and Community Climate System Model 4 (CCSM4) projections.

2. Data And Methods

2.1 Study Domain

The study area for this research is Pakistan shown in Figure.1, a country located in South Asia at coordinates of 24.3539 to 35.9186° N and 61.74681 to 75.16683° E making it a country of the temperate zone. Generally, climate of Pakistan is arid being hot in summers while cool or cold in winters. There is a large deviations between extremes of precipitation and temperature at different locations because of varied landscape and terrain from north to south. Study of Pakistan's precipitation patterns is important not only due to its distinctive geographical location and complex geomorphology, but also because of being part of the South Asian monsoon system that has a huge influence on the global and regional water cycle and climate change (Rasul and Chaudhry, 2010).

2.2 Ground stations data

Pakistan is divided into 5 climatic zones according to its climate and geographical features, each with their distinctive climatic conditions (Salma et al., 2012). These zones are briefly described below;

Zone A: Consists of stations with high mountains and a cold climate, located in the north of Pakistan.

Zone B: Stations having mild to cold climate and sub-mountains, consisting of fertile agricultural plains as well.

Zone C: Stations consisting of mountainous region to the west of Pakistan with climate cold in winters and hot in summers.

Zone D: The hottest and dry zone of the country. This region consists of agricultural plains of the country.

Zone E: Comprised of stations present on and around coastal areas of Pakistan, located in Sindh and Baluchistan provinces.

Table 1. Geographical location and altitude of rain gauge stations included in the study.

(Source: pmd.gov.pk)

	LATITUDE	LONGITUDE	Altitude		LATITUDE	LONGITUDE	Altitude
Zone A				1	31°21' N	69°28'	1405.0 m
1	35° 20'	74° 54'	2168.0 m	2	28°53' N	64°24'	0848.0 m
2	35° 40'	74° 38'	1372.0 m	3	30°05' N	66°58'	1719 m
3	35° 25'	74° 06'	1250.0 m	ZONE D			
4	35° 51'	71° 50'	1497.8 m	1	28° 18'	68° 28'	55 m
5	35° 12'	71° 51'	1375.0 m	2	29°33'	67°53'	133 m
6	35° 34'	71° 47'	1463.9m	3	29° 20'	73° 51'	161.05 m
7	34° 13'	73° 37'	813.5 m	4	29° 20'	71° 47'	110.00 m
8	35° 55'	74° 20'	1460.0 m	5	31° 26'	73° 08'	185.6 m
9	34° 11'	73° 15'	1308.0 m	6	30° 12'	71° 26'	121.95 m
10	34° 22'	73° 29'	838.0 m	7	27° 40'	68° 54'	66 m
11	35° 18'	75° 41'	2317.0 m	8	28° 39'	70° 41'	88.41 m
Zone B				ZONE E			
1	31° 49'	70° 56'	171.20 m	1	24° 38'	68° 54'	09 m
2	32° 56'	73° 44'	287.19 m	2	25° 23'	68° 25'	28 m
3	31° 35'	74° 24'	216.15 m	3	25° 04'	61° 48'	56 m
4	32° 31'	74° 32'	255.1 m	4	24° 54'	66° 56'	22 m
5	34.02	71.56	327 m	5	26° 15'	68° 22'	37 m
6	33° 54'	73° 23'	2291.0 m	6	28°-49'	62°-45'	682m
7	33° 37'	73° 5'	508.0 m	7	26° 58'	64° 06'	968 m
8	33° 31'	73° 54'	614.0 m	8	25° 16'	63° 29'	09 m
Zone C				9	29° 53'	69° 43'	05 m

2.3 Satellite data

Satellite data used for analyzing temporal and spatial properties of precipitation over Pakistan is TRMM's monthly mean product TRMM 3B43 version 7 from 1998 till 2017. It was made available as one of the TRMM Multi-satellite Precipitation Analysis (TMPA) products in July 2011 and combines several precipitation estimates from the TRMM Microwave Imager (TMI), advanced microwave scanning radiometer for Earth Observing Systems and Global Precipitation Climatology Centre rain gauge analysis (Kummerow et al., 1998; Huffman et al., 2007; Cao, Zhang and Wang, 2018). Data was downloaded from the "Earthdata" online portal Giovanni (<https://giovanni.gsfc.nasa.gov>). The satellite product utilized for current study is average monthly precipitation in the units of mm/month for all the months from January 1998 to December 2018 at a resolution of 0.25x0.25°.

2.4 Model data

The Community Climate System Model 4 (CCSM4) projections for Pakistan, data obtained from Pakistan Meteorological Department (PMD), was utilized to project variations in precipitation till the year 2100. CCSM4 is a sub-set of Community Earth System Model (CESM), which is “a fully-coupled, global climate model that provides state-of-the-art computer simulations of the Earth's past, present, and future climate states” (Gent et al., 2011). The scenarios in CCSM4 are used as specific inputs to for estimating future variations in climate for IPCC by archiving them in the Climate Model Inter-comparison Project (CMIP5 for AR5). Four new scenarios were developed for CMIP5, referred to as Representative Concentration Pathways (RCPs) (Moss et al., 2010; ‘AR5 Climate Change 2013: The Physical Science Basis – IPCC’, no date).

The baseline years for CCSM4 data over Pakistan are 1975-2005 and prediction have been made for time period 2010-2100. Ground observations for precipitation from 2010-2018 have been compared with the model observations to investigate how well they represent the reality on ground and future precipitation estimates have been studied to observe the estimated precipitation trends till the end of this century.

2.5 Statistical indices and validation methods

The statistical methods employed for the current study are briefly explained below;

i. Mann-Kendall Test

Mann-Kendall test has been used in this study to investigate whether a time series for precipitation has a monotonic upward or downward trend. It is extensively used in studies pertaining to climatic parameters (e.g. Latif et al., 2020; Safdar, 2019; Río et al., 2013; Mann, 1945). Mann-Kendall Test uses the following equation for a time series units x_1, \dots, x_n ;

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^n \text{sign}(x_j - x_i)$$

$$\text{var} = \frac{1}{18} \left[n(n-1)(2n+5) - \sum_t ft(ft-1)(2ft+5) \right]$$

$$z = \begin{cases} \frac{S-1}{se}, & S > 0 \\ 0, & S = 0 \\ \frac{S+1}{se}, & S < 0 \end{cases}$$

Where se is the square root of the variance of S (var).

ii. Sen's Slope Estimator

Sen's slope estimator has been used for calculating the slope of the trend line (Sen, 1968). Following equation is utilised to estimate the slope;

$$\text{Sen's slope} = \text{median} \left\{ \frac{x_j - x_i}{j - i} \right\}$$

iii. Root Mean Square Error

Root Mean Square Error (RMSE) has been used as a standard statistical parameter to analyse satellite data and model comparison RMSE denotes the standard deviation of the residuals (errors) or how far the points are from the regression line (Yang et al., 2016).

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (P_i - O_i)^2}$$

Where O_i is the observation and P_i is the satellite/model estimate.

iv. Mean Bias Error

In order to evaluate how well the satellite data estimates the precipitation values on ground, Mean Bias Error (MBE) has been used. Positive (negative) value of bias error indicates that the model or satellite values over-estimates (under-estimates) the actual values (Yang et al., 2016). Following is the equation used for calculating MBE;

$$MBE = \frac{1}{n} \sum_{i=1}^n P_i - O_i$$

Where O_i represents the observation and P_i the satellite/model value.

3. Results And Discussions

3.1 Precipitation trends over all climatic zones using ground-based gauge network observations

Using Pakistan Meteorological Department's (PMD) ground station data, the variation and trends of rainfall for all five zones of Pakistan and the country as a whole are depicted in Figures 2 - Figure 6, whereas Table 2 provides the statistical summary of the long term trends using Mann-Kendall test and Sen's slope estimator. The long term trend from 1978-2018 has a significant variability in all zones and all seasons, which are attributed to large-scale occurrences like El Nino Southern Oscillation (ENSO) (Safdar et al., 2019). Despite large variability between annual precipitation, zone C showed a significant decrease of 0.47 mm/year in winter rainfall and zone A and D exhibited a significant decrease of 0.15 and 0.17 mm/year respectively in the post-monsoon rainfall which hits these zones in the months of October and November. Zone C is a mountainous area located in the western part of the country and is effected by the western disturbance that brings rainfall to the country in winter and the spring (Ahmad et al., 2015). Decreasing tendency of winter and pre-monsoon precipitation in Zone C can pose a detrimental effect on the weather and crop yield in the region. Rest of the climatic zones do not depict any significant trend in any season. Recent studies have demonstrated a decline in the monsoon precipitation over Indian subcontinent as well as Pakistan (Annamalai et al., 2012; Roxy et al., 2015; Safdar et al., 2019, 2019), which is also evident in the current study through a decrease in monsoon rainfall in all zones of Pakistan in both time scales of 1978-2018 and 1998-2017 except Zone C which is only impacted by the monsoon system to a very small extent because of it being located at the farthest west of the country. It is important to mention here that during the last 11 years data analysis of rain, a sharp decrease in winter precipitation has been identified as compared to the long term trend in all climatic zones of Pakistan. Another study over Pakistan has found decreasing trends in precipitation in the average rainfall during 1991-2005 as compared to time period of 1976-1990 (Salma, Rehman and Shah, 2012) and another study identified a decreasing trend of precipitation in the higher elevation regions of Punjab and increase in the low elevation regions of the province during 1967 – 2017 (Nawaz et al., 2019). The winter and pre-monsoon precipitation are discussed further in the sections 3.3 and 3.4.

Table 2. Man-Kendall's test for significance of precipitation trends in all zones of Pakistan for the time period 1978-2018. Significant values are shown in bold (alpha = 0.05)

	Alpha	ZONE A		ZONE B		ZONE C		ZONE D		ZONE E		PAKISTAN	
		p-value	Sen's slope value	p-value	Sen's slope value	p-value	Sen's slope value	p-value	Sen's slope value	p-value	Sen's slope value	p-value	Sen's slope value
WINTER	0.05	0.92	-0.04	0.30	-0.26	0.002	-0.47	0.87	-0.01	0.06	-0.15	0.25	-0.26
PRE-MONSOON	0.05	0.17	-0.31	0.18	-0.41	0.11	-0.24	0.69	-0.02	0.22	-0.05	0.07	-0.24
MONSOON	0.05	0.50	-0.11	0.68	-0.03	0.10	0.10	0.25	0.18	0.10	-0.11	0.66	0.03
POST-MONSOON	0.05	< 0.0001	-0.15	0.99	0.00	0.06	0.21	< 0.0001	-0.17	0.13	-0.03	0.87	0.02

In order to further evaluate the decreasing pattern of winter rainfall and increasing pattern of pre-monsoon rainfall in Pakistan, absolute and relative change, along with p-values have been calculated for the time period 2008 - 2018. One

sample t-test has been used to check the significance of variation in winter and pre-monsoon precipitation. Table 3 gives an overview of winter precipitation while Table 4 gives an overview of variability of pre-monsoon precipitation in Pakistan. There is a decrease observed in seven out of eleven years for winter precipitation during 2008-2018.

Table 3

Variation in winter rainfall during 2008-2018. A significant decrease in winter precipitation at 95% confidence interval has been observed in most of the years during the last decade

	Average winter rainfall (mm/month)	Absolute change from baseline (mm/month)	% Relative Change	p-value
Baseline (1978-2007)	49.77	-	-	-
2008	45.47	-4.3	-8.60%	0.04
2009	58.28	8.51	17.00%	0
2010	45.68	-4.01	-8.05%	0
2011	46.78	-2.99	-6.01%	0.06
2012	38.26	-11.5	-23.11%	0.15
2013	56.82	7.05	14.16%	0.002
2014	71.71	21.94	44.00%	0
2015	38.20	-11.57	-23.24%	0
2016	12.07	-37.7	-75.75%	0
2017	30.64	-19.13	-38.43%	0
2018	10.88	-38.89	-78.14%	0

Table 4

Variation in pre-monsoon rainfall during 2008-2018. There is a high variability in pre-monsoon precipitation in the last decade with significant deviations to both high and low sides of the baseline value

	Average pre-monsoon rainfall (mm/month)	Absolute change from baseline (mm/month)	% Relative Change	p- value
Baseline (1978-2007)	35.24			
2008	24.90	-10.34	-0.29%	0
2009	30.63	-4.61	-0.13%	0.01
2010	26.48	-8.76	-0.25%	0
2011	30.49	-4.75	-24.60%	0.01
2012	27.86	-7.38	-20.94%	0
2013	30.95	-4.29	-12.17%	0.02
2014	44.51	9.27	26.31%	0
2015	53.02	17.78	50.45%	0
2016	39.57	4.33	12.29%	0.02
2017	21.92	-13.32	-37.80%	0
2018	25.53	-7.71	-21.88%	0

3.2 Satellite observations of precipitation over Pakistan

Satellite measurements of Tropical Rainfall Measuring Mission (TRMM) have been employed from 1998-2018 for comparison of these estimates for applications over the region. Furthermore, these satellite measurements have been used to estimate the area affected by winter and pre-monsoon precipitation in Pakistan.

Figure 7 depicts the average monthly precipitation for the years 1998-2018 for both ground and satellite data whereas Figure 8 displays the spatial extent of precipitation in Pakistan over the last 21 years. Figure 7 depicts two distinct rainy seasons in the country as classified by the Pakistan Meteorology Department; i) the monsoon rainy season from June – September and ii) the winter rainy season originally from December – February can be extended to the pre-monsoon in some parts of the country. Average monthly values of precipitation from TRMM and PMD ground stations correlate closely as evident from Table 5 and monthly maps in Figure 9, with TRMM slightly underestimating rainfall in May, November and December. RMSE and MBE values also depict good coherence between the two datasets, which makes TRMM_3B43 a good alternative for ground stations for precipitation studies over Pakistan and similar regions with limited ground-based observation.

Table 5

Pakistan Meteorological Department's (PMD) ground stations versus TRMM satellite estimates for monthly precipitation during the years 1998-2018

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
CC (r)	0.92	0.93	0.94	0.93	0.91	0.93	0.97	0.97	0.94	0.90	0.89	0.91
RMSE (mm/month)	13.52	20.24	17.35	14.76	8.75	14.91	23.93	21.29	13.81	7.07	6.38	6.00
MEAN BIAS ERROR (MBE) (mm/month)	4.53	4.04	2.89	1.48	-0.09	3.33	4.85	4.78	0.94	-0.92	0.33	-0.08

Numerous studies have explored the correlation and performance accuracy of TRMM products with ground observations and other satellite data products for various areas of the globe (Islam and Uyeda, 2007; Zulkafli et al., 2013, 2013; Khan et al., 2014; Prakash et al., 2015; Zhang et al., 2016b; Kumar et al., 2017; Cao, Zhang and Wang, 2018; Mohd Zad, Zulkafli and Muharram, 2018; Fang et al., 2019). Over China, satellite products TRMM and Global Precipitation Measurement (GPM) were studied to investigate the spatial pattern of precipitation. TRMM 3B42 product exhibited an inadequate capability to measure extreme precipitation episodes, whereas performance of GPM IMERG was somewhat better. Furthermore, the performances were better in regions having humid monsoon climate, compared to dry and arid regions with high altitudes, demonstrating an important effect of climate and terrain on the satellite estimates. Khan et al. 2014 suggested that the TMPA-RT product has a tendency to overestimate rates of light rain events by approximately 100 percent and high rain rates by about 20 percent over Pakistan. They also concluded that During the time span of 2005-2010, best agreement over Pakistan is found between the TMPA-V7 data product and ground station gauge observations with correlation coefficient values ranging from moderate (0.4) to high (0.8).

TMPA data products were compared with Indian Meteorological Department gridded ground observations over India for 2001-2013 period. Both satellite datasets exhibited overestimation over most parts of the country (Prakash et al., 2015). A study over Malaysia depicted a good agreement between TRMM_3B42 version 7 as well as TRMM_3B43 version 7 data set with rain gauge stations (Semire et al., 2012; Mohd Zad, Zulkafli and Muharram, 2018). The differences can be attributed systematic errors with satellite and the ground data both. Therefore, TRMM rainfall products can be employed as a replacement for ground measurement, particularly in places which are not covered by rain gauges (Semire et al., 2012).

3.3 Spatial distribution of of winter and pre-monsoon precipitation in Pakistan

Figure 10 highlights the areas impacted by winter and pre-monsoon precipitation in Pakistan. As evident from the maps, winter precipitation largely affects Zone A (in the north) and Zone C (in the west) of the country while pre-monsoon precipitation pre-dominantly falls over the Zone A and Zone B. Ahmad et al. (2015) found the effect of land forms on spatial distribution of precipitation and suggested a possibility of rugged topography being the trigger of precipitation in winter-spring rainfall which also explains the less rainfall in plains of Pakistan. The mountains of Zones A and C can intercept the westerlies and cause rain in the months of winter and pre-monsoon. The characteristics of monsoon precipitation are entirely different from winter and premonsoon rainfall, where plain areas of Zones B and D receive more precipitation than the northern and western aptrts of the country.

According to the PMD data, Zone C to the west of the country has shown a significant decrease ($\alpha=0.05$) with a decrease of 0.47 mm/year during 1978-2018 and a much steeper fall of 1.45 mm/year durign the time span of 2008-2018 (Figure 4 and Table 2). The pre-monsoon rainfall in Zone C has also decreased unlike Zone A and B. This decrease in winter

and pre-monsoon precipitation in Zone C can have an adverse effect on crops which rely mainly on rain water as the area has already been hit by two repeated droughts in the recent decades (Rasul, 2008; Naz et al., 2020).

Zone A and Zone B are primarily effected by winter and pre-monsoon rains (Figure 10) and have shown an insignificant decrease in the rainfall in both the seasons during the timespan of 1978-2018. An interesting feature of these two zones is identified as a temporal shift towards an increase in the pre-monsoon precipitation in the recent years of 2008-2018. Zone A indicated a decrease of 2.27 mm/year in winter whereas an increase of 1.46 mm/year increase in pre-monsoon rainfall. Similarly, Zone B showed a decrease of 1.89 mm/year in winter and an increase of 1.36 mm/ year in the pre-monsoon precipitation (Figure 2 and Figure 3).

Winter rainfall is brought to Pakistan and Indian Subcontinent by westerly winds and the process is known as the “Western Disturbance” (WD), which in turn is affected by both El-Nino Southern Oscillation (ENSO) and North Atlantic Oscillation (NAO), where precipitation in winter season increases with the occurrence of warm ENSO and positive NAO phase (Syed et al., 2010; YADAV, RUPA KUMAR and RAJEEVAN, 2012; Afzal et al., 2013; Adnan et al., 2017). The impact of NAO was highest between 1940–1980 but diminished in the following three decades, while influence of ENSO became strong over following three decades in Indian Subcontinent (YADAV, RUPA KUMAR and RAJEEVAN, 2012). Positive NAO phases have an impact of winter precipitation enhancement, while a weak pressure gradient over north Atlantic has an effect of suppressed winter precipitation activity over northern Pakistan, which can explain the decreasing quantity of winter rainfall over Pakistan (Afzal et al., 2013). A study using a tracking algorithm for archiving behaviour of Western Disturbances in CMIP5 representative concentration pathway (RCP) and historical experiments of the future concluded that owing to the falling WD activity, a decline is predicted in winter precipitation in northern India and Pakistan over the twenty first century (Hunt, Turner and Shaffrey, 2019).

3.4 Spatial shift of winter and pre-monsoon precipitation in Pakistan

An attempt has been made to map the area affected by winter and pre-monsoon precipitation in Pakistan. A related study by Safdar et al., (2019) drew a conclusion that area impacted by summer monsoon has decreased in Pakistan, but there is no study that highlights the spatial extent and shift of winter and pre-monsoon precipitation over Pakistan. TRMM monthly rainfall product TRMM_3B43 satellite data has been used to plot the area that has received rainfall according to two set criteria: a) spatial extent of precipitation >1 mm/day and b) spatial extent of precipitation >2.5 mm/day as shown in Figure 11. All the pixels above the threshold values are used to discriminate such changes.

The average area of years 2010 - 2018 have been compared to the average of available years of TRMM data i.e. 1998-2018 for this purpose. The results are presented in Figure 11 and Figure 12 whereas Table 6 gives the summary of the area increased or decreased. In terms of precipitation amounts, the area of winter precipitation has also decreased during the last 9 years as compared to the baseline years. This decrease is 66,000 km² during 2010-2018 for precipitation greater than 2.5 mm/day (75 mm/month). Whereas the area effected by pre-monsoon precipitation greater than 2.5 mm/day (75 mm/month) has increased by around 60,000 km² during 2010-2018. This finding complements the trend of decreasing precipitation in the winter season and increasing in the pre-monsoon season in zones A and B of Pakistan, according to the ground observation of PMD.

Table 6 Area effected by winter and pre-monsoon precipitation in Pakistan

	Average area (1998-2018) (km ²)	Average area (2010-2018) (km ²)	Difference (km ²)
WINTER			
≥1 mm/day (light rainfall)			
Baseline (1998-2018)	356,278	321,803	-34,474
≥2.5 mm/day (Moderate to heavy rainfall)			
Baseline (1998-2018)	89,520	23,202	-66,318
PRE-MONSOON			
≥1 mm/day (light rainfall)			
Baseline (1998-2018)	577,861	470,365	+107,365
≥2.5 mm/day (Moderate to heavy rainfall)			
Baseline (1998-2018)	158,391	98,228	+60,163

3.5 Future projection of precipitation in Pakistan

Future projections for precipitation changes in Pakistan have been investigated by utilizing the Community Climate System Model 4 (CCSM4) data. In Assessment Report 5 of IPCC, new set of scenarios called the Representative Concentration Pathways (RCPs), were utilized for CCSM4 model. This model is prepared under the framework of the Coupled Model Inter-comparison Project Phase 5 (CMIP5) of the WRCP-World Climate Research Programme (IPCC, 2013). The present study uses two scenarios from the IPCC AR5 to estimate the changes in the future climate; RCP 4.5 and RCP 8.5. The data has been extracted over Pakistan and has been investigated for its accuracy over the region by comparing it to ground based observations (PMD data), and precipitation changes has been calculated for two time spans 2040-2049 and 2090-2099. As evident from Figure 13 and Table 7, the model generally over-estimated precipitation over Pakistan except over Zone A for RCP 4.5 scenario and zone D for RCP 8.5 scenario. Table 7 depicts the error analysis of the observations and forecasts.

Table 7
Error analysis of CCSM4 Model projections with ground observations

			ZONE A	ZONE B	ZONE C	ZONE D	ZONE E
PRECIPITATION PROJECTIONS	RCP 4.5	RMSE (mm)	3.06	5	1.34	1.17	0.94
		MEAN BIAS (mm)	-0.05	0.50	0.32	0.14	0.34
	RCP 8.5	RMSE (mm)	3.47	5.20	1.38	1.25	1.00
		MEAN BIAS (mm)	0.44	0.31	0.35	-0.03	0.33

Figure 14 demonstrates the changes expected in precipitation at the mid and end of this century according to IPCC scenarios used in AR5. These are the difference maps made by subtracting the baseline average values from the specific year we want to estimate a change for. Both scenarios portrayed an increase in precipitation in Pakistan specifically over western and northern areas of Pakistan. There is an estimate of a decrease in precipitation at the end of 2100 in RCP 4.5 for Zone B and D which are agricultural plains and monsoon-hit areas of the country. The western and northern parts of the country, usually hit by western disturbances are observed to be indicating a small increase in the precipitation by years 2040-49 as well as 2090-2099 in both RCPs.

The projections from CCSM4 for RCP 4.5 estimate an increase in average precipitation over Pakistan by 1.41 mm/day and 1.28 mm/day for 2040-49 and 2090-99 periods respectively as shown in Table 8. The rise in precipitation is 0.68 mm/day and 0.55m/day in RCP 8.5 for these periods. Most of this increase is seen to be occurring in Zones A and Zone C till 2049 and also for Zone E for years 2090-2099.

Table 8
Precipitation projections based on CCSM4 for Pakistan

PRECIPITATION PROJECTIONS (mm/day)		Mean		Absolute change	
		RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
Baseline (1975-2005)		0.73	0.73	-	-
2040-49		1.09	1.41	0.36	0.68
2090-99		1.03	1.28	0.30	0.55

4. Conclusions

There is a decreasing trend in winter precipitation in all zones of the country with a significant decrease in western mountains i.e. Zone C of the country. During the time period of 2008-2018, there is a sharp decrease in winter precipitation as compared to the baseline value of 1978-2007 in all climatic zones of Pakistan. There seems to be a temporal shift in winter precipitation towards pre-monsoon season as pre-monsoon precipitation during last 11 years has increased in all zones except Zone C. Coherently there is a decrease in area effected by winter precipitation and an increase in area affected by pre-monsoon precipitation.

Comparison of ground stations data with Tropical Rainfall Measuring Measurement (TRMM) depicts a good correlation, whereas RMSE and MBE values also depict good coherence between the two datasets, which makes TRMM_3B43 a good alternative of ground stations for precipitation studies over Pakistan and similar regions with limited ground based observations. Future precipitation estimates from CCSM4 for RCP 4.5 and RCP 8.5 over estimate precipitation in most parts of the country for the first 9 years (2010-2018) and predict a rise in precipitation by the mid and end of twenty first century which is more pronounced in the northern and western Pakistan while a decrease is predicted in the plains regions of Zone B and D. Overall, there is a tendency of decreasing precipitation in both main rainfall systems i.e. winter and monsoon with a temporal shift in both systems.

Declarations

Acknowledgments

The authors would like to acknowledge Pakistan Meteorological Department (PMD) for providing its ground stations' monthly precipitation data used in this study. Satellite data analyses used in this study were produced with the Giovanni online data system, developed and maintained by the NASA GES DISC.

Ethics approval and consent to participate

Not applicable

Consent for publication

Not applicable

Availability of data and materials

Satellite data analyses used in this study were produced with the Giovanni online data system, developed and maintained by the NASA GES DISC. It can be accessed at <https://giovanni.gsfc.nasa.gov>.

The ground data that support the findings of this study are available from Climate Data Processing Center (CDPC) of Pakistan Meteorological Department (PMD) but restrictions apply to the availability of these data, which were used under license for the current study, and so are not publicly available.

Competing interests

The authors declare that they have no competing interests.

Author contributions

Fasiha Safdar: Investigation, Formal data analysis, Visualization and writing-Original draft preparation

Muhammad Fahim Khokhar: Supervision, Visualization, Writing- Review and editing

Fatimah Mahmood: Investigation, Formal data analysis

Muhammad Zeeshan Ali Khan: Methodology, Writing- review and editing

Muhammad Arshad: Methodology, Writing- review and editing

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Figures

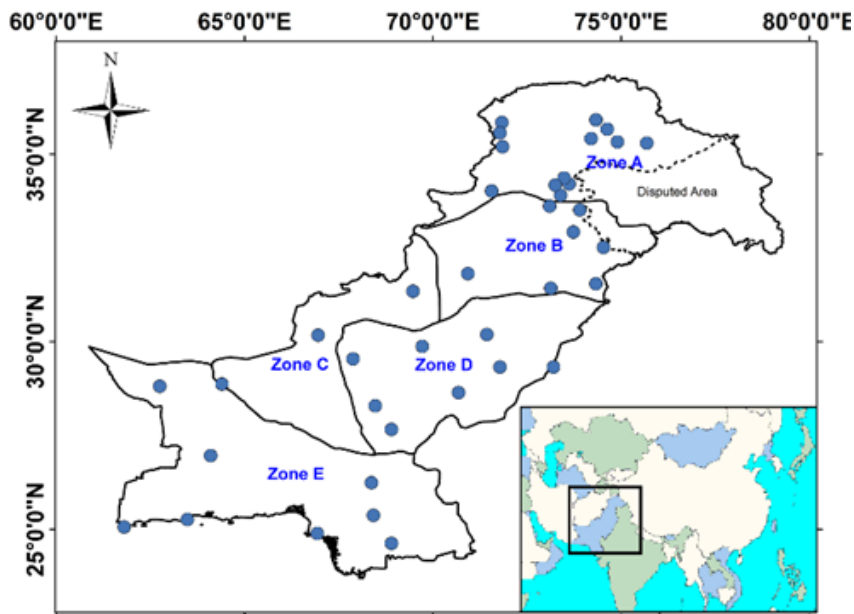


Figure 1

The study area showing the five climatic zones of Pakistan, The blue dots represent the location of Pakistan Meteorological Department's (PMD) rain gauge stations

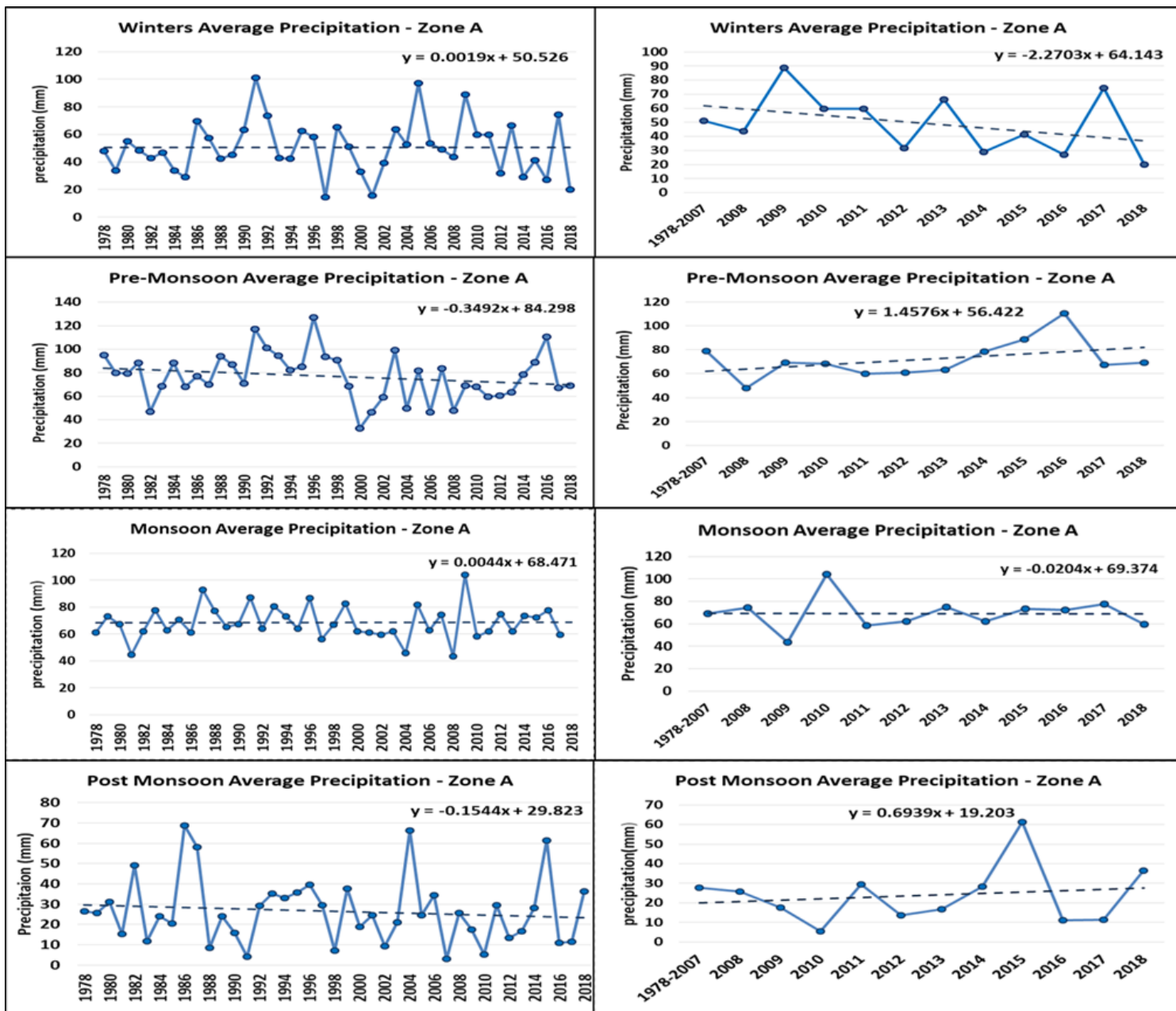


Figure 2

The figure depicts trends and variations of precipitation in Zone A of the country based on Pakistan Meteorological Department's (PMD) station data over two time scales: a) 1978-2018 and b) 2008-2018 compared to the 30 year baseline value of 1978-2007.

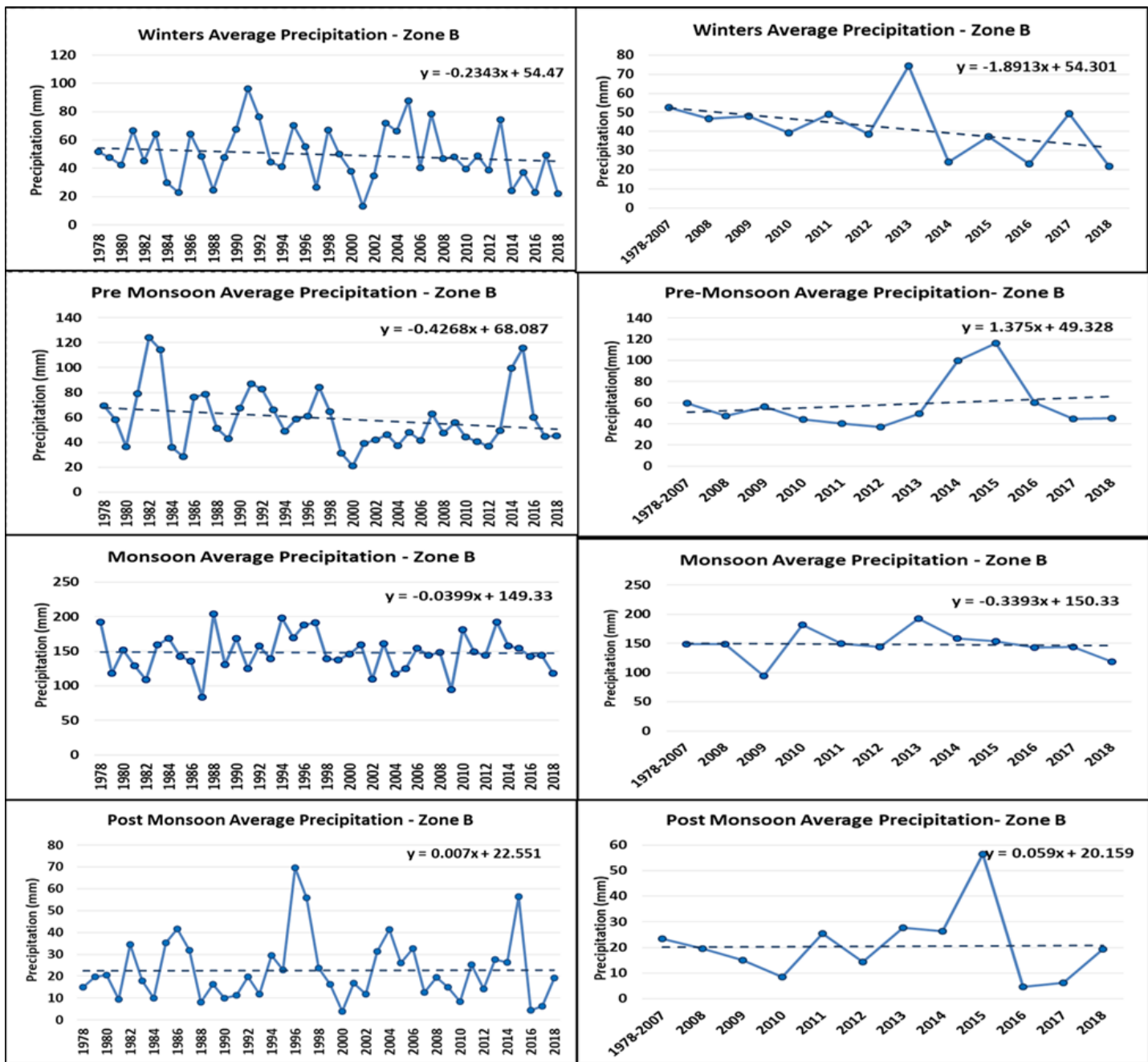


Figure 3

The figure depicts trends and variations of precipitation in Zone B of the country based on Pakistan Meteorological Department's (PMD) station data over two time scales: a) 1978-2018 and b) 2008-2018 compared to the 30 year baseline value of 1978-2007

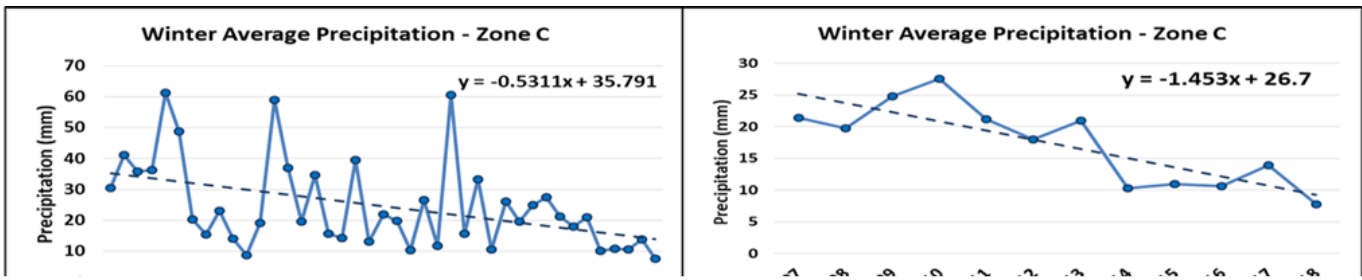


Figure 4

The figure depicts trends and variations of precipitation in Zone C of the country based on Pakistan Meteorological Department's (PMD) station data over two time scales: a) 1978-2018 and b) 2008-2018 compared to the 30 year baseline value of 1978-2007

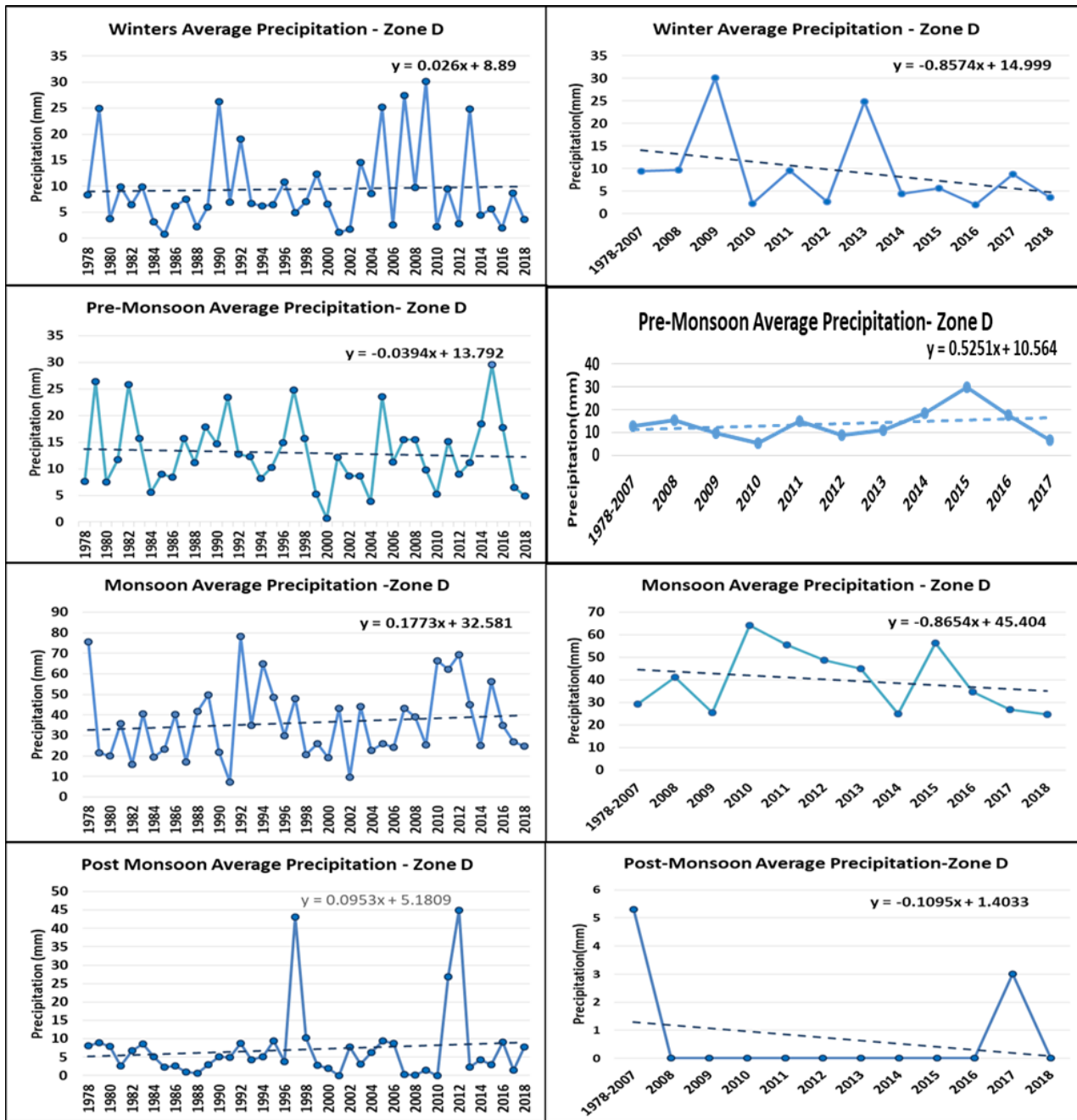


Figure 5

The figure depicts trends and variations of precipitation in Zone D of the country based on Pakistan Meteorological Department's (PMD) station data over two time scales: a) 1978-2018 and b) 2008-2018 compared to the 30 year baseline value of 1978-2007

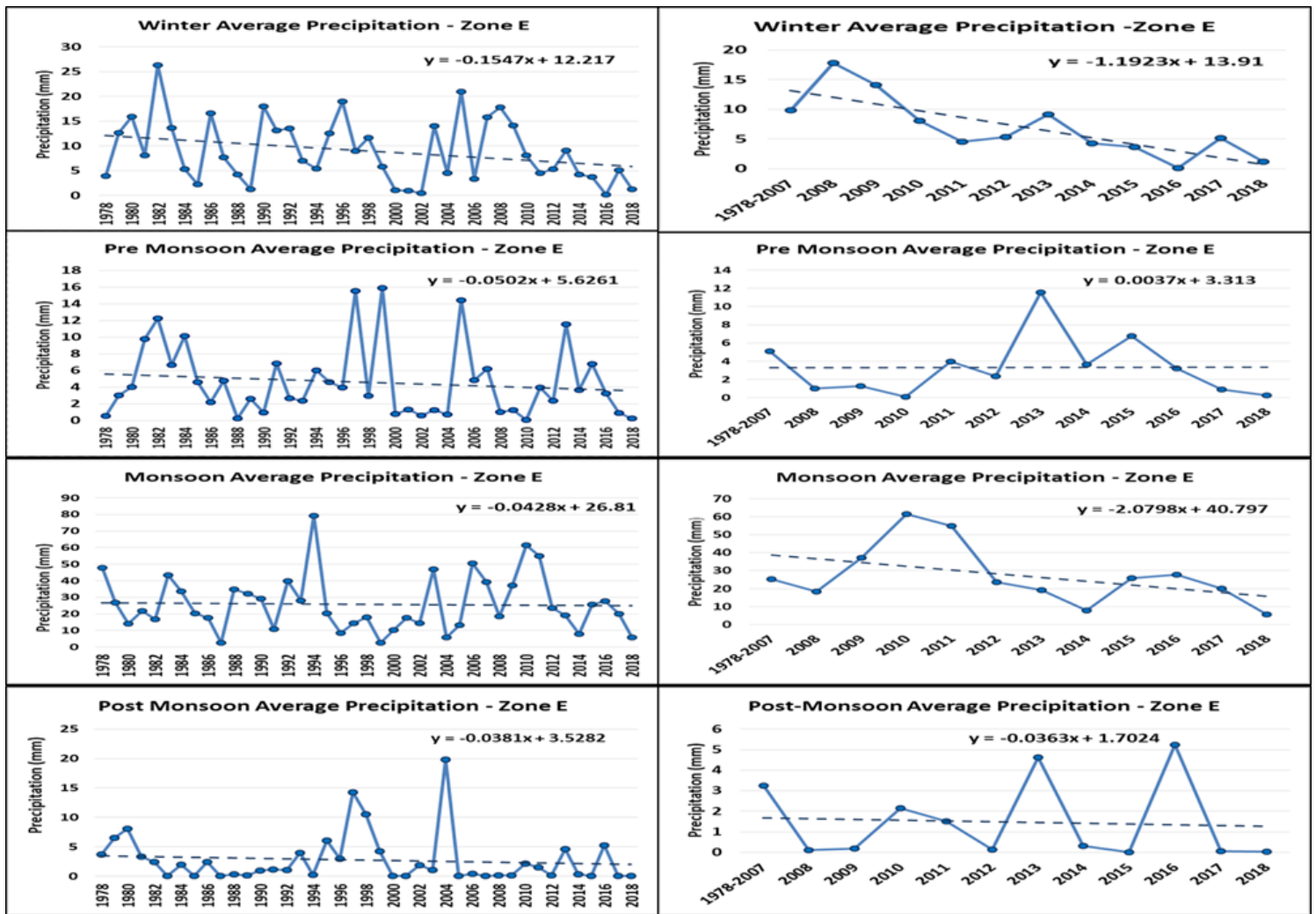


Figure 6

The figure depicts trends and variations of precipitation in Zone E of the country based on Pakistan Meteorological Department's (PMD) station data over two time scales: a) 1978-2018 and b) 2008-2018 compared to the 30 year baseline value of 1978-2007

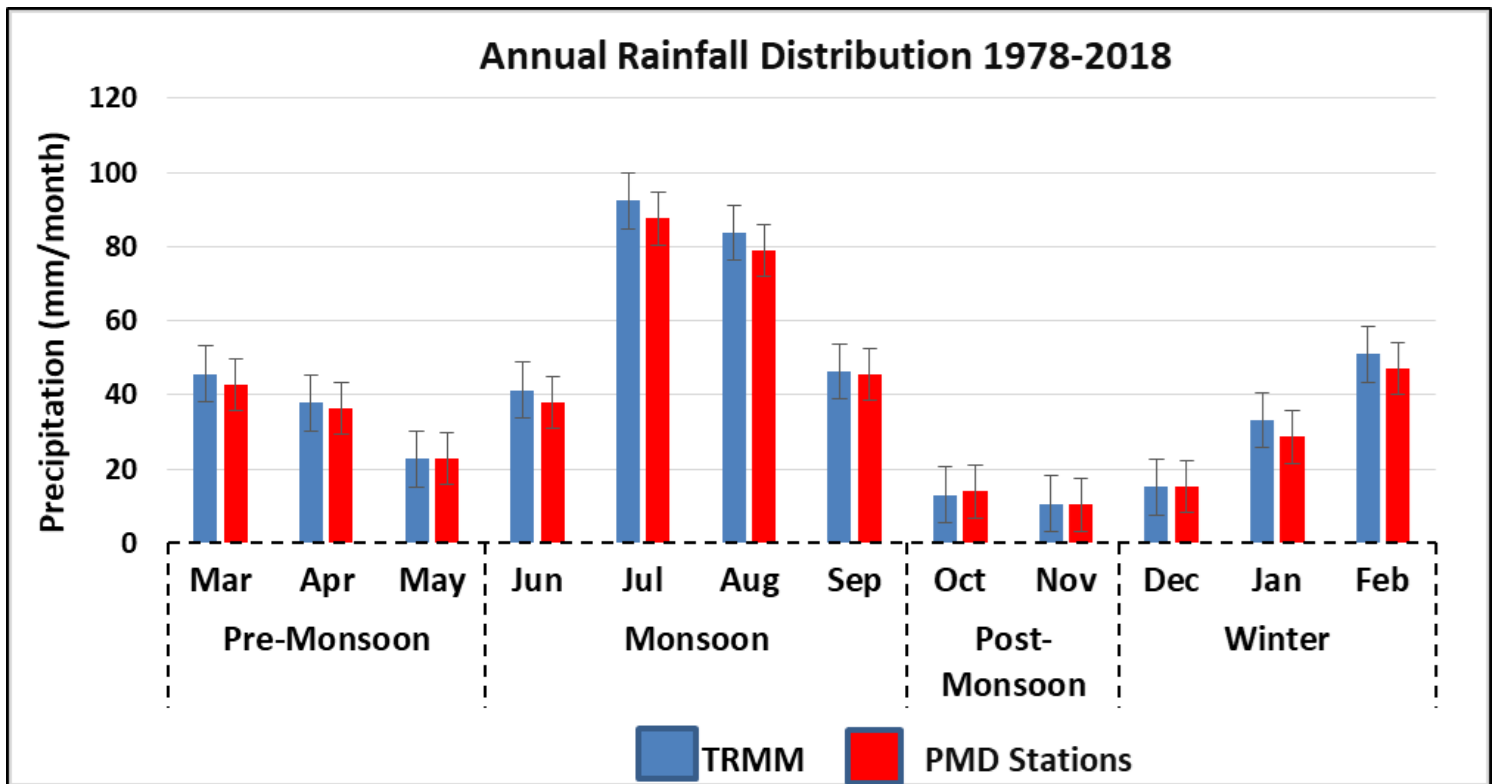


Figure 7

Precipitation distribution in Pakistan during the years 1998 – 2018; Two distinct rainy seasons are noticeable i.e., winter rainfall from December to February and monsoon rainfall from June to September

Figure 8

Spatial distribution of average annual precipitation in Pakistan. The background in the map is TRMM data and the circles on top depict PMD stations data for precipitation in the same color range as the TRMM data

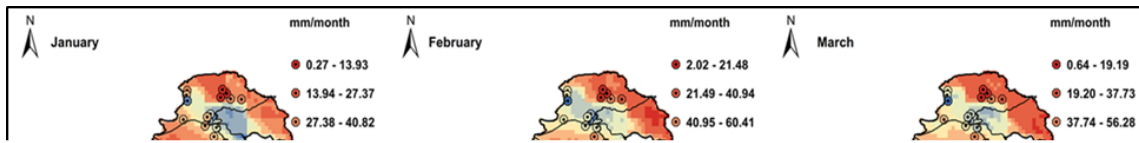


Figure 9

Maps depicting monthly precipitation over Pakistan (1998-2018) through satellite and ground observations for all the months (a – k). Comparison between PMD ground data and TRMM_3B43 satellite data monthly precipitation for selected stations is shown by the same color in the legend for both the data sets. Both the data sets show a strong correlation with Pearson’s correlation “r” values ranging from 0.89 (November) to 0.97 (July and August)

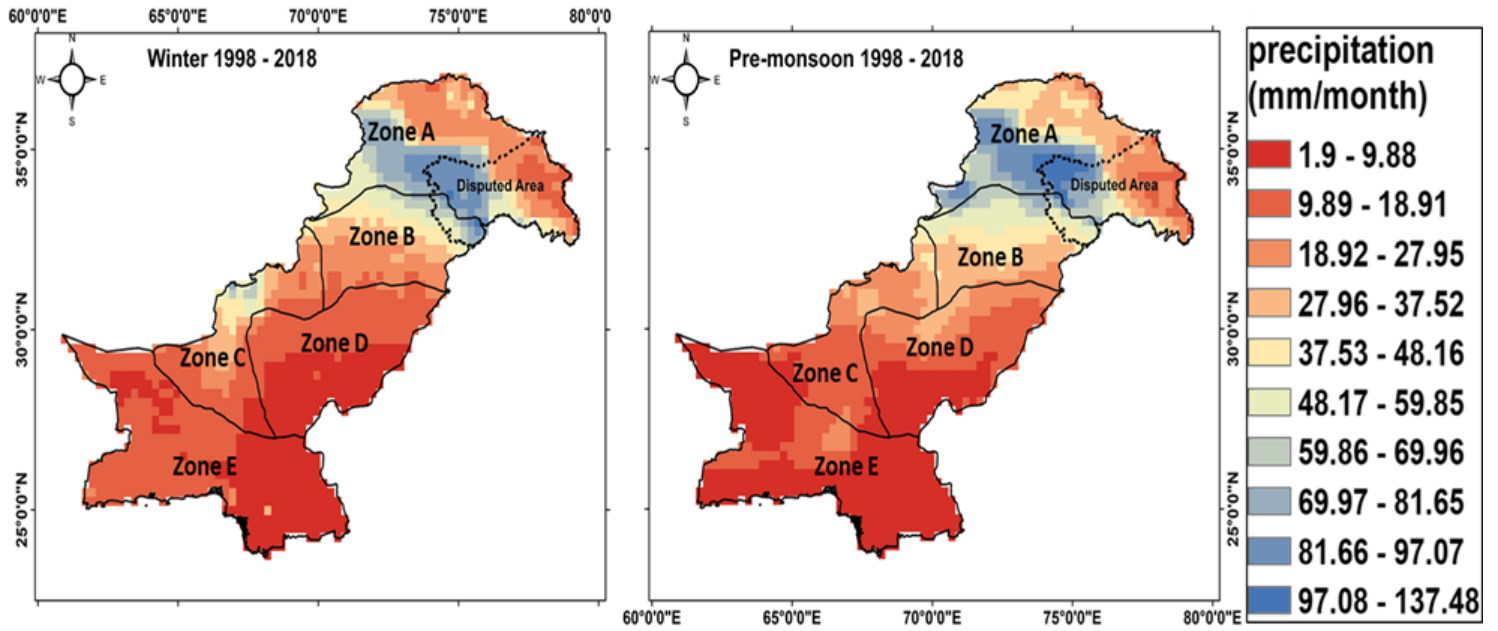


Figure 10

Distribution of average winter and pre-monsoon precipitation in Pakistan from 1998-2018

Figure 11

Spatial extent of winter rainfall in Pakistan; There is a decline in area equating to 34,474 km² for precipitation ≥ 1 mm/day and a fall of 66,318 km² in area with precipitation ≥ 2.5 mm/day

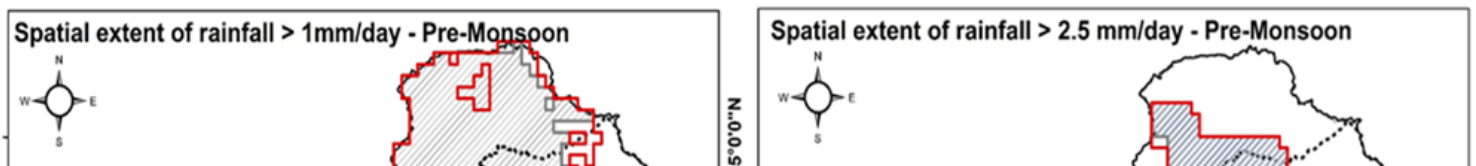


Figure 12

Spatial extent of pre-monsoon rainfall in Pakistan; There is an increase of 107,365 km² in area with precipitation ≥ 1 mm/day and a decrease of 60,163 km² in area with precipitation ≥ 2.5 mm/day

Figure 13

Comparison of CCSM4 model projections with ground observation during 2010-2018: model generally over-estimated precipitation over Pakistan except over Zone A for RCP 4.5 scenario

Figure 14

Difference maps from baseline 1975-2005; a) RCP 4.5 showing changes in Precipitation for the year 2040-2049 b) RCP 4.5 showing changes in Precipitation for the year 2090-2099 c) RCP 8.5 showing changes in Precipitation for the year 2040-2049 d) RCP 8.5 showing changes in Precipitation for the year 2090-2099