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Spatio-temporal trends in observed and downscaled precipitation over Ganga Basin

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Abstract. This paper focuses on the spatio-temporal trends of precipitation over the Ganga Basin in India for over 2 centuries. Trends in precipitation amounts are detected using observed data for historical period in 20th century and using downscaled precipitation data from 37 GCMs for 21st century. The ranking of 37 GCMs (from CMIP5 archive) is done employing a statistics based skill score. The best ranked GCM output is then bias corrected with observed precipitation prior to further analysis. The direction and magnitude of trend in annual and seasonal precipitation series is determined using Mann Kendall's test statistic (ZMK) and Thiel Sen's Slope estimator (β). The plots depicting the spatial variation of ZMK and β are prepared which provides a comprehensive inter-scenario comparison of spatio-temporal trends in precipitation series. Highly non-uniform spatio-temporal trends are detected for observed precipitation series. It is observed that the precipitation for annual and southwest monsoon season is indicating a rising trend for all future emission scenarios in the region adjacent to Himalayas (northeast side of study area) but shows falling trends in the plains away from the Himalayas. Insignificant trends are observed in pre-monsoon and winter season precipitation. An inter-emission-scenario comparison shows that for higher emission scenarios the annual and southwest monsoon precipitation is showing rising trends with increasing spatial dominance i.e. the area under rising trends increases as we observe it from low to high emission scenarios.

1 Introduction

The Ganga basin is of great social, economic and religious importance to India. The basin which is a part of northern plains of India is predominantly covered by fertile alluvial soils brought down by various tributaries of Ganga. Agriculture being the dominant economy sector in this basin is therefore dependent on rainfall. The monsoon season for the region is mainly in the months of June to September. Similar is the season for cultivation of Kharif season crops in India. Main Kharif crops are rice and millet, which are highly dependent on quantity and timing of availability of rain water. More than 85% of the total rainfall occurs in monsoon season in this region. Rabi crops are sown in winter and harvested in spring season. In India, the

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main Rabi crop is wheat, for which the main source of water is groundwater and irrigation. Excess rainfall in this season may spoil the Rabi crops but on the contrary is beneficial to Kharif crops.

Interpreting the importance of rainfall in the region, this study is targeted for determining the possible future trends in precipitation for the area. Ganga basin is already of great interest to many researchers, hydrologists and water resource planners. Few of them have already reported the trends in observed precipitation series in some regions which are subsets of Ganga basin (Kothyari et al. 1997; Duhan and Pandey 2013; Suryavanshi et al. 2013). They have utilized monthly time series of observed precipitation and aggregated them to annual and seasonal amount to capture the trends embedded in them.

A number of studies related to trends analysis of rainfall/precipitation are reported in literature. Diversities are found in various studies from around the world which include not only temporal trends but also spatial trends in precipitation patterns, out of which some of them are enlisted in Table 1. The studies are based on rainfall/precipitation on various time scales such: annual extreme of 5-30 min and 1-12 h rainfall (Adamowski et al. 2003), annual total rainfall, seasonal total rainfall (as per most of the authors enlisted in Table 1); whereas as in few studies, researchers have focused on rainfall amounts of a particular season only such as monsoon season rainfall (Bashistha et al. 2009). Some authors have also utilized certain indices for trend detection such as frequency indices in daily rainfall for total, light, moderate, intense and very intense rainfall (Gallego et al. 2011), seasonality index (Celleri et al. 2007). Most of the researchers have used rain-gauge station data, whereas few of them have considered data for meteorological subdivisions of a region for trend analysis (Guhathakurta and Rajeevan, 2008).

Popular methods used by researchers for trend analysis of rainfall/precipitation time series are parametric linear regression analysis (Guhathakurta and Rajeevan 2008; Caloiero et al. 2011; Kumar et al. 2013), robust locally weighted regression (Kothyari et al. 1997), non-parametric Mann-Kendall's test (used by most of the authors enlisted in Table 1), modified Mann-Kendall's Test (Bashistha et al. 2009), Sen's slope estimator (Gallego et al. 2011; Barua et al. 2013; Duhan et al. 2013; Suryavanshi et al. 2013). Jain and Kumar (2012) have shown insignificant Sen's slope estimates for annual as well as seasonal observed rainfall series in Ganga Basin as a whole. Duhan and Pandey (2013) have also observed a dominating negative trend at most of the rain gauge stations except for a few in the study area which lies in western part of Ganga Basin. Arora et al. (2016) have provided a scenario-wise comparison of downscaled rainfall over a upper Yamuna sub-basin.

A number of agencies have developed their own GCMs following the norms provided by Intergovernmental Panel on Climate Change, yet every GCM cannot be stated as ideal for a particular location. Ranking for best fitting GCMs is done on the basis of skill scores which are subsequently based on certain statistical parameters in order to determine the GCMs with best precipitation capturing capability (Perkins et al., 2007; Ojha et al., 2013)

In this study, along with the spatial and temporal trends in annual and seasonal precipitation, future-emission-scenario-wise trends are also presented. For this, the observed and downscaled precipitation data is used which is made available by various sources in gridded form. Ranking is done on the basis of skill score which is further based on various statistical parameters and other statistics. Bias correction is performed on downscaled precipitation to reduce the systematic biases present in them. After that the trend analysis is performed on observed and bias-corrected downscaled precipitation series

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over the entire study area. The methods used for this purpose are Mann-Kendall's test and Thiel-Sen's slope estimator. The details of study area and methodology followed are discussed in subsequent sections.

Table 1: Summary of studies related to trend analysis of rainfall/precipitation

No.	References and study area	Duration and data length	Methods employed
Studies around the World			
1	Lettermaier et al. (1994) 1036 stations in continental United States	monthly precipitation for data between 1948-1988	Nonparametric seasonal Kendall's test, Thiel-Sen's slope
2	Adamowski et al. (2003) 44 rainfall stations in Ontario, Canada	annual extreme of 5,10, 15, 30 min and 1, 2, 6 and 12 h rainfall with 20 years data	Regional average Mann-Kendall S trend test, L moments method, A bootstrap methodology
3	Celleri et al. (2007) 23 rainfall stations, Paute Basin, Ecuadorian Andes	seasonality index and; annual, seasonal and monthly rainfall for data between 1964-1998	Two sided Mann-Kendall's test
4	Aldrian et al. (2008) 40 rainfall stations, Brantas Catchment Area (DAS Brantas), East Java	annual changes in monthly and seasonal rainfall with 50 years data (1955-2005)	Empirical Orthogonal Function (based on multivariate statistics), non-parametric Mann-Kendall Test, Wavelet Transform Method
5	Beecham and Chowdhary (2010) Melbourne, Australia	point rainfall (rainfall intensities at 0.1, 0.5, 1, 3, 6, 12 h and monthly) for data between 1925-2002	Statistical moments, lag1 autocorrelation, the Buishand's Q test, Mann-Kendall test and wavelet analysis
6	Gallego et al. (2011) 27 stations in Portugal and Spain, Iberian Peninsula	frequency indices in daily rainfall (total, light, moderate, intense and very intense rainfall) for data between1903–2003	Mann-Kendall test, Sen's slope estimator
7	Caloiero et al. (2011) 109 rain gauge stations, Calabria (Southern Italy)	annual and seasonal rainfall with 50 years data	Mann-Kendall test, parametric linear regression analysis
8	Iwasaki (2012) 758 stations in Eastern Japan	hourly rainfall amounts for June and September with 31 years data (1976-2006)	Non-parametric Wilcoxon rank-sum test
9	Casimiro et al. (2013) 58 stations in Peruvian Amazon–Andes basin	annual and seasonal rainfall with 40 years data	Mann-Kendall non- parametric test, Pettitt non-parametric test
10	Barua et al. (2013) 15 rainfall stations, Yarra River catchment, Victoria, Australia	monthly and annual rainfall with 54 years data (1953-2006)	Mann-Kendall test, Sen's slope estimator, CUSUM test, pre-whitening criteria test
11	Kumar et al. (2013) 14 stations in Fiji	annual, wet and dry seasonal rainfall with 100 years data	Linear Regression
Studies in India			
1	Guhathakurta and Rajeevan (2008) 36 meteorological subdivisions of India	monthly, seasonal and annual rainfall for data between 1901-2003	Linear regression
2	Guhathakurta et al. (2011) 2599 raingauge stations all over India	annual one-day extreme rainfall with 30 years (and more) data	Mann-Kendall's test, least square linear fit
Studies in Ganga Basin			
1	Kothyari et al. (1997) 3 stations Agra, Dehradun and Delhi in Ganga Basin, India	total monsoon rainfall with 89 years data (1901-1989)	robust locally weighted regression, Mann-Kendall test
2	Bashistha et al. (2009) 30 rain gauge stations in Indian Himalayas	annual and monsoon rainfall with 80 years data (1901-1980)	Modified Mann-Kendall Test, Pettitt-Mann-Whitney test
3	Duhan et al. (2013) 45 stations, Madhya Pradesh, India	annual and seasonal precipitation with 102 years data (1901-2002)	Mann-Kendall Test, Thiel-Sen's slope estimator, Cumulative deviations test and Mann–Whitney–Pettitt method
4	Suryavanshi et al. (2013) Betwa Basin, India	annual and seasonal precipitation (monsoon, winter and summer)	Mann-Kendall Test, Thiel-Sen's slope estimator
5	Arora et al. (2016) Yamuna-Hindon Interbasin, India	monthly precipitation series	scenario-wise comparison

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2 Study Area and Data Used

2.1 Ganga Basin

India lies in a tropical monsoon climate zone with spatially diversified rainfall pattern (Guhathakurta et al. 2011). The study area considered is the portion of Ganga basin which lies in India only. It lies between latitudes from 21.25º N to 31.5º N and longitudes from 73.25º E to 89.25º E. As per the Köppen-Geiger climate type map of Asia (Peel et al. 2007), the study area predominantly lies in humid-subtropical climatic zone of India. A smaller region of it in the western most part lies in semi-arid zone, whereas the downstream-most part of it lies in tropical wet and dry zone of India. The length of main stream of Ganga is more than 2500 kms and the catchment area is about 20% of the total geographical area of India. The River Ganga originates in the laps of Himalayas (at Gaumukh), flows eastwards through the northern plains of India and finally drains into the Bay of Bengal, forming the biggest delta in the world along with the River Brahmaputra. Along its complete stretch, many tributaries unite themselves with the Ganga at various locations. Tributaries like Gomati, Ghaghra and Gandak conjoins with main stream of Ganga from the northern side. These tributaries are glacier fed and are perennial. Whereas tributaries like Chambal, Sind, Betwa, Ken and Son conjoins it from the southern side.

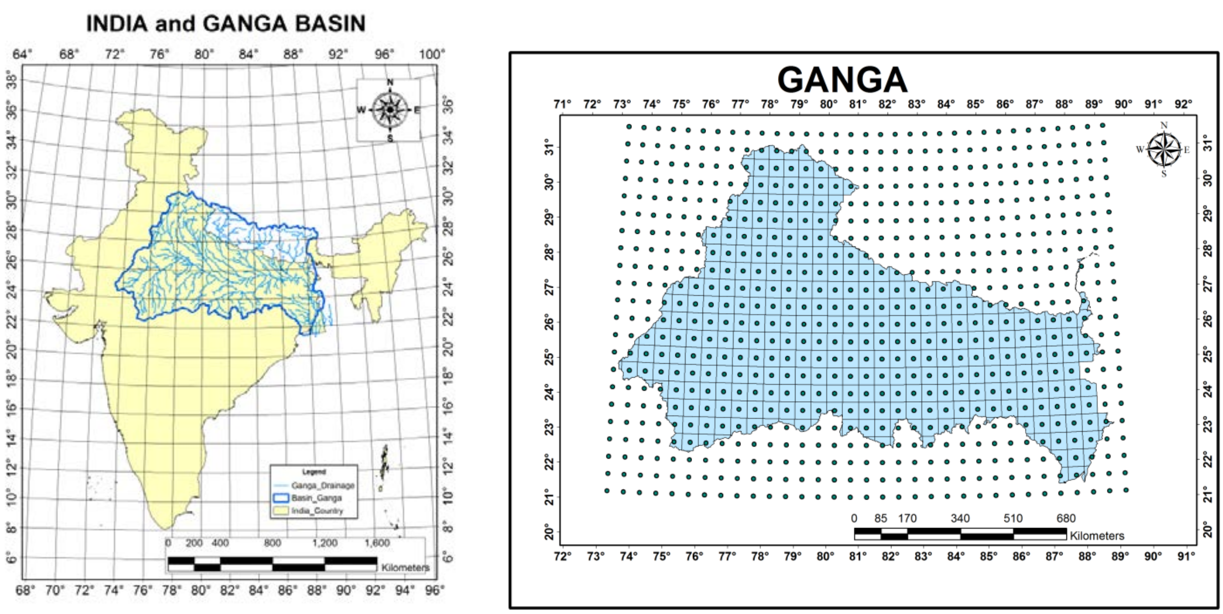

Figure 1: Study Area - Ganga Basin

2.2 Precipitation Data Used

The precipitation dataset used for the study in this paper consists of gridded observed and downscaled precipitation.

Observed Precipitation data (Pobs): The observed daily precipitation is made available by the Indian Meteorological Department (IMD) in gridded form for the time period ranging between January 1901 and December 2015. The horizontal

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resolution of this data in geographical coordinates is 0.25° x 0.25° (latitudes x longitudes). For this study, seasonal and annual aggregate amount of precipitation is computed and used for analysis. The meteorological seasons considered in the study area (as per IMD definition) are: southwest monsoon season (Jun-Sep), northeast monsoon season (Oct-Dec, also termed as post-monsoon), winter season (Jan-Feb), and pre-monsoon season (Mar-May). From now onwards in this paper, these seasons are denoted by SWM, NEM, WS and PM respectively.

Downscaled Precipitation data: Downscaled CMIP5 climate and hydrology projections are obtained from archive at http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/ (Maurer et al. 2007). The precipitation was downscaled using the bias-correction and spatial disaggregation (BCSD) method. Downscaled precipitations for 37 GCMs from CMIP5 archive (ensemble r1i1p1) are used in this study. The GCMs are enlisted in Table 2. The horizontal resolution of this data in geographical coordinates is 0.5° x 0.5° (latitudes x longitudes). This data is available for various emission scenarios such as: RCP2.6, RCP4.5, RCP6.0 and RCP8.5 (for CMIP5). As per the 5th assessment report (AR5) of IPCC (2013), the newer families of emission scenarios are introduced which are termed as Representative Concentration Pathways (RCPs) (Vuuren et al. 2011). RCPs are referred according to radiative forcing target level of greenhouse gases and other forcing agents for year 2100. RCP2.6 is termed as a mitigation scenario leading to a very low forcing level with peak in radiative forcing at ~3 W/m2 (~490 ppm CO2 equivalent) before 2100 and then decline. RCP4.5 and RCP6.0 are two medium stabilization scenarios, which corresponds to stabilization without overshoot pathway to 4.5 W/m2 (~650 ppm CO2 equivalent) and 6 W/m2 (~850 ppm CO2 equivalent) respectively, at stabilization after year 2100. RCP8.5 is termed as a very high baseline emission scenario with rising radiative forcing pathway leading to 8.5 W/m2 (~1370 ppm CO2 equivalent) by year 2100.

Length of the data considered for the fulfilment of objective of this paper is 56 years for observed data (1950 to 2005) and 95 years for CMIP5 data (2006-2100) for all future emission scenarios (RCP2.6, RCP4.5, RCP6.0 and RCP8.5). The spatial resolution of data considered for further analysis is 0.5° x 0.5° (latitudes x longitudes). A total of 358 grid point covers the study area as shown in Fig.1. As the data is available for multiple GCMs (37 CMIP5), ranking of GCMs for downscaled monthly precipitation is done on the basis of a skill score, which is discussed later. The monthly precipitation series is then aggregated annually and seasonally (SWM, NEM, WS and PM). For comparison of downscaled precipitation dataset from different CMIP archives over Ganga basin, the spatial variation of seasonal and annual means of precipitation time series over Ganga basin are plotted as shown in Fig. 2. It can be inferred from this figure that in Ganga Basin, major percentage of observed annual precipitation occurs in southwest monsoon season (about 85%), where as a smaller percentage of it occurs in post monsoon (about 6%) and pre-monsoon season (about 6%).

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Table 2 List CMIP5 GCMs and developer agencies

No.	Model	Institution and country
1	ACCESS1-0	Commonwealth Scientific and Industrial Research Organization/Bureau of Meteorology (CSIRO-BOM), Australia.
2	ACCESS1-3	
3	BCC-CSM1-1	Beijing Climate Center (BCC), China.
4	BCC-CSM1-1-M	
5	BNU-ESM	Beijing Normal University (BNU), China.
6	CANESM2	Canadian Centre for Climate Modelling and Analysis (CCCma), Canada.
7	CCSM4	National Center for Atmospheric Research (NCAR), USA.
8	CESM1-BGC	
9	CESM1-CAM5	
10	CMCC-CM	Centro Euro-Mediterraneo sui Cambiamenti Climatici (CMCC), Italy.
11	CNRM-CM5	Centre National de Recherches Météorologiques (CNRM), France.
12	CSIRO-MK3-6-0	Commonwealth Scientific and Industrial Research Organization/Queensland Climate Change Centre of Excellence (CSIRO-QCCCE), Australia.
13	FGOALS-G2	Institute of Atmospheric Physics, Chinese Academy of Sciences (LASG-CESS), China.
14	FIO-ESM	The First Institute of Oceanography (FIO), SOA, China.
15	GFDL-CM3	Geophysical Fluid Dynamics Laboratory (NOAA-GFDL), USA.
16	GFDL-ESM2G	
17	GFDL-ESM2M	
18	GISS-E2-H-CC	Goddard Institute for Space Studies (NASA-GISS), USA.
19	GISS-E2-R	
20	GISS-E2-R-CC	
21	HADCM3	Met Office Hadley Centre (MOHC), UK.
22	HADGEM2-AO	
23	HADGEM2-CC	
24	HADGEM2-ES	
25	INMCM4	Russian Academy of Sciences, Institute of Numerical Mathematics (INM), Russia.
26	IPSL-CM5A-LR	Institut Pierre Simon Laplace (IPSL), France.
27	IPSL-CM5A-MR	
28	IPSL-CM5B-LR	
29	MIROC-ESM	Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology, Japan.
30	MIROC-ESM-CHEM	
31	MIROC4H	
32	MIROC5	
33	MPI-ESM-LR	Max Planck Institute for Meteorology (MPI-M), Germany.
34	MPI-ESM-MR	
35	MRI-CGCM3	Meteorological Research Institute (MRI), Japan.
36	NORESM1-M	Bjerknes Centre for Climate Research, Norwegian Meteorological Institute (NCC, NMI), Norway.
37	NORESM1-ME	

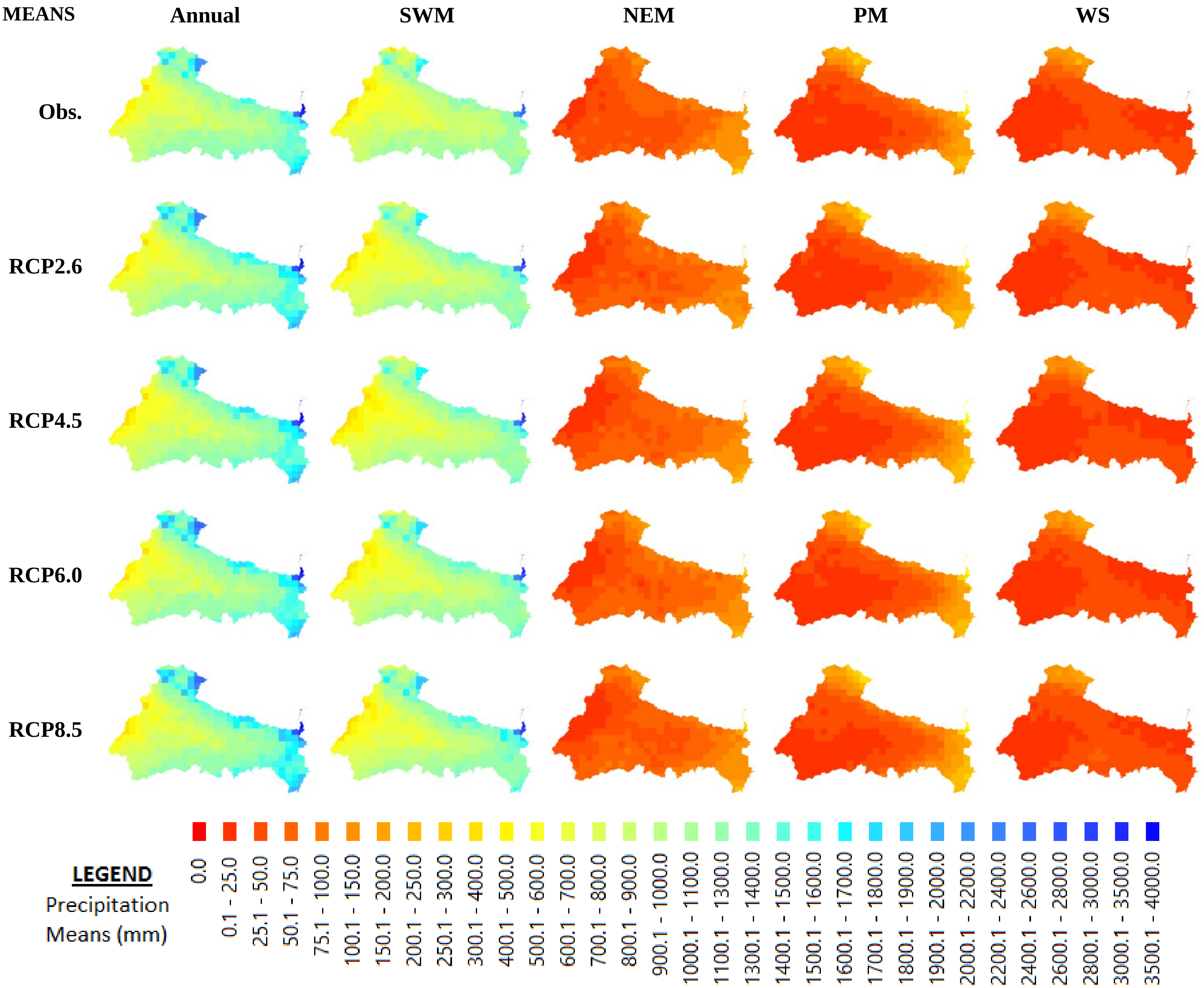

Figure 2: Long term means of annual and seasonal (SWM, NEM, PM and WS) aggregates of precipitation amount.

3 Methodology

The methodology followed in this paper includes: skill score based ranking of GCMs; bias correction of best performing GCM output w.r.t. observed precipitation; trend analysis on the basis of non-parametric Mann-Kendall test statistic and Thiel Sen's slope estimator.

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3.1 Ranking of GCMs

Various researchers have practiced the ranking of GCMs for the purpose of getting better estimates of downscaled precipitation. In Fig. 3, just by visual inspection, it can be inferred that there is a large variability in predicted values of target variable, when an ensemble of GCMs is considered. Therefore ranking of GCMs is necessary to determine the GCMs in best agreement with observed data. Raju et al. (2016) have practiced a compromise programming based methodology for ranking of CMIP5 based GCMs for evaluating the performance of maximum and minimum temperature (Tmax and Tmin) simulations over India. For determining the performance of GCM for prediction of different hydro-meteorological variables, skill scores based ranking methods are also exercised by respective authors. (Anandhi and Nanjundiah, 2015; Fu et al., 2013).

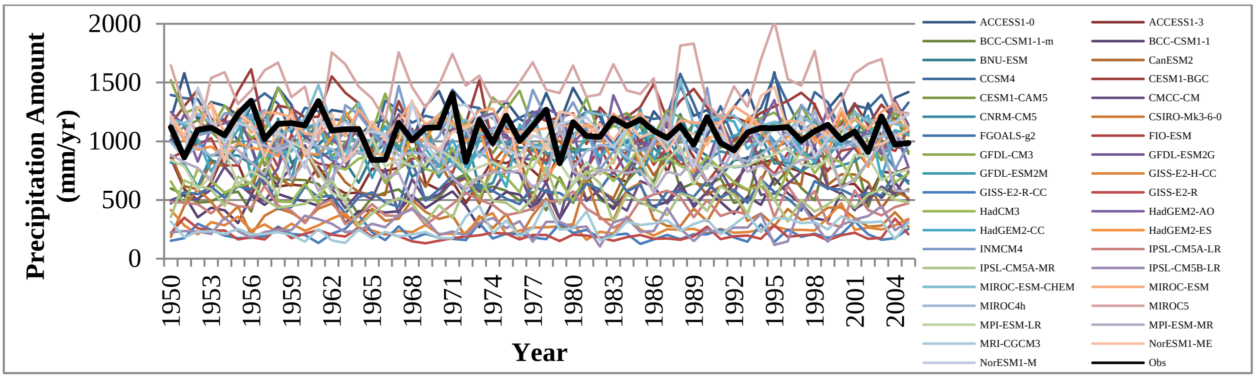

Figure 3: Annual precipitation time series plots for observed and CMIP5 data for historical period (1950-2005)

In this study, for evaluating the performance of GCM in simulating the precipitation series, ranking of GCMs is done based on an skill score (SS). This skill score is developed based on combined magnitude of several statistical measures. These are: coefficient of correlation (CC), absolute relative error in: means (REMN), standard deviation (RESD), coefficient of skewness (RECS), coefficient of kurtosis (RECK), Mann-Kendall statistic (REMK) (Kendall 1975), Thiel-Sen's slope (RETS) (Thiel 1950; Sen 1968), shape and scale parameters of gamma distribution (REG1 and REG2). The lower the value of SS the better will be the performance of GCM in predicting the precipitation for an area.

$$SS = (1-CC) + |REMN| + |RESD| + |RECS| + |RECK| + |REMK| + |RETS| + |REG1| + |REG2| \qquad (1)$$

Spatially averaged skill score (SASS) is obtained by averaging the SS values over study area. The formula is as shown below.

$$SASS = \frac{\sum_{n=1}^{P} SS_P}{P} \qquad (2)$$

Where, SSp = skill score at a particular grid point, P = number of grid points covering the study area.

3.2 Bias Correction

Even after determining the best performing GCM in predicting precipitation, there are still some biases present in the downscaled precipitation series. To remove those biases, an equi-probability transformation based bias-correction technique is applied to downscaled precipitation series. Here the cumulative distribution functions are obtained for observed precipitation and downscaled precipitation for baseline period (historical scenario). Using these two CDF, the projected precipitation series is bias-corrected for historical as well as future emission scenarios (RCP 2.6, RCP 4.5, RCP 6.0 and RCP 8.5). The detailed procedure is being illustrated by Ghosh and Mujumdar (2008) and Arora et al. (2016).

3.3 Trend Analysis

For comparison purpose, the long-term means of precipitation time series for observed and downscaled values are computed which are shown in Fig. 2. In this paper, the methods used for trend detection are: Mann-Kendall's test and Thiel-Sen's slope estimator.

Few researchers have emphasized on pre-whitening of precipitation time series prior to trend analysis due to the presence of serial correlation effect in a series. According to Partal and Kahya (2006), this effect may cause inaccuracy and misinterpretation in trend detection of a hydrologic time series. But in case the sample size is large enough (n>70), few researchers (Yue and Wang 2002; Bayazit and Onoz 2007) have recommended not to perform pre-whitening of dataset as the serial correlation does not have a major effect on MK test as well as it may cause reduction of power in it.

3.3.1 Mann-Kendall's test for trend detection

The rank-based non-parametric Mann-Kendall's test (Mann 1945; Kendall 1975) is applied to seasonal and annual total precipitation time series for observed and downscaled dataset. Being non-parametric in nature, this test have several advantages over parametric test for trend detection in hydrologic series, such as: (1) normality in data and homogeneity in its variance need not be assumed, (2) no effect of outliers on its performance since it compare central values such as medians rather than means, (3) transformation of data is also not required due to its non-parametric nature, (4) performs effectively for the dataset even if it's distribution is skewed in nature (5) can be employed to the dataset below detection limit as it uses the relative position of data points with each other. (Helsel 1987)

The null hypothesis (H_0) for this test which is applied on annual as well as seasonal precipitation is: the time series data has no trend and the data is a series of identical and independently distributed random variables (Gallego et al. 2011). Whereas the alternate hypothesis (H_1) for the same is: the time series data has a significant rising or falling trend. For this, 's' statistic is calculated as shown in Eq. (3) and (4). The mean and variance of 's' under null hypothesis, can be calculated as shown in Eq. (5). Thereafter, Mann Kendall statistic (Z_{MK}) is calculated which is normally distributed with zero mean and unit standard deviation. The positive value of Z_{MK} shows a rising trend and a negative value of it indicates a falling trend in the series. In this study, the significance of Z_{MK} is observed on confidence level 90%, 95% and 99%.

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$$s=\sum_{i=1}^{n-1}\sum_{j=i+1}^{n} signum(p_j-p_i) \quad (3)$$

$$signum\left(p_j-p_i\right)=\begin{cases}1 \,......... if\,(p_j-p_i)>0\\ 0 \,......... if\,(p_j-p_i)=0\\ -1......... if\,(p_j-p_i)<0\end{cases} \quad (4)$$

$$E(s)=0\,;\, Var(s)=\frac{n(n-1)(2n+5)-\sum_{i=1}^{T}t_i(t_i-1)(2t_i+5)}{18} \quad (5)$$

$$Z_{MK}(s)=\begin{cases}\dfrac{s-1}{\sqrt{Var(s)}}.......... if\;\; s>0\\ 0 \qquad .... if\;\; s=0\\ \dfrac{s+1}{\sqrt{Var(s)}}.......... if\;\; s<0\end{cases} \quad (6)$$

Where, p_j and p_i = data points of precipitation time series, Z_{MK}=test statistic for Mann Kendall test, E(*)=Expected value, Var(*)=variance, n=length of precipitation time series (in years), T=number of ties in precipitation time series, t_i=number of data point for i^{th} tie.

3.3.2 Thiel Sen's slope estimator

Although the Mann Kendall test shows its proficiency in detecting trends in a time series but does not provide slope estimates. Therefore Hirsch (1982) proposed a method for this using Thiel-Sen's slope estimator. The Thiel-Sen's slope (β) is used to determine the magnitude of trend in terms of its slope (Thiel 1950a, 1950b, 1950c; Sen 1968). Assumption of linear slope is applied to this method. Unlikely linear regression method, the Thiel-Sen's slope is insensitive to the presence of extreme values in the data series (Lettermaier et al. 1994), as it requires calculation of median. In this study, it is employed on seasonal and annual total precipitation time series. The slopes are determined between all data points of precipitation time series and the median of all slopes results in β. For a data series of size n, the total number of slopes will be $^{n}C_2$ (i.e., n(n-1)/2). The β is formulated as shown in Eq. 7.

$$\beta=Median\left(\frac{p_j-p_i}{j-i}\right) \quad for\ all\ i<j \quad (7)$$

Where, p_j and p_i = data points of precipitation time series, i and j = indices of data points.

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4 Results and Discussion

4.1 Ranking of GCMs

The SASS is calculated and ranking is done on its basis. The minimum score is obtained for the GCM named CESM1-CAM5 (GCM no. 9 in Table 2) developed by National Center for Atmospheric Research, USA. HadCM3 (Met Office Hadley Centre, UK) and IPSL-CM5A-MR (Institut Pierre Simon Laplace, France) holds second and third rank in skill for prediction of precipitation over Ganga basin. Fig 4 shows the SASS of all the 37 GCM in order of their ability to predict the precipitation in the study area.

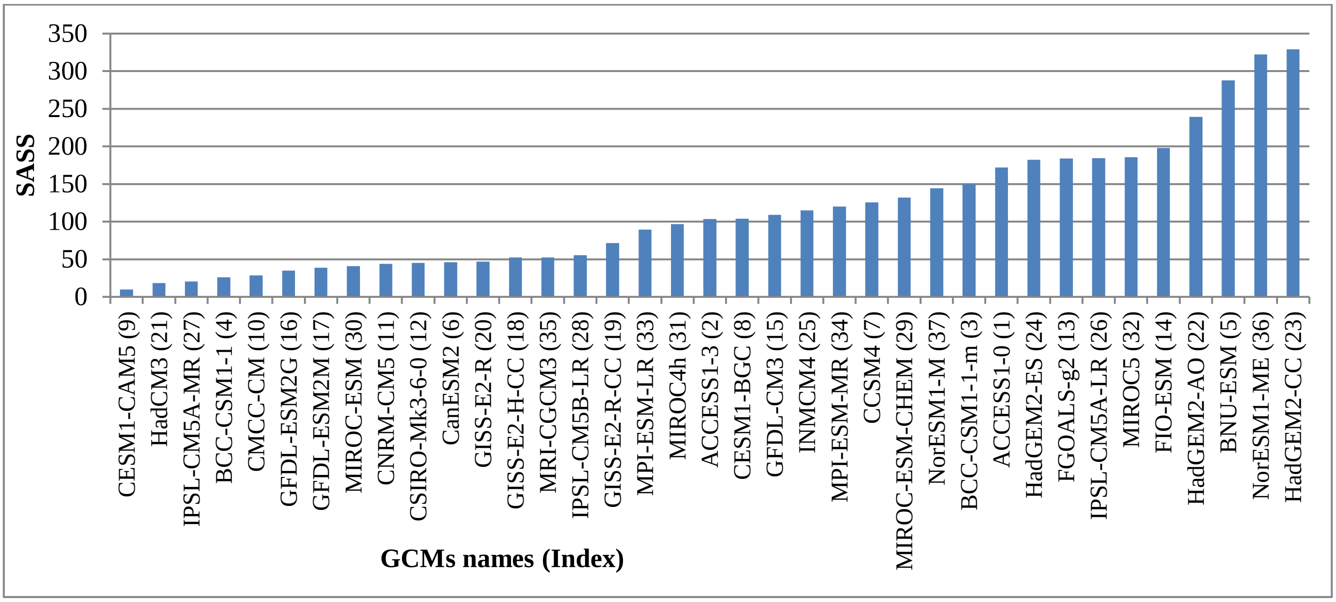

Fig. 4. Spatially average skill score (SASS) for various CMIP5 GCMs

4.2 Trend Detection

A comparison is made among annual and seasonal (SWM, NEM, PM and WS) precipitation time series for observed and downscaled data. The comparison is in terms of: (1) spatial trends of precipitation time series over the Ganga Basin which lies in the Indian administrative boundary; (2) temporal trends of precipitation time series in terms of Z_{MK} and β; and (3) scenario-wise comparison of trends in observed and downscaled precipitation time series for all AR5 (RCP2.6, RCP4.5, RCP6.0 and RCP8.5) emission scenarios of IPCC.

Plots indicating the spatial variation of Z_{MK} and β for annual and seasonal precipitation are presented in Fig 5 and 6 respectively. The color scale used (as shown in legends of these figures) indicates the significance of trends at certain significance levels, for example $|Z_{MK}|$>1.645, 1.960 and 2.576 indicated significance of trends at 10%, 5% and 1%

significance levels respectively. The plots provide a spatio-temporal comparison among observed and downscaled precipitation for all considered AR5 scenarios.

4.2.1 Detection of trend in precipitation: Annual and Southwest monsoon season

It can be observed that the Z_{MK} and β computed for gridded-observed-precipitation series is showing highly non-uniform spatial variation over the study area for annual as well as seasonal time series. A comparable spatial trend can be seen between annual and SWM seasonal observed precipitation as the clusters of significant rising trends can be observed in the portion of study area adjacent to Himalayas as well as downstream side of River Ganga (eastern portion of study area) whereas significant falling trends are observed in the central portion of study area. Insignificant trends in observed precipitation can be seen in remaining part of study area.

As per Z_{MK} (Fig. 5), for all AR5 future scenarios the precipitation time series is showing a dominant rising trend in annual and SWM season near Himalayas. For lower emission scenario (RCP2.6), insignificant trend is observed in most part of study area. As per β (Fig. 6), the magnitudes of slopes for downscaled precipitation are smaller ($0<\beta<1.645$) for lower emission scenarios (RCP2.6) throughout the basin. The area classified under higher magnitudes of slopes ($\beta>1.960$) increases as we observe it from lower emission scenarios to higher emission scenarios.

4.2.2 Detection of trend in precipitation: North-East monsoon season (Post-monsoon)

In case of observed precipitation for NEM season (Fig. 5), a mixture of significant negative and insignificant trends are detected in upper and middle reaches of River Ganga respectively , with insignificant trends being spatially pre-dominant throughout the study area.. Similar pattern can be seen in β (Fig. 6) for observed precipitation, with β being negative ($-1.645<\beta<0$) in upper and middle reaches, and β being positive ($0<\beta<1.645$) in lower reaches of Ganga basin.

For downscaled precipitation, area under significant positive trends (Z_{MK}) has a greater spatial coverage for all emission scenarios. The trend remains significant in western region for all emission scenarios except RCP 4.5. As per β (Fig. 6), the downscaled precipitation has a mild positive slope ($0<\beta<1.645$) which is spatially dominant throughout the study area for all the AR5 emission scenarios.

4.2.3 Detection of trend in precipitation: Pre-monsoon season and winter season

A spatially dominant insignificant trend can be observed all over the study area for observed as well as all RCPs. Small clusters of significant positive trend can be seen at the downstream side of Ganga (eastern portion of Ganga basin) for observed, RCP 2.6 and RCP 8.5 precipitation data,

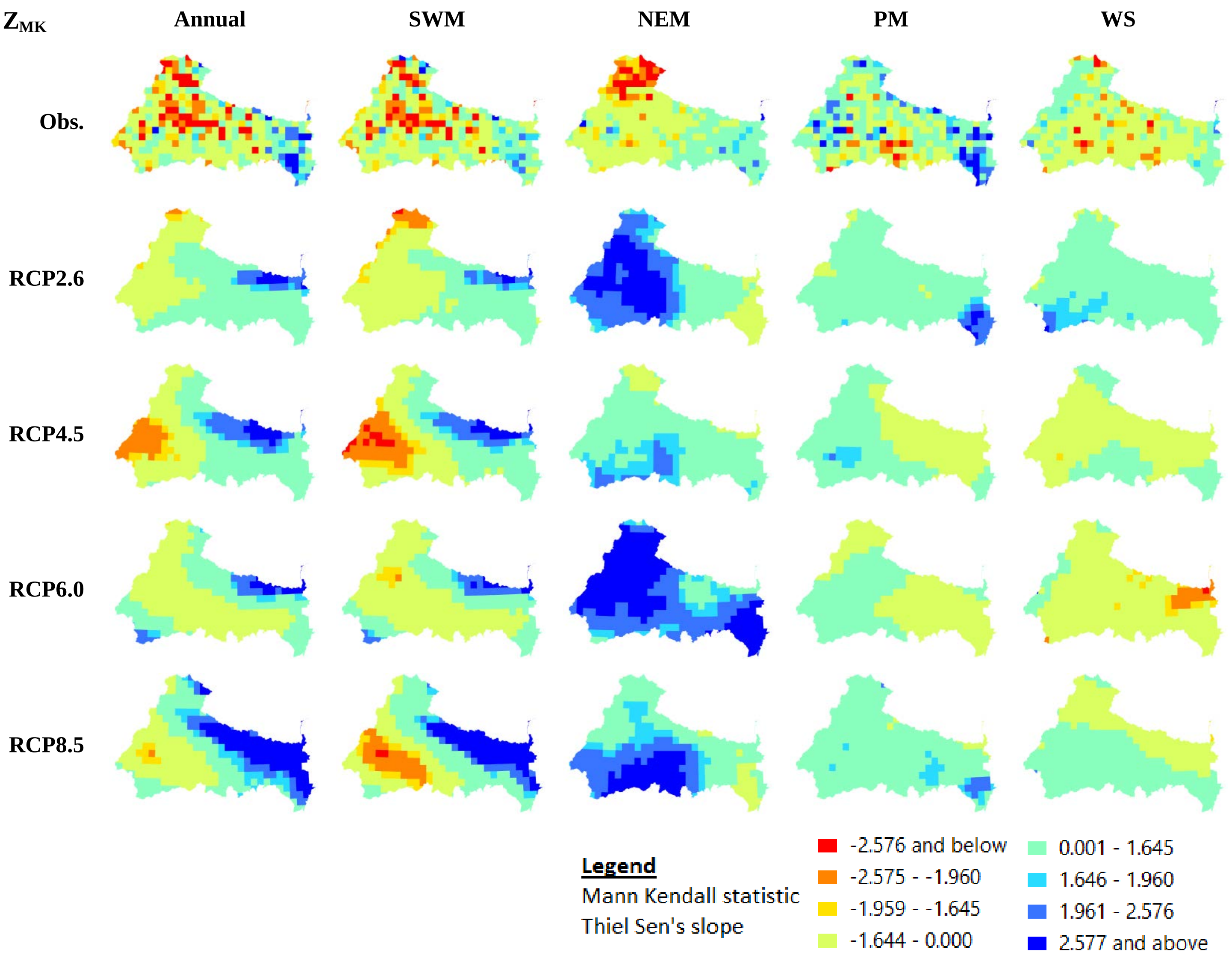

Figure 5: Spatio-temporal variation of Mann Kendall statistic (Z_{MK}) for annual and seasonal amounts of precipitation (observed and downscaled) over Ganga Basin in Indian administrative boundary

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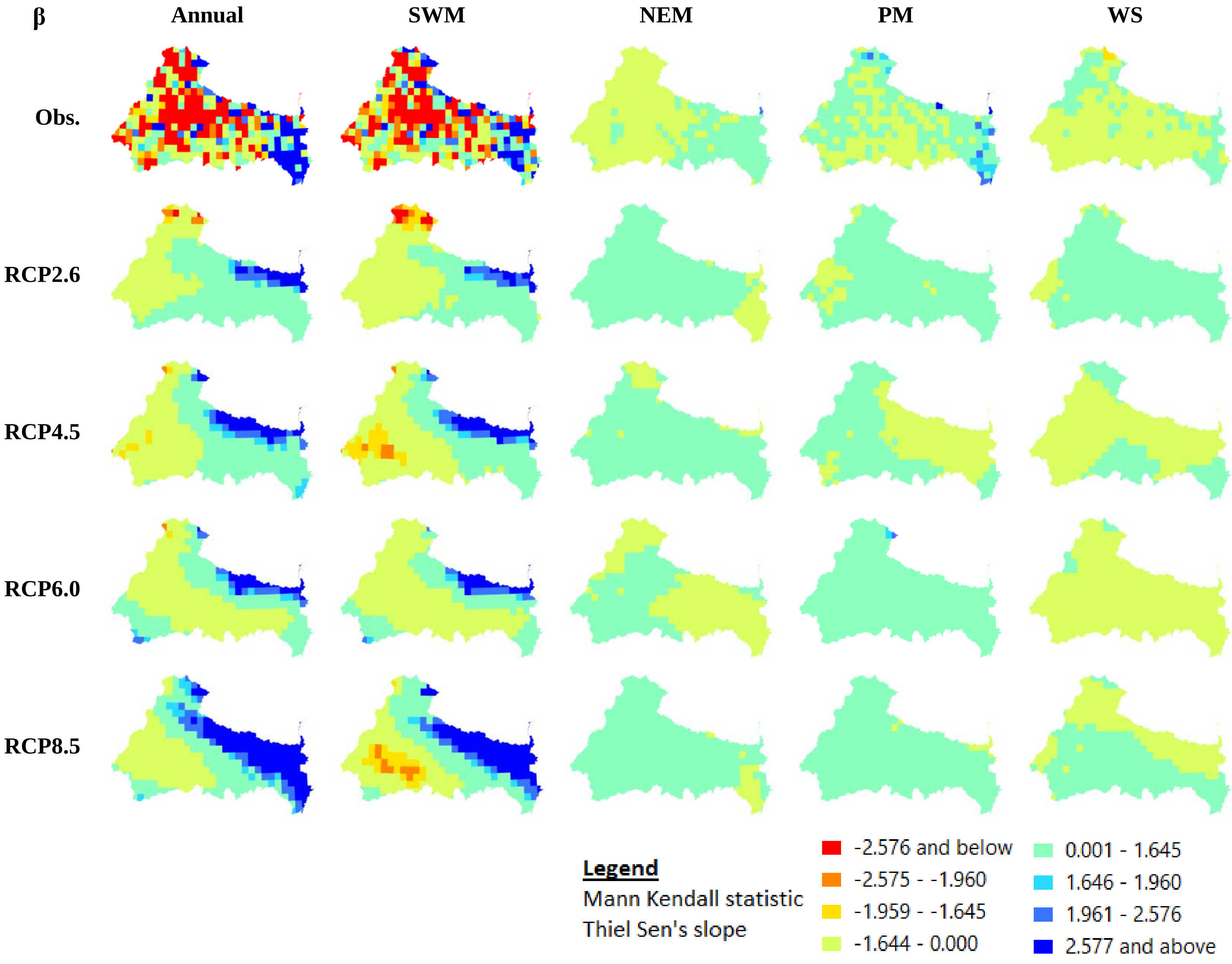

Figure 6: Spatio-temporal variation of Thiel Sen's slope (β) for annual and seasonal amounts of precipitation (observed and downscaled) over Ganga Basin in Indian administrative boundary

5 Conclusion

In this paper a comprehensive methodology for comparison of precipitation trends among observed and all future emission scenarios is presented. Ranking of GCMs proved to be necessary to avoid the variability in ensemble of GCMs for a particular study area. USA-NCAR's GCM (CESM1-CAM5) proved to be the best performing GCM for precipitation over Ganga basin. Plots are prepared to show the spatial distribution and comparison of trends based on Mann-Kendall's statistic and Thiel-Sen's slope. In case of observed precipitation, the spatial variation of trends is found to be highly non-uniform as compared to downscaled precipitation. The spatio-temporal-scenariowise comparison is performed for annual and seasonal precipitation showed that the precipitation amounts for annual and south-west monsoon seasonal time scales are going to increase significantly in the north eastern side of study area for all future emission scenarios but subsequently decrease significantly in the western side. The spatial coverage for significant positive trends in precipitation is also increasing with higher emission scenarios. For post-monsoon season (NEM), the western side of study area is showing a significant increasing trend and rest of the area is showing insignificant trends for precipitation. In case of pre-monsoon and winter season, downscaled future precipitation is showing an insignificant trend in major portion of study area. As this study gives an inter-scenario comparison of projected precipitation in 21st century, therefore, this study could be very useful for the future planning and development of water resources in agriculturally dominated areas of Ganga basin.

Abbreviations

AR5: Assessment Report 5
β: Thiel-Sen's slope estimate
BCSD: Bias-correction and spatial disaggregation
CMIP5: Coupled Model Intercomparison Project phase 5
IPCC: Intergovernmental Panel on Climate Change
Pobs: Observed Precipitation Series
RCP: Representative Concentration Pathways
WCRP: World Climate Research Program
Z_{MK}: Mann-Kendall's test statistic

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