Fate of Rainfall over the North Indian States of India in the 1.5°C and 2°C Warming Scenarios

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Abstract

The rise in mean temperature put a great deal of uncertainty about how weather and climate extremes may play out, particularly in India's varied climatic zones. Consequently, it is important to understand the possible changes in both magnitude and direction of weather and climate extremes like rainfall for different warming levels of 1.5 and 2 °C scenarios concerning preindustrial and present levels. Hence in the present study, the precipitation behavior of seven North Indian states i.e., Haryana, Himachal Pradesh, J&K, Punjab, Rajasthan, Uttar Pradesh, and Uttarakhand carefully studied using observations and CMIP5 models. Future projection of precipitation has been done for two warming levels of 1.5 and 2 °C scenarios. Along with model validation and future projection of precipitation, the return period of extreme rainfall is also discussed to understand the behavior of the occurrence of extreme precipitation. Statistical analysis shows that the ensemble means have the least error as compared to the other six CMIP5 models. Therefore, future analysis has been done with the ensemble mean. Our findings show that the precipitation is likely to decrease in the 1.5°C scenarios, while it is likely to increase in the 2°C scenarios. The occurrence and intensity of extreme rainfall events are likely to be more frequent in all the models. The return period of the extreme rainfall events is likely to increase in all the states in both the warming scenarios. A three-fold rise is likely to increase extreme rainfall events in the 2°C scenario.

Keywords: Climate Change, Climate Projection, Paris Agreement, Extreme Rainfall Events, Heatmap, Return Period

Introduction

Due to climate change, the rate of extreme weather events like extreme rainfall events, heat waves, cyclones, typhoons, severe thunderstorms, etc., has increased, in which the frequency and intensity of precipitation play a significant direct and indirect role (Li et al., 2021). Along with other parameters, precipitation is one of the meteorological variables responsible for different types of weather formation (Gavahi et al., 2022). Rainfall is crucial as it is a commonly available source of water for agriculture (Yang et al., 2020). So, variations in rainfall are closely connected to the cultivation calendar, hence playing an important role in the economy of any country. Whereas, extreme rainfall events are accountable for numerous socioeconomic losses, particularly in urban areas, as well as human losses due to natural disasters (Cabré et al., 2016; Dash et al., 2015; Corada-Fernández et al., 2017; Shi et al., 2021). Hence, it is important to understand the spatial and temporal characteristics of rainfall in the warming atmosphere (Panda et al., 2020; Pattnayak et al., 2019).

Due to change in the normal composition of the atmosphere, pollution level is increasing gradually due to which different natural phenomenon are varied that ultimately poses a serious effect on society in different ways (Awasthi et al., 2017). To understand the behavior/pattern of rainfall, Satellite microwave and infrared (IR) remote-sensing data have been used to calculate monthly and daily precipitation over the oceans, as well as over land. Nowadays, algorithms have been created that generate near real-time hourly or 3-hourly precipitation of resolution of 0.25 degree or finer resolution. After quantitative assessments, this type of high-resolution and near real-time data can be highly valuable in different types of research related to hydrology, weather, climate, etc.

The 2015 Paris Agreement recommended, “Holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels” (UNFCCC, 2015). The concentrations of greenhouse gases (GHGs) must fall before 2060 to accomplish the 1.5°C warming objective, whereas to achieve the 2°C warming target, GHGs must fall before 2085 (Sanderson et al., 2016). Due to the change in the concentration of GHGs, the ocean warming pattern changes and hence show different climate response in term of precipitation in the atmosphere (Chadwick et al., 2013; Long et al., 2014).

Temperature and rainfall data is used mainly for understanding the various climate trends. Alteration in the rainfall volume, frequency, distribution, and intensity is supposed to be a consequence of climate change (Duan et al., 2019, 2015; Zhang et al., 2012) which requires immediate thought and in-depth investigation. Change and variability in climate due to an increase in GHGs result in change in the rainfall pattern throughout the world (Bhatla et al., 2016; Deng et al., 2019; Gergis and Henley, 2017; Singh et al., 2019). In the Indian context, several studies demonstrate a decrease in the number of rainy days and total annual precipitation and an increase in the frequency of heavy rainfall events (Dash et al., 2009; Dash and Hunt, 2007; Goswami et al., 2006; Lal, 2003; Maharana et al., 2022). The southwest monsoon season (June to September), brings about 60–90% of India's yearly rainfall, which is crucial for the nation's economy (Joshi and Rajeevan, 2006). Rainfall's pattern, intensity and frequency play an important role in irrigation and extreme events like drought and flood, etc (Guo et al., 2018; Kulshrestha et al., 2009). Hence, seasonal and annual rainfall and changes in extreme rainfall are important to understand and proper investigation is required.

Lacombe and McCartney, (2014) carried rainfall analysis from 1951–2007 and showed increasing trends in rainfall in southern peninsular India and decreasing trends in rainfall over central India. Increasing trends in precipitation during autumn and winter, whereas decreasing trends during monsoon and spring were reported by Pal and Al-Tabbaa, (2011) based on the analysis for the period of 1954–2003. Many other studies were done by the authors in which rainfall pattern, distribution, frequency, etc. of different North Indian states were studied, i.e., Haryana (Chauhan et al., 2022; Nain and Hooda, 2019), Himachal Pradesh (Jaswal et al., 2015), Punjab (Kaur et al., 2021), Rajasthan (Mundetia and Sharma, 2014; Pingale et al., 2013), Uttarakhand (Malik and Kumar, 2020) and Uttar Pradesh (Guhathakurta et al., 2020).

Earlier researchers reported that the 1.5 °C and 2 °C scenarios might lead to higher warming at the regional scale, particularly over the landmass of the Northern Hemisphere (Karmalkar and Bradley, 2017; Sahu et al., 2008; Sharma and Babel, 2014; Tiwari et al., 2014; Vautard et al., 2014; Xu et al., 2017). Therefore, it is a challenge for the economist and Government to design balanced strategies and plans to fulfill the Paris agreement's target along with the economic growth of India. In this paper, the authors present the performance of precipitation for four periods i.e., preindustrial period (1871 – 1890), present (1986 – 2005), 1.5° and 2° scenario to understand and project the future climate scenario. The 1.5° and 2° scenario periods have been considered based on global temperature anomaly reaching respective values in the CMIP5 models(Maharana et al., 2020)..

Data and Methodology

Historical and future climate data have been obtained from the Fifth Coupled Model Inter-comparison Project (Taylor et al., 2012). The models used in this study are listed in Table 1, together with their host institutions, and their abbreviations used in this study. There are 26 climate models from CMIP5 have been considered for this study.

Sub-selecting a representative subset from available General Circulation Models (GCMs) provides an efficient approach to generating a set of regional climate projections which represent the range of future climates indicated by the full ensemble (McSweeney et al., 2012). The methodology employed to select the CMIP5 GCMs which perform satisfactorily over India is to generate higher-resolution scenarios of future climate for North India under 1.5° and 2° scenarios. The models were first assessed in their simulation of a realistic baseline climate, with unsatisfactory models being eliminated before; secondly, a subset of models was selected to span the range of projected changes in precipitation. The approach of the evaluation criteria and the method is described in Table 2. Here the most important and difficult decision occurs in allocating a model its position on the performance scale (Table 3) between 'Include' and 'Exclude'. We compare the performance summary information in Table 4 with the projections for future change in mean rainfall in order to assess which models are to be eliminated, according to the decision-making framework set out in Table 1.

The model simulations are available from 1860 to 2100. This historical period of simulation has been divided into two periods, the pre-industrial period (1870 – 1900) and the present-day climate (1976 – 2005). The historical simulations have been forced by observed atmospheric composition changes (including Green House Gas (GHG), natural and anthropogenic aerosols, and volcanic forcing), solar variations, and time-evolving land cover in a bid to simulate the observed climate of the recent historical period. The projected climate simulations have been forced by GHGs, solar constant, ozone, and aerosol are kept changing with time. For evaluating the model simulations, fifth generation ECMWF reanalysis ERA5 (Hersbach et al., 2020), Climatic Research Unit (CRU) gridded rainfall (Harris et al., 2014) with 0.5° grid resolution at land points have been considered. The model has been validated for the present period. To compute model bias against CRU observations, the CMIP5 data at coarser resolution have been interpolated to the CRU data at finer resolution onto a $0.5 \times 0.5°$ grid. The multi-model ensemble has been calculated in a similar way. For calculating the interannual variations, the climatic fields have been computed by masks of the corresponding states, then the grid points present within the mask have been averaged. Analysis of the future projections has been carried out at the model resolution (without applying any interpolation).

3 Study Region

Northern states of India occupy the largest region of the country comprising seven states Haryana, Himachal Pradesh, Jammu & Kashmir (J&K), Punjab, Rajasthan, Uttar Pradesh, and Uttarakhand (Confederation of Indian Industry, 2014). This part has consistently outperformed India's national average in terms of GDP, with the region accounting for approximately 26% of the national GDP. The dominant geographical features of North India are the Indus-Gangetic Plain and the Himalayas, which demarcate the region from the Tibetan Plateau and Central Asia. The Northern part of India is endowed with immense topographical diversity, historical monuments, different cultures, wildlife parks and sanctuaries, holy temples and rivers, and diversified climatic conditions. The entire northern part of the country shares its borders with countries like Pakistan, China, Nepal, and Bhutan (Figure 1). Towards its north is the Himalayas which define the boundary between the Indian subcontinent and the Tibetan plateau. To its west is the Thar desert, shared between North India and Pakistan and the Aravalli Range, beyond which lies the state of Gujarat. The Vindhya mountains are, in some interpretations, taken to be the southern boundary of North India. The predominant geographical features of North India are the Indo-Gangetic plain, which spans the states of Punjab, Haryana, and Uttar Pradesh, the Himalayas, which lie in the states of Uttarakhand, Himachal Pradesh, and J&K, and the Thar desert, which lies mainly in the state of Rajasthan. The states of Himachal Pradesh, Uttarakhand, and J&K also have a large forest coverage.

The northern state of India lies mainly in the temperate zone. The general pattern of this region is cold winters, hot summers, and moderate monsoons. It is one of the most climatically diverse regions on Earth. The region receives heavy rain in plains and light snow in Himalayas (J&K, Himachal Pradesh, and Uttarakhand) precipitation through two primary weather patterns: the Indian Monsoon and the Western Disturbances. The Monsoon carries moisture northwards from the Indian Ocean, occurs in late summer, and is important to the autumn harvest (Jain and Chatterjee, 1972; Katiyar, 1990). Western Disturbances is an extratropical weather phenomenon that carries moisture eastwards from the Mediterranean Sea, the Caspian Sea, and the Atlantic Ocean (Datta and Gupta, 1967; Dimri, 2004; Tiwari et al., 2014; Wang, 2006). They primarily occur during the winter season and are critically important for the spring harvest, which includes the main staple food of North India, wheat (Wang, 2006).

Results and Discussion

The results have been analyzed broadly in two categories i.e., model validation for the reference period and future climate projections. First, the model simulations have been validated against the corresponding observations in terms of climatology and interannual time scales. Further, the climate change in the two future scenarios with respect to the preindustrial and present periods has been analyzed in detail.

4.1 Model Validation

Rainfall variability has been represented in terms of box and whisker plot for the period of 1976-2005 on the basis of 6 CMIP5 models and ensemble with respect to the CRU (Figure 2). The minimum, first quartile (Q1), median, third quartile (Q3), and maximum of the box plots in the figure are used to compare the distribution of rainfall during the period among the different data sets. It is observed on the basis of symmetry of different plots, that variability is minimum in the case of ensemble data with respect to CRU in comparison to other data sets. Box plot in case of ensemble data shows a minimum spread, and is tightly grouped, more symmetrical, and skewed in comparison to other data sets. The confirmation of model validation and selection of the best-mapped data set is shown in Figure 3. Taylor diagrams are drawn to understand that which model is most realistic for the approximation on the basis of correlation coefficient and standard deviation. In most of the states, except Himachal Pradesh, the correlation coefficient value is maximum (>0.8) for the Ensemble in comparison to other models. It is also observed that the deviation is less than or equal to 20% for the ensemble data set for all the states except Punjab. Based on the median, standard deviation, and correlation values of most of the states, it is observed that error and uncertainty in ensemble mean plot are minimum in comparison to other models. This is the reason that in the coming section data on the basis of ensemble means are taken into main focus for further analysis and discussion.

The precipitation climatology in the ensemble mean of CMIP5 models has been validated with the CRU observation for the present/reference period (1976-2005) as shown in Figure 4. The left and middle columns represent mean precipitation based on CRU and CMIP5 model during the years 1976-2005, while the right column (Figure 4c) shows the difference between the model and observation. The starting year is chosen as 1976 since the precipitation data from the CMIP5 model are available from that year. The ENSEMBLE mean can reproduce the mean rainfall features over the north Indian states as in the CRU observation such as low rainfall over Rajasthan, and high rainfall along the Gangetic plains and foothills of the Himalayas. The model shows bipolar bias i.e., wet bias over the Himalayas and dry bias over central India.

Mean precipitation simulated by CMIP5 models during the reference period is compared with the corresponding CRU values in Figure 4c and white patches depict a small difference lying within -1 to 1 mm/day. The model has a significant difference compared to the observation based on CRU. Figure 4c shows that difference in the precipitation is negative for Rajasthan (up to -2 units), whereas other states have a positive value of precipitation difference. This indicates that the model underestimated the value of precipitation for Rajasthan whereas for other states values are overestimated. It is also observed that overall precipitation during the period (1976-2005) is less in Rajasthan in comparison to other north Indian states. The precipitation is slightly overestimated in most of the states except in Rajasthan, J&K, Himachal Pradesh, and Uttarakhand as compared to the other states.

4.2 Future Projection of Precipitation

Four scenarios/periods are investigated in the present study. These periods are categorized as the present/reference period (1975 – 2005), 1.5 degrees, and 2 degrees which are compared with the preindustrial period (1871 – 1890). Figure 5 shows mean precipitation in the preindustrial, present, 1.5 °C, and 2 °C scenarios and changes during the three scenarios with respect to the preindustrial period based on the ENSEMBLE mean of the models. The left column represents the mean precipitation of the preindustrial period, and the middle column presents the mean precipitation for the present, 1.5, and 2.0 °C scenarios. The right column represents the projected changes by taking the differences of various scenarios with respect to preindustrial periods. Figures 5c and 5e show almost common behavior which indicates that precipitation decreases during the reference period and 1.5°C scenario with respect to the preindustrial period. Whereas Figure 5g indicates an increase in precipitation up to 0.5 mm/day with respect to the 2 °C scenario, and white patches are also observed which depicts a small difference in precipitation during 2 °C with respect to the industrial period. The precipitation is likely to increase up to 0.7 mm/day during the 2 °C scenario in almost all observed northern states of India. Based on the 1.5°C scenario, all the states show a significant decrease in precipitation, which is interesting to understand.

Figure 6 represents the box plots that display the ensemble spread, medians, interquartile (IQ) ranges, and outliers of the changes in the different rainfall for seven states at the preindustrial, present, and two warming levels of 1.5 and 2 °C scenarios. Based on the median and interquartile range of precipitation values of seven states shown by the box plot in Figure 6, it is observed that rainfall values observed during the present period and 1.5 °C scenario are almost similar to that of preindustrial values for almost all the studied states. Whereas the value of precipitation with a 2 °C scenario shows a large range in comparison to the preindustrial values. Large interquartile range of rainfall during the 2 °C scenario in comparison to preindustrial, present, and 1.5 °C scenarios signifies the high rainfall during the 2 °C scenario.

It is observed from the Heatmap of annual rainfall (Figure 7) that precipitation is maximum during the 2 °C scenario in comparison to the present and 1.5 °C scenario. Both Heatmap and box-whisker plots clearly indicate the increase in rain events during the warming scenario of 2 °C. Similar remark was given by Lee and Min, 2018 in which the conclusion was done that extreme precipitation is projected to increase very strongly in a 2 °C scenario.

4.3 Return Period of the Extreme Rainfall Events in the Future Scenarios

The incidence of intense rainfall events is a popular topic across the world since the repercussions of such occurrences are the primary cause of human deaths from natural disasters as well as innumerable socioeconomic losses (Marengo et al., 2009). In addition, some of the studies have predicted a rise in the recurrence of intense rainfall events (De Oliveira et al., 2014; Niyogi et al., 2017; Zou and Ren, 2015). Keep this thing in mind, figure 8 represents the return level of extreme events for all the seven states in the Preindustrial period, Present Period, 1.5 oC and 2.0 oC scenarios as simulated by ensemble mean. Our analysis shows that their predominance of rainfall estimates higher than 7 mm in all the return periods. It is observed that northern states which are close to the Himalayas i.e., J&K, Uttarakhand, and Himachal Pradesh show a large return level of more than 10 mm that reaches up to 15 to 20 mm in the return periods of more than 60 years. It is also observed that the recurrence level of rainfall increases in all the states and the rise is maximum as per 2 °C scenario.

Conclusion

For policy formulation, it is essential to understand the behavior of variation in rainfall in the present, industrial and future global warming levels. This study performs a detailed analysis of rainfall behavior in four periods i.e., preindustrial period (1871 – 1890), present (1986 – 2005), 1.5° scenario, and 2° scenario are cautiously studied to recognize and project the future climate scenario. There were 26 CMIP5 climate models considered for this study. However, only six models were selected based on the capability of simulating the different aspects of rainfall and its associated mechanism.

An interesting feature is seen in the 1.5°C scenario, the precipitation is likely to decrease in most of the states except J&K. However, in 2 °C scenario, the precipitation is likely to increase in all the north Indian states except Himachal Pradesh. There is no significant change is likely to occur in Rajasthan in both scenarios. This result is consistent with Dash et al. (2015) and Pattnayak et al. (2017). The return period of the extreme rainfall events is likely to increase in all the states in both the scenarios. In a 2 °C scenario, there is a three-fold rise likely to increase in extreme rainfall events. Overall, this study robustly provides some conclusions with some degree of confidence, but it still has some limitations. The major limitation is the resolution of the models, the selected models are very coarse resolution. This coarser resolution makes it difficult to reduce the uncertainty at the local scale. Further, this type of study is required to help the policymakers to adapt to the 1.5 and 2 °C scenarios. Our plan is to extend the present work in the future to study the changing climate extreme under future climate change scenarios using CMIP6 climate model outputs.

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Author contribution

A.A. and K.C.P. conceived the study. A.A., K.S. B.B.P and K.C.P. performed the analyses and wrote the initial draft of the manuscript. All authors contributed to the interpretation of the results, discussion of the associated mechanisms, and refinement of the paper.

Conflict of Interest

The authors declare no competing interest.

Data Availability Statement

All data used in this study are freely available and can be requested from the authors or obtained directly from the source: CRU data (http://www.cru.uea.ac.uk/data).

References

Awasthi, A., Hothi, N., Kaur, P., Singh, N., Chakraborty, M., Bansal, S., 2017. Elucidative analysis and sequencing of two respiratory health monitoring methods to study the impact of varying atmospheric composition on human health. Atmos. Environ. 171, 32–37. https://doi.org/10.1016/j.atmosenv.2017.10.008Awasthi, A., Vishwakarma, K., Pattnayak, K.C., 2022. Retrospection of heatwave and heat index. Theor. Appl. Climatol. 147, 589–604. https://doi.org/10.1007/s00704-021-03854-zBhatla, R., Ghosh, S., Mandal, B., Mall, R.K., Sharma, K., 2016. Simulation of Indian summer monsoon onset with different parameterization convection schemes of RegCM-4.3. Atmos. Res. 176–177, 10–18. https://doi.org/10.1016/j.atmosres.2016.02.010Cabré, M.F., Solman, S., Núñez, M., 2016. Regional climate change scenarios over southern South America for future climate (2080-2099) using the MM5 Model. Mean, interannual variability and uncertainties. Atmósfera 29, 35–60. https://doi.org/10.20937/atm.2016.29.01.04Chadwick, R., Wu, P., Good, P., Andrews, T., 2013. Asymmetries in tropical rainfall and circulation patterns in idealised CO2 removal experiments. Clim. Dyn. 40, 295–316. https://doi.org/10.1007/s00382-012-1287-2Chauhan, A.S., Singh, S., Maurya, R.K.S., Rani, A., Danodia, A., 2022. Spatio-temporal trend analysis and future projections of precipitation at regional scale: a case study of Haryana, India. J. Water Clim. Chang. 13, 2143–2170. https://doi.org/10.2166/WCC.2022.005Corada-Fernández, C., Candela, L., Torres-Fuentes, N., Pintado-Herrera, M.G., Paniw, M., González-Mazo, E., 2017. Effects of extreme rainfall events on the distribution of selected emerging contaminants in surface and groundwater: The Guadalete River basin (SW, Spain). Sci. Total Environ. 605–606, 770–783. https://doi.org/10.1016/J.SCITOTENV.2017.06.049Dash, S.K., Hunt, J.C.R., 2007. Variability of climate change in India. Curr. Sci. https://doi.org/10.2307/24099122Dash, S.K., Kulkarni, M.A., Mohanty, U.C., Prasad, K., 2009. Changes in the characteristics of rain events in India. J. Geophys. Res. 114. https://doi.org/10.1029/2008jd010572Dash, S.K., Mishra, S.K., Pattnayak, K.C., Mamgain, A., Mariotti, L., Coppola, E., Giorgi, F., Giuliani, G., 2015. Projected seasonal mean summer monsoon over India and adjoining regions for the twenty-first century. Theor. Appl. Climatol. 122, 581–593. https://doi.org/10.1007/s00704-014-1310-0Datta, R.K., Gupta, M.G., 1967. Synoptic study of the formation and movements of western depressions. Indian J. Meteorol. Geophys.De Oliveira, P.T., Silva, C.M.S. e., Lima, K.C., 2014. Linear trend of occurrence and intensity of heavy rainfall events on Northeast Brazil. Atmos. Sci. Lett. 15, 172–177.

https://doi.org/10.1002/asl2.484Deng, S., Yang, N., Li, M., Cheng, L., Chen, Z., Chen, Y., Chen, T., Liu, X., 2019. Rainfall seasonality changes and its possible teleconnections with global climate events in China. Clim. Dyn. 53, 3529–3546. https://doi.org/10.1007/S00382-019-04722-3Dimri, A.P., 2004. Models to improve winter minimum surface temperature forecasts, Delhi, India. Meteorol. Appl. 11, 129–139. https://doi.org/10.1017/S1350482704001215Duan, W., Hanasaki, N., Shiogama, H., Chen, Y., Zou, S., Nover, D., Zhou, B., Wang, Y., 2019. Evaluation and Future Projection of Chinese Precipitation Extremes Using Large Ensemble High-Resolution Climate Simulations. J. Clim. 32, 2169–2183. https://doi.org/10.1175/JCLI-D-18-0465.1Duan, W., He, B., Takara, K., Luo, P., Hu, M., Alias, N.E., Nover, D., 2015. Changes of precipitation amounts and extremes over Japan between 1901 and 2012 and their connection to climate indices. Clim. Dyn. 45, 2273–2292. https://doi.org/10.1007/S00382-015-2778-8Gavahi, K., Abbaszadeh, P., Moradkhani, H., 2022. How does precipitation data influence the land surface data assimilation for drought monitoring? Sci. Total Environ. 831, 154916. https://doi.org/10.1016/J.SCITOTENV.2022.154916Gergis, J., Henley, B.J., 2017. Southern Hemisphere rainfall variability over the past 200 years. Clim. Dyn. 48, 2087–2105. https://doi.org/10.1007/S00382-016-3191-7Goswami, B.N., Venugopal, V., Sangupta, D., Madhusoodanan, M.S., Xavier, P.K., 2006. Increasing trend of extreme rain events over India in a warming environment. Science (80-.). 314, 1442–1445. https://doi.org/10.1126/SCIENCE.1132027Guhathakurta, P., Khedikar, S., Menon, P., Prasad, A.K., Sable, S.T., Advani, S.C., 2020. Observed Rainfall Variability and Changes over Uttar Pradesh State, Climate Research and Services. IMD Annu. Rep. ESSO/IMD/H, 28.Guo, J., Huang, G., Wang, X., Li, Y., Yang, L., 2018. Future changes in precipitation extremes over China projected by a regional climate model ensemble. Atmos. Environ. 188, 142–156. https://doi.org/10.1016/J.ATMOSENV.2018.06.026Harris, I., Jones, P.D., Osborn, T.J., Lister, D.H., 2014. Updated high-resolution grids of monthly climatic observations - the CRU TS3.10 Dataset. Int. J. Climatol. 34, 623–642. https://doi.org/10.1002/joc.3711Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., Nicolas, J., Peubey, C., Radu, R., Schepers, D., Simmons, A., Soci, C., Abdalla, S., Abellan, X., Balsamo, G., Bechtold, P., Biavati, G., Bidlot, J., Bonavita, M., De Chiara, G., Dahlgren, P., Dee, D., Diamantakis, M., Dragani, R., Flemming, J., Forbes, R., Fuentes, M., Geer, A., Haimberger, L., Healy, S., Hogan, R.J., Hólm, E., Janisková, M., Keeley, S., Laloyaux, P., Lopez, P., Lupu, C., Radnoti, G., de Rosnay, P., Rozum, I., Vamborg, F., Villaume, S., Thépaut, J.N., 2020. The ERA5 global reanalysis. Q. J. R. Meteorol. Soc. 146, 1999–2049. https://doi.org/10.1002/qj.3803Jain, A.P., Chatterjee, S.P., 1972. Report of the Irrigation Commission, 1972.Jaswal, A.K., Bhan, S.C., Karandikar, A.S., Gujar, M.K., 2015. Seasonal and annual rainfall trends in himachal pradesh during 1951-2005. Mausam 66, 247–264. https://doi.org/10.54302/mausam.v66i2.534Joshi, U.R., Rajeevan, M., 2006. Trends in precipitation extremes over India.Karmalkar, A. V., Bradley, R.S., 2017. Consequences of Global Warming of 1.5 °C and 2 °C for Regional Temperature and Precipitation Changes in the Contiguous United States. PLoS One 12, e0168697. https://doi.org/10.1371/JOURNAL.PONE.0168697Katiyar, V.S., 1990. Indian Monsoon and Its Frontiers.Kaur, N., Yousuf, A., Singh, M.J., 2021. Long term rainfall variability and trend analysis in lower Shivaliks of Punjab, India, MAUSAM.Kulshrestha, U.C., Reddy, L.A.K., Satyanarayana, J., Kulshrestha, M.J., 2009. Real-time wet scavenging of major chemical constituents of aerosols and role of rain intensity in Indian region. Atmos. Environ. 43, 5123–5127. https://doi.org/10.1016/J.ATMOSENV.2009.07.025Lacombe, G., McCartney, M., 2014. Uncovering consistencies in Indian rainfall trends observed over the last half century. Clim. Change 123, 287–299. https://doi.org/10.1007/S10584-013-1036-5Lal, M., 2003. GLOBAL CLIMATE CHANGE - INDIA ' s MONSOON 6, 1–34.Li, X., Zhang, K., Gu, P., Feng, H., Yin, Y., Chen, W., Cheng, B., 2021. Changes in precipitation extremes in the Yangtze River Basin during 1960–2019 and the association with global warming, ENSO, and local effects. Sci. Total Environ. 760, 144244. https://doi.org/10.1016/J.SCITOTENV.2020.144244Long, S.M., Xie, S.P., Zheng, X.T., Liu, Q., 2014. Fast and slow responses to global warming: Sea surface temperature and precipitation patterns. J. Clim. 27, 285–299. https://doi.org/10.1175/JCLI-D-13-00297.1Maharana, P., Dimri, A.P., Choudhary, A., 2020. Future changes in Indian summer monsoon characteristics under 1.5 and 2 °C specific warming levels. Clim. Dyn. 54, 507–523. https://doi.org/10.1007/S00382-019-05012-8Maharana, P., Kumar, D., Rai, P., Tiwari, P.R., Dimri, A.P., 2022. Simulation of Northeast Monsoon in a coupled regional model framework. Atmos. Res. 266, 105960. https://doi.org/10.1016/J.ATMOSRES.2021.105960Malik, A., Kumar, A., 2020. Spatio-temporal trend analysis of rainfall using parametric and non-parametric tests: case study in Uttarakhand, India. Theor. Appl. Climatol. 140, 183–207. https://doi.org/10.1007/S00704-019-03080-8Marengo, J.A., Jones, R., Alves, L.M., Valverde, M.C., 2009. Future change of temperature and precipitation extremes in south america as derived from the precis regional climate modeling system. Int. J. Climatol. 29, 2241–2255. https://doi.org/10.1002/joc.1863McSweeney, C.F., Jones, R.G., Booth, B.B.B., 2012. Selecting Ensemble Members to Provide Regional Climate Change Information. J. Clim. 25, 7100–7121. https://doi.org/10.1175/JCLI-D-11-00526.1Mundetia, N., Sharma, D., 2014. Analysis of rainfall and drought in Rajasthan state, India. Glob. Nest J. 17, 12–21. https://doi.org/10.30955/gnj.001379Nain, M., Hooda, B.K., 2019. Probability and trend analysis of monthly rainfall in Haryana. Int. J. Agric. Stat. Sci. 15, 221–229. https://doi.org/10.18805/bkap161Niyogi, D., Lei, M., Kishtawal, C., Schmid, P., Shepherd, M., 2017. Urbanization impacts on the summer heavy rainfall climatology over the eastern United States. Earth Interact. 21, 1–17. https://doi.org/10.1175/EI-D-15-0045.1Pal, I., Al-Tabbaa, A., 2011. Assessing seasonal precipitation trends in India using parametric and non-parametric statistical techniques. Theor. Appl. Climatol. 103, 1–11. https://doi.org/10.1007/S00704-010-0277-8Panda, S.K., Hong, M., Dash, S.K., Oh, J., Pattnayak, K.C., 2020. Relative Roles of

Eurasian Snow Depth and Sea Surface Temperature in Indian and Korean Summer Monsoons based on GME Model Simulations. Earth Sp. Sci. https://doi.org/10.1029/2020ea001105Pattnayak, K.C., Abdel-Lathif, A.Y., Rathakrishnan, K.V., Singh, M., Dash, R., Maharana, P., 2019. Changing Climate Over Chad: Is the Rainfall Over the Major Cities Recovering? Earth Sp. Sci. 6. https://doi.org/10.1029/2019EA000619Pattnayak, K.C., Kar, S.C., Dalal, M., Pattnayak, R.K., 2017. Projections of annual rainfall and surface temperature from CMIP5 models over the BIMSTEC countries. Glob. Planet. Change 152, 152–166. https://doi.org/10.1016/j.gloplacha.2017.03.005Pingale, S.M., Khare, D., Jat, M.K., Adamowski, J., 2013. Spatial and temporal trends of mean and extreme rainfall and temperature for the 33 urban centers of the arid and semi-arid state of Rajasthan, India. https://doi.org/10.1016/j.atmosres.2013.10.024Sahu, S.K., Beig, G., Sharma, C., 2008. Decadal growth of black carbon emissions in India. Geophys. Res. Lett. 35. https://doi.org/10.1029/2007gl032333Sanderson, B.M., O'Neill, B.C., Tebaldi, C., 2016. What would it take to achieve the Paris temperature targets? Geophys. Res. Lett. 43, 7133–7142. https://doi.org/10.1002/2016GL069563Sharma, D., Babel, M.S., 2014. Trends in extreme rainfall and temperature indices in the western Thailand. Int. J. Climatol. 34, 2393–2407. https://doi.org/10.1002/joc.3846Shi, X., Chen, J., Gu, L., Xu, C.Y., Chen, H., Zhang, L., 2021. Impacts and socioeconomic exposures of global extreme precipitation events in 1.5 and 2.0 °C warmer climates. Sci. Total Environ. 766, 142665. https://doi.org/10.1016/J.SCITOTENV.2020.142665Singh, C., Ganguly, D., Sharma, P., 2019. Impact of West Asia, Tibetan Plateau and local dust emissions on intra-seasonal oscillations of the South Asian monsoon rainfall. Clim. Dyn. 53, 6569–6593. https://doi.org/10.1007/s00382-019-04944-5Taylor, K.E., Stouffer, R.J., Meehl, G.A., 2012. An Overview of CMIP5 and the Experiment Design. Bull. Am. Meteorol. Soc. 93, 485–498. https://doi.org/10.1175/bams-d-11-00094.1Tiwari, P.R., Kar, S.C., Mohanty, U.C., Kumari, S., Sinha, P., Nair, A., Dey, S., 2014. Skill of precipitation prediction with GCMs over north India during winter season. Int. J. Climatol. 34, 3440–3455. https://doi.org/10.1002/JOC.3921Vautard, R., Gobiet, A., Sobolowski, S., Kjellström, E., Stegehuis, A., Watkiss, P., Mendlik, T., Landgren, O., Nikulin, G., Teichmann, C., Jacob, D., 2014. The European climate under a 2 °C global warming. Environ. Res. Lett. 9, 034006. https://doi.org/10.1088/1748-9326/9/3/034006Wang, B., 2006. The Asian monsoon 787.Xu, Y., Zhou, B.T., Wu, Jie, Han, Z.Y., Zhang, Y.X., Wu, Jia, 2017. Asian climate change under 1.5–4 °C warming targets. Adv. Clim. Chang. Res. 8, 99–107. https://doi.org/10.1016/J.ACCRE.2017.05.004Yang, M., Mou, Y., Meng, Y., Liu, S., Peng, C., Zhou, X., 2020. Modeling the effects of precipitation and temperature patterns on agricultural drought in China from 1949 to 2015. Sci. Total Environ. 711, 135139. https://doi.org/10.1016/J.SCITOTENV.2019.135139Zhang, X., Jiang, H., Jin, J., Xu, X., Zhang, Q., 2012. Analysis of acid rain patterns in northeastern China using a decision tree method. Atmos. Environ. 46, 590–596.

https://doi.org/10.1016/J.ATMOSENV.2011.03.004Zou, X., Ren, F., 2015. Changes in regional heavy rainfall events in China during 1961–2012. Adv. Atmos. Sci. 32, 704–714. https://doi.org/10.1007/s00376-014-4127-y