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CHANGES IN EXTREME RAINFALL EVENTS AND THEIR INFLUENCE ON FLOOD RISK UNDER A CHANGING CLIMATE

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Abstract

The changes in extreme precipitation patterns due to climate change are of concern, given the potential for increases in flood hazards and hydrologic vulnerability. In this study, historical extreme rainfall characteristics and future projections of changing one-day probable maximum precipitation (PMP) over Indian region have been studied. Historical precipitation records (1971-2010) were compared with future climate projections for the 2071-2100 period, considering both RCP4.5 and RCP8.5 scenarios. Precipitation variability and intensification were evaluated using descriptive statistical analysis, spatial classification, and multiple model comparisons. Historical PMP showed large geographical variation with an average of 720.77 mm. Mean PMP increases of 31.46% and 41.01% were projected under RCP4.5 and RCP8.5, respectively, and maximum increases of 235.97% and 281.27% under RCP4.5 and RCP8.5, respectively. Spatial analysis showed significant spatial variation and climate-model comparisons showed variation in the magnitude of projected precipitation. The results indicate that the impact of climate change on extreme precipitation and related flood risks in India may become more severe with increasing greenhouse-gas emissions. But additional hydrological and vulnerability data are needed for flood-risk quantification to be done directly. The findings from the study emphasize the need for regional flood preparedness, infrastructure planning and adaptation strategies to consider the impacts of climate projections.

Keywords: Extreme rainfall, Climate change, Probable maximum precipitation, Flood hazard, Climate projections

1. Introduction

Climate change has become a significant cause of hydrological variability and is affecting the frequency, intensity and spatial distribution of extreme precipitation events globally. Increased temperatures in the atmosphere lead to higher moisture-holding capacity and changes to its circulation patterns, which could lead to more intense precipitation events with related hydrometeorological risks. Excessive rain can cause natural drainage systems to fail, leading to surface runoff and excessive flooding, in urban and rural areas, which is a major environmental issue. It is thus crucial to comprehend its evolution of the extreme precipitation properties to assess the possible future hydrological risks and to design climate adaptation measures. The complex relationships between atmospheric processes, rainfall extremes and regional climate conditions have been brought to the forefront in recent research, so that the study of rainfall variability at different spatial and temporal scales is highlighted (Gimeno et al., 2022).

Multiple atmospheric mechanisms are at play between climate change and extreme precipitation. Changes in circulation patterns and moisture transport pathways, along with the increased availability of water vapor in the atmosphere with rising temperatures, influence the formation and distribution of precipitation. These processes can lead to more extreme rain events, but the intensity and direction of the rain is different in different climatic regions. Hydrological systems are also sensitive to changes in precipitation extremes due to temperature, as short-duration and high-intense precipitation events can cause significant runoff and put strain on existing flood control infrastructure. The impact of temperature sensitivity has been demonstrated through quantitative investigations, which showed that it is important to consider the environmental conditions when assessing extreme precipitation characteristics under changing environmental conditions (Zhu et al., 2022). In addition, regional climatic conditions can have a significant impact on precipitation extremes, highlighting the importance of regional assessment rather than using only global climate projections only (Fowler & Ali, 2022).

For floods, rainfall intensity also has important implications for flood occurrence and intensity, but by itself does not necessarily mean a flood. Antecedent soil moisture, catchment characteristics, river-channel capacity, land-use changes and drainage infrastructure affect flood responses. Therefore, geographical variations in hydrological response to rainfall extremes can occur. Climate-model projections and the hydrological simulations offer a chance to evaluate how the peak flood magnitude and frequency might change with future climate conditions. These comprehensive evaluations are crucial for comprehending potential atmospheric impacts on hydrological hazards and uncertainty of climate projections (Meressa et al., 2022). The increased importance of rainfall-related processes in explaining regional variation in flood characteristics is also reflected in changes in river flood regimes. Rainfall-related processes are also increasingly important in explaining regional variation in flood characteristics, reflected in changes in river flood regimes (Burn & Whitfield, 2023).

The impacts of extreme flooding events in recent years have reinforced the need to study climate related precipitation changes. Studies on severe flooding in Western Europe in July 2021 have pointed to anthropogenic climate change as a cause for the exceptionally heavy rainfall conditions (Tradowsky et al., 2023). In the same way, studies on the extreme monsoon precipitation in Pakistan have shown how climate-enhanced precipitation can exacerbate existing

socio-economic vulnerabilities to cause devastating impacts on exposed communities (Otto et al., 2023). The results indicate that geographical exposure and vulnerability are intricately intertwined with extreme rainfall hazards. The impacts of floods are the result of the interactions between the meteorology and the nature of the populations, infrastructure and landscapes affected. Thus, analysis of future changes in precipitation extremes needs to be separated from changes in overall flood risk.

The urbanization also creates extra problems due to changes in natural infiltration, increased impervious surface, and changes in drainage networks. These adjustments can exacerbate surface runoff and the effects of heavy rain, especially in rapidly growing metropolitan areas. Studies have highlighted the increasing demand for adaptation responses in urban areas that can confront the adaptation challenges of the variable rainfall extremes and their infrastructure demands (Hemmati et al., 2022). Additionally, the effects of climatological change and urbanization can be compounded to affect geographical variation in flood susceptibility, necessitating spatially-specific approaches to assessment (Han et al., 2024). In addition, exposure to urban floods can be affected by economic development and related exposure pathways, indicating that physical changes in precipitation are just part of the picture of overall disaster exposure (Fan et al., 2025). These results highlight the need to understand changes in projected precipitation in broader environmental and socio-economic frameworks.

The use of climate projections, spatial modeling and adaptation-oriented approaches in the flood-hazard assessment has been increasing to pinpoint potential impacts due to intensified precipitation. Regional studies have shown that modifying the characteristics of extreme rainfall can impact pluvial flood hazards, especially when the drainage system cannot manage the large volume of rainfall. (Bezdan et al., 2024) Other studies have concluded that the flood hazards will grow in the major river basins in response to global climate change, emphasizing the regional hydrology characteristics (Lan et al., 2024). Projected rainfall intensification does not however automatically lead to proportional changes in flooding of rivers: hydrological responses are the result of several interacting processes (Blöschl, 2022). A focus on vegetation restoration and enhancement of landscape water retention has thus emerged as a complementary focus for minimising the impacts of high rainfall events (Nature based solutions (NbS)) (Manes et al., 2024).

India's geographical context is significant for such a study on extreme rain because the overall precipitation pattern in India is influenced by the monsoons, topography, and regional atmospheric circulation. Hydrological pressures can be significant during heavy rainfall episodes and especially in high density areas where there are significant infrastructure exposures. Recent international experiences of flooding disasters also indicate that extreme rainfall can also cause significant economic losses when coupled with high exposure and low adaptive capacity (Kimutai et al., 2024). Other studies involving extreme weather events highlight the fact that environmental and public health issues must be integrated into DRR policies (Chukwuma Sr, 2025). Yet, there are significant uncertainties in the spatiotemporal distribution and intensity of precipitation extremes in future in India.

In the backdrop of this, the present study explores historical and projected extreme precipitation in India using high-resolution observations and future climate simulations. The historical precipitation characteristics are compared to projections from RCP4.5 and RCP8.5 for the 2071-

2100 time period. A focus is placed on 1-day PMP values, spatial variations, and variations between climate scenarios. The study combines the historical extreme rainfall characteristics with projected precipitation changes to supply evidence that will be relevant to the assessment of precipitation-related flood hazard, while acknowledging that direct quantification of flood risk will require further hydrological and vulnerability information. The objectives of this study are as follows:

1. To characterize historical extreme rainfall patterns and spatial variability in probable maximum precipitation across India.
2. To quantify projected changes in extreme precipitation under RCP4.5 and RCP8.5 climate scenarios.
3. To evaluate the potential implications of changing extreme rainfall magnitudes for future precipitation-driven flood hazards.

2. Materials and Methods

2.1. Study Area and Research Design

The combination of retrospective and projection based quantitative approach was used to analyze changes in extreme precipitation over India under altered climatic conditions (Sarkar & Maity, 2023). A 41-year period of historical observations (1971-2010) were compared with a future climate period (2071-2100) from the climate simulations. The annual maximum daily precipitation and one-day probable maximum precipitation (PMP) were considered as measures of extreme rainfall magnitudes. The differences between moderate and high emission scenarios were assessed by two representative concentration pathways (RCPs): RCP4.5 and RCP8.5. Spatial variability, projections of precipitation changes, and implications for flood hazards were discussed.

2.2. Dataset Characteristics and Variable Selection

A high-resolution precipitation dataset with historical observations, future climate simulations and model averaged changes in probable maximum precipitation was used for the analysis. The annual maximum daily precipitation (AMDP) and spatially distributed PMP estimates for 1971–2010 were included in the historical records. The future projections included three climate models' outputs under RCP4.5 and RCP8.5 scenarios for the period 2071–2100. Other data that were added were the geographical coordinates and precipitation frequency factors. The major variables included were the magnitude of precipitation, maximum annual precipitation, percentage change in precipitation, climate scenarios and spatial location. These variables enabled comparisons of precipitation characteristics in the past and into the future.

2.3. Data Preprocessing and Quality Assessment

The NetCDF files were uploaded for analysis of variable dimensions, geographical coordinates, temporal coverage, measurement units, and missing observations. Precipitation was reported in millimetres and model-averaged changes in precipitation were reported in percentages for future. The values outside of the geographical domain were excluded from descriptive calculations as they were not finite. The historical array was analyzed separately from the projected array due to

the differences in their spatial resolution and number of valid cells. Numerical summaries were generated from the available observations, rather than filling in missing values or implying that model output of zero precipitation means that no observations were made.

2.4. Extreme Rainfall and Climate Scenario Assessment

Extreme precipitation characteristics were assessed with observed PMP magnitude and annual maximum daily precipitation and through model-averaged percentage changes for the two climate scenarios. The historical PMP's were categorized into precipitation-magnitude classes to represent spatial variations in extreme rainfall potential. Further changes were sorted into three categories: decreasing, moderately increasing and strongly increasing. Mean, median and upper percentile changes were observed when comparing scenarios. The three outputs of the climate models were also compared individually to estimate the difference in the simulated annual maximum precipitation between RCP4.5 and RCP8.5 for the future time period of 2071–2100.

2.5. Statistical Analysis and Flood-Hazard Interpretation

All numerical procedures were done using statistical analysis in Python, which calculated the mean, standard deviation, median, percentile, frequency and difference between scenarios. Changes and historical PMPs were summarized over valid geographical grid cells. Changes were calculated separately for each climate scenario and the percentage of locations with projected positive or negative change was determined. Descriptive comparisons were made of annual maximum precipitation distributions by model. Changes in the probability of extreme rainfall were not quantified as changes in flood hazard; instead, they were used as indicators of potential changes in flood hazard caused by changes in precipitation.

3. Results

3.1. Historical Characteristics of Extreme Daily Precipitation

The historical one-day probable maximum precipitation (1DPMP) values showed significant geographical difference over India for the period 1971–2010. There was significant geographical variation of historical values of one day probable maximum precipitable (1DPMP) over India during 1971–2010. The mean PMP for 4,949 valid grid cells was 720.77 mm while the median was 703.41 mm. The standard deviation was as large as 230.17 mm, showing the great spatial dispersion. Estimated extremes of precipitation were between 260.22 mm and 1,826.00 mm with the 95th percentile being 1,090.01 mm. These results showed significant variation in the potential for extreme rainfall over the area studied and were used to assess the expected changes in this rainfall (Table 1) (Figure 1).

Table 1. Descriptive Statistics of Historical One-Day Probable Maximum Precipitation (1971–2010)

Statistical parameter	Value (mm)
Mean	720.77

Standard deviation	230.17
Minimum	260.22
25th percentile	551.59
Median	703.41
75th percentile	863.62
95th percentile	1,090.01
Maximum	1,826.00

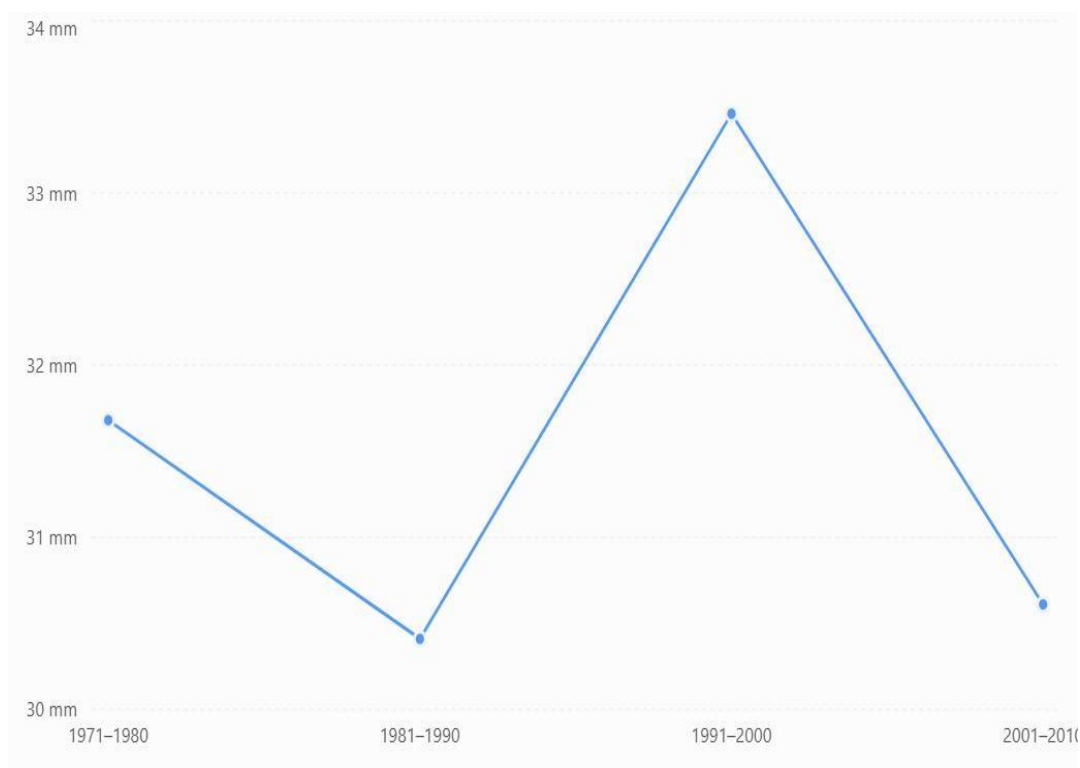


Figure 1. Decadal Variation in Historical Annual Maximum Daily Precipitation Across India (1971–2010)

3.2. Spatial Distribution of Historical Extreme Precipitation

A significant variation was observed in extreme precipitation potential distributions among geographical grid cells from a historical precipitation classification. The highest precipitation class (above 1000 mm) represented the fewest cells (92), while the highest PMP class (1500-2000 mm) represented the fewest cells (42). These patterns suggested that the very high PMP estimates were only associated with a relatively small percentage of the grid that was analyzed

(Table 2) (Figure 2).

Table 2. Distribution of Historical PMP Across Precipitation Categories

PMP category (mm)	Grid cells (n)	Percentage (%)
<500	891	18.00
500–<750	1,965	39.70
750–<1,000	1,592	32.17
1,000–<1,250	409	8.26
≥1,250	92	1.86
Total	4,949	100.00

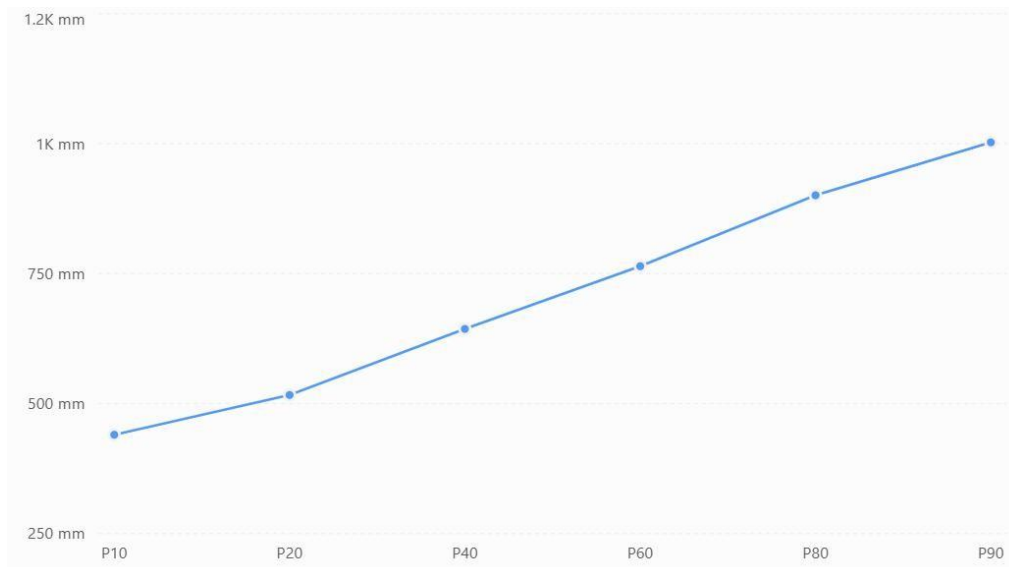


Figure 2. Percentile Distribution of Historical One-Day Probable Maximum Precipitation Across India

3.3. Projected Changes in Extreme Precipitation Under Climate Scenarios

Climate projections for the future showed an increase in model-averaged one-day PMPs in both emission scenarios on 2071-2100. The mean projected increase was 31.46% for RCP4.5 and 41.01% for RCP8.5. The median intensified by 22.08% and 32.49%, respectively, showing a greater projected intensification under the higher-emission scenario. Maximum increases reached 235.97% under RCP4.5 and 281.27% under RCP8.5. However, there were some reductions in rainfall in certain regions, which show that the projected increase in rainfall intensity was not a

uniform increase across India for both the projections (Table 3) (Figure 3).

Table 3. Projected Percentage Changes in One-Day PMP Under RCP4.5 and RCP8.5

Statistical parameter	RCP4.5 (%)	RCP8.5 (%)
Mean	31.46	41.01
Median	22.08	32.49
Standard deviation	39.33	40.96
Minimum	-39.92	-26.40
90th percentile	83.60	94.87
Maximum	235.97	281.27

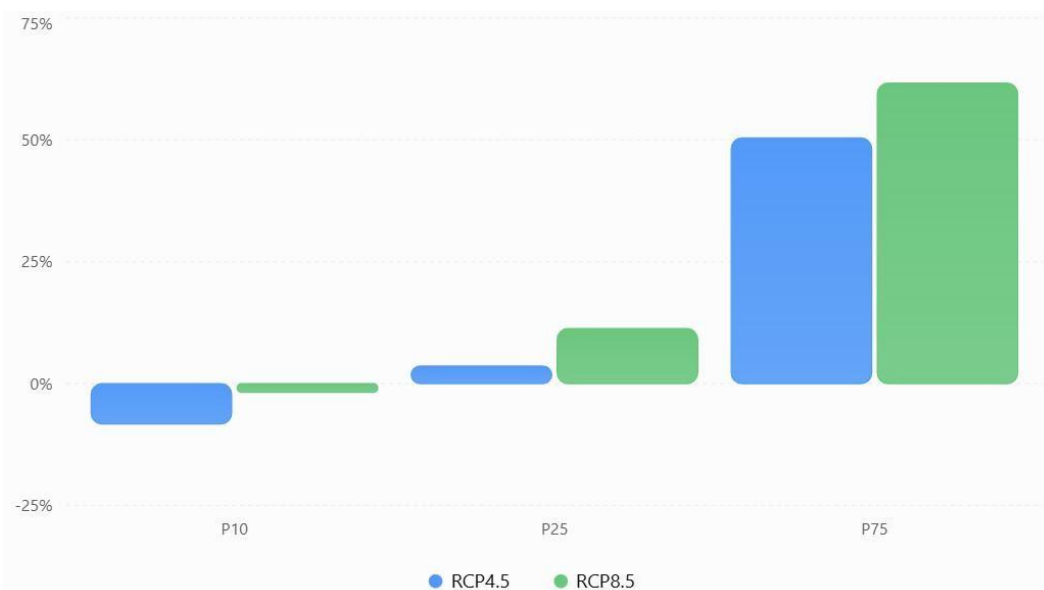


Figure 3. Comparison of Projected PMP Changes Under RCP4.5 and RCP8.5 (2071–2100)

3.4. Spatial Variability in Projected Precipitation Changes

Projected changes in PMP varied between the two climate scenarios. RCP 4.5: 217 cells with non-positive changes compared to RCP 8.5: 133. 321 and 358 cells, respectively, experienced moderate increases of 0–25%. The number of cells showing a higher increase between 205% and 100% was 205 in RCP4.5 and 281 in RCP8.5. Significant increases (100% or greater) also occurred more frequently under RCP8.5. The results indicated a larger spatial extent of extreme precipitation increases in the future (2016 to 2100), in both intensity and volume (Figure 4)

(Table 4) under higher greenhouse-gas emissions.

Table 4. Distribution of Projected PMP Changes Across Grid Cells

PMP change (%)	RCP4.5 (n)	RCP8.5 (n)
≤ 0	217	133
>0–25	358	321
>25–50	234	258
>50–100	205	281
>100	69	90
Total	1,083	1,083

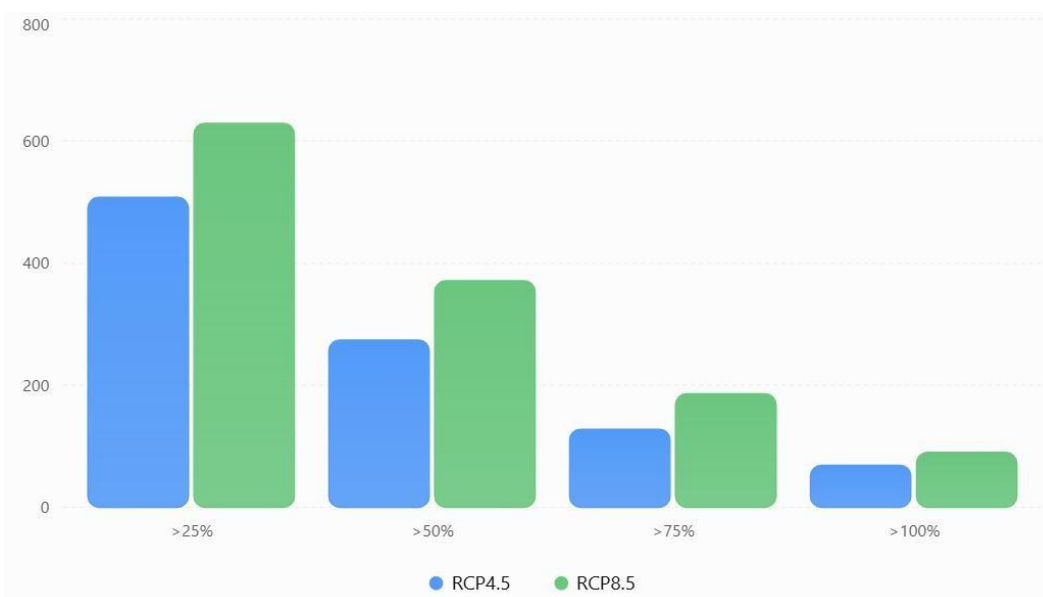


Figure 4. Number of Grid Cells Exceeding Projected PMP Increase Thresholds Under Climate Scenarios

3.5. Climate Model Variability and Implications for Flood Hazard

There were significant differences in annual maximum daily precipitation projections across the models for future climate. All models simulated higher means under RCP8.5 than under RCP4.5, with model 3 always being the highest mean precipitation value across the two scenarios. The higher magnitudes of precipitation under RCP8.5 indicated a potential for increased flood

hazards from precipitation. Without the hydrological, exposure and vulnerability information, however (Table 5) (Figure 5), actual changes in flood risk could not be quantified.

Table 5. Model-Specific Annual Maximum Daily Precipitation Under Future Climate Scenarios (2071–2100)

Climate model	RCP4.5 mean (mm)	RCP8.5 mean (mm)	RCP4.5 maximum (mm)	RCP8.5 maximum (mm)
Model 1	68.40	76.69	602.39	799.14
Model 2	87.34	98.73	791.17	896.71
Model 3	91.85	108.77	861.43	920.16

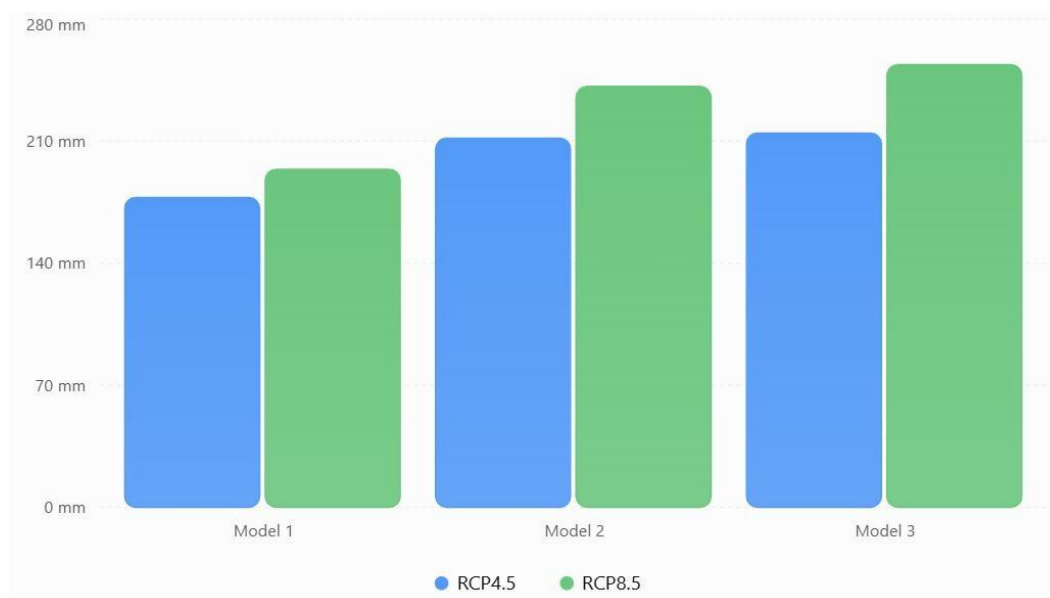


Figure 5. Model-Wise 95th Percentile of Future Annual Maximum Daily Precipitation Under RCP4.5 and RCP8.5

4. Discussion

Significant spatial variability of historical extreme precipitation and future projections of 1-day probable maximum precipitation (PMP) over India for future climate scenarios. Historical estimates of PMPs had been averaged to 720.77 mm, with a significant geographical variation in terms of standard deviation (230.17 mm). These differences suggest regional climatic, topographic and atmospheric moisture differences throughout the country, which may cause differences in extreme precipitation potential. Rainfall responses are also found to be significantly different across the climatic regions and model projections in tropical monsoon regions, with similar geographical variations in extreme rainfall characteristics (Das et al., 2022). The results underscore the need for regionalized rainfall assessments instead of making a blanket assumption about the intensification of rainfall due to climate change.

The historical precipitation distribution showed that around 39.70% of the analyzed grid cells

had PMP values between 500 to 750 mm while only 1.86% of the grid cells had PMP above 1,250 mm. This non-uniform distribution implies that there are geographical regions with very high precipitation potentials, and others with very low ones. The spatial heterogeneity has implications for the design of infrastructure and hydrological planning as the areas experiencing the higher precipitation extremes may need different engineering thresholds and adaptation strategies. The identification of extreme rainfall has been pointed out in the previous investigations to rely on the definition of extreme rainfall, their precipitation thresholds and their dependence structures in rainfall analysis (Yin et al., 2022). The present results thus point to the use of PMP as a gauge of extreme precipitation potential, not actual rainfall-event frequencies.

RCP8.5 and RCP4.5 climate projections for the future showed a significant increase in the PMP values, with average increases of 31.46% and 41.01% respectively. The larger rise under RCP8.5 suggests that the response to increased greenhouse-gas emission scenarios could lead to larger extreme precipitation rise. The results here are inline with larger studies indicating that projected changes in rainfall extremes may be larger for some regions than others, and for different climate models (Shu et al., 2022). Likewise, the assessment approaches of precipitation have been highlighted as important for adaptation planning and infrastructure designing to consider projected changes of extreme precipitation (Zhao et al., 2022). The difference between the two scenarios highlights the importance of considering emission pathways when assessing future precipitation-related hazards.

The mean change also varied significantly from one geographic cell to another, with some areas experiencing a decrease in the change, and others a large increase. Under RCP4.5, projected PMP changes ranged from -39.92% to 235.97%, compared with -26.40% to 281.27% under RCP8.5. Such large ranges mean that precipitation variations around the globe have a non-uniform spatial structure. Greater precipitation extremes can exacerbate flood risk but this relationship is a local one, depending on specific hydrologic and geographic conditions. Studies on urban flash flooding have also shown that the characteristics of rainfall and the local environment are related to flood outcomes (Fofana et al., 2022). So, variations between geographical projections of PMP must be taken into account when assessing the potential need for adaptation and preparedness for flooding in particular geographical regions.

Another graph showing the distribution of projected changes further showed that there were 371 grid cells with projected increases in PMPs under RCP8.5 compared to 274 under RCP4.5. This disparity indicates that larger increases in significant precipitation intensity could result in a wider spatial footprint of higher emissions. The impacts of flooding are not only sensitive to the extreme rainfall but must also be interpreted carefully as extreme rainfall does not necessarily translate to similar changes in the magnitude or extent of inundation. Studies focusing on flood hazards have showed that urban development, drainage features, and hydrological interactions have significant impacts on flood inundation during extreme precipitation (Zhao et al., 2024). Likewise, evaluations of compound flooding have pointed to the need to account for climate change effects and coastal processes, urbanization, and interacting flood mechanisms (Ruan et al., 2024). The present results, therefore, indicate potential hazard intensification from precipitation instead of the direct quantification of flood risk.

Model-specific projections showed further uncertainty in the projections of future rainfall extremes. The mean annual maximum daily precipitation was found to differ among the three

climate models, with Model 3 giving the highest values in either of the scenarios. The model under RCP8.5 range from 76.69 mm to 108.77 mm indicating wide differences in simulated precipitation features. The differences are highlighted and point to the need to assess all climate models when assessing future rainfall extremes. The difficulties of assessing climate change impacts on a specific precipitation event have also been demonstrated in previous studies of extreme precipitation events related to Cyclone Gabrielle in New Zealand (Harrington et al., 2023). This kind of evidence can be used to support the understanding of model variability as an important factor in the assessment of climate impact.

The results have implications for disaster risk communication and climate adaptation planning. Rising extreme precipitation events indicate that current rainfall design assumptions might need review, especially those used for building infrastructure that rely on historical rainfall characteristics. Effective communication should differentiate between rainfall intensities change, extreme events' probability, and extreme events' possible impact on exposed communities. The distinction is relevant as it requires the right scientific evidence and nuancing of uncertainty to link changes in extreme rainfall to climate change (King et al., 2023). In addition, rainfall reinforcement analysis of future climate scenarios for landslide occurrence shows that the precipitation reinforcement can have an impact on other environmental hazards besides flooding (Araújo et al., 2022). The present work, therefore, is useful in providing evidence for precipitation-hazard screening, and future studies should consider combining hydrological simulations, land use and vulnerability indicators to quantify real flood risk.

Last, however, the study was constrained by the use of historical and projected precipitation data without flood discharge or inundation or damage observations. The 1971-2010 and 2071-2100 periods were also considered as different climatic periods rather than a continuous period of observation. However, significant projected increases in extreme precipitation were found, especially under RCP8.5, and the need for spatial differentiation was highlighted. Combining these projections with catchment-scale hydrological modelling and exposure data would help provide more comprehensive future flood-risk assessments and inform more targeted climate adaptation actions.

5. Conclusion

The historical extreme precipitation characteristics and future intensity changes of rainfall were looked at for the Indian region under changing climate conditions. A significant spatial variation of one-day probable maximum precipitation (PMP) was found through the historical analysis, where the mean value is 720.77 mm and there are large variations in different geographical and climatic regions. The overall increase in extreme precipitation was projected under both RCP4.5 and RCP8.5 by the average additional PMP of 31.46% and 41.01% respectively for 2071–2100. The higher emission scenario has been shown to have larger increases in precipitation in all cases, implying more potential for precipitation-related hydrological hazards. Spatial analysis also indicated significant regional variations, with both areas seeing projected decrease and increase of over 100%. There were uncertainties with future projections of precipitation due to model differences, and multi-model assessments were emphasized. The results indicate that climate change could further aggravate extreme rainfall risk, which could lead to greater stress on drainage systems, water management and flood prone areas. Projected changes in precipitation,

however, cannot adequately define changes in the actual flood risk without taking into account runoff, land use, exposure, and vulnerability. The study highlights the need to consider climate projections in infrastructure planning, flood preparedness, and regional adaptation strategies. However, future work is needed to combine high-resolution projections with hydrological simulations and socio-economic factors for better flood-risk assessment and enhance climate resilience in India.

References

1. Araújo, J. R., Ramos, A. M., Soares, P. M., Melo, R., Oliveira, S. C., & Trigo, R. M. (2022). Impact of extreme rainfall events on landslide activity in Portugal under climate change scenarios. *Landslides*, 19(10), 2279-2293.
2. Bezdan, J., Bezdan, A., Blagojević, B., Antić, S., Greksa, A., Milić, D., & Lipovac, A. (2024). Impact of climate change on extreme rainfall events and pluvial flooding risk in the Vojvodina region (North Serbia). *Atmosphere*, 15(4), 488.
3. Blöschl, G. (2022). Three hypotheses on changing river flood hazards. *Hydrology and Earth System Sciences*, 26(19), 5015-5033.
4. Burn, D. H., & Whitfield, P. H. (2023). Climate related changes to flood regimes show an increasing rainfall influence. *Journal of Hydrology*, 617, 129075.
5. Chukwuma Sr, C. (2025). Invariance of extreme hydrologic events and climate change in the risk reduction on environment and health. *Greenfort International Journal of Applied Medical Science*, 3(2), 92-102.
6. Das, S., Kamruzzaman, M., & Islam, A. R. M. T. (2022). Assessment of characteristic changes of regional estimation of extreme rainfall under climate change: A case study in a tropical monsoon region with the climate projections from CMIP6 model. *Journal of hydrology*, 610, 128002.
7. Fan, J., Liu, B., Lei, T., Sun, Y., Ma, Y., Guo, R., ... & Gao, X. (2025). Exploring how economic level drives urban flood risk. *Nature Communications*, 16(1), 4857.
8. Fofana, M., Adoukpe, J., Larbi, I., Hounkpe, J., Koubodana, H. D. N., Toure, A., ... & Limantol, A. M. (2022). Urban flash flood and extreme rainfall events trend analysis in Bamako, Mali. *Environmental Challenges*, 6, 100449.
9. Fowler, H. J., & Ali, H. (2022). Analysis of extreme rainfall events under the climatic change. In *Rainfall* (pp. 307-326). Elsevier.
10. Gimeno, L., Sorí, R., Vazquez, M., Stojanovic, M., Algarra, I., Eiras-Barca, J., ... & Nieto, R. (2022).

Extreme precipitation events. Wiley Interdisciplinary Reviews: Water, 9(6), e1611.

11. Han, F., Yu, J., Zhou, G., Li, S., & Sun, T. (2024). Projected urban flood risk assessment under climate change and urbanization based on an optimized multi-scale geographically weighted regression. *Sustainable Cities and Society*, 112, 105642.
12. Harrington, L. J., Dean, S. M., Awatere, S., Rosier, S., Queen, L., Gibson, P. B., ... & Otto, F. E. (2023). The role of climate change in extreme rainfall associated with Cyclone Gabrielle over Aotearoa New Zealand's East Coast.
13. Hemmati, M., Kornhuber, K., & Kruczkiewicz, A. (2022). Enhanced urban adaptation efforts needed to counter rising extreme rainfall risks. *NPJ Urban Sustainability*, 2(1), 16.
14. Kimutai, J., Vautard, R., Zachariah, M., Tolasz, R., Šustková, V., Cassou, C., ... & Von Weissenberg, A. (2024). Climate change and high exposure increased costs and disruption to lives and livelihoods from flooding associated with exceptionally heavy rainfall in Central Europe. *World Weather Attribution*.
15. King, A. D., Reid, K. J., & Saunders, K. R. (2023). Communicating the link between climate change and extreme rain events. *Nature Geoscience*, 16(7), 552-554.
16. Lan, H., Zhao, Z., Li, L., Li, J., Fu, B., Tian, N., ... & Clague, J. J. (2024). Climate change drives flooding risk increases in the Yellow River Basin. *Geography and Sustainability*, 5(2), 193-199.
17. Manes, S., Vale, M. M., & Pires, A. P. (2024). Nature-based solutions potential for flood risk reduction under extreme rainfall events. *Ambio*, 53(8), 1168-1181.
18. Meresa, H., Tischbein, B., & Mekonnen, T. (2022). Climate change impact on extreme precipitation and peak flood magnitude and frequency: observations from CMIP6 and hydrological models. *Natural Hazards*, 111(3), 2649-2679.
19. Otto, F. E., Zachariah, M., Saeed, F., Siddiqi, A., Kamil, S., Mushtaq, H., ... & Clarke, B. (2023). Climate change increased extreme monsoon rainfall, flooding highly vulnerable communities in Pakistan. *Environmental Research: Climate*, 2(2), 025001.
20. Ruan, X., Sun, H., Shou, W., & Wang, J. (2024). The impact of climate change and urbanization on compound flood risks in coastal areas: A comprehensive review of methods. *Applied Sciences*, 14(21), 10019.
21. Sarkar, S., & Maity, R. (2023). High-resolution one-day probable maximum precipitation dataset

across India and its future-projected changes over India (Version 2) [Data set]. Mendeley Data. <https://doi.org/10.17632/zx99xr4wkr.2>

22. Shu, Z., Li, W., ZhANG, J., Jin, J., Xue, Q., Wang, Y., & Wang, G. (2022). Historical changes and future trends of extreme precipitation and high temperature in China. *Strategic Study of Chinese Academy of Engineering*, 24(5), 116.
23. Tradowsky, J. S., Philip, S. Y., Kreienkamp, F., Kew, S. F., Lorenz, P., Arrighi, J., ... & Wanders, N. (2023). Attribution of the heavy rainfall events leading to severe flooding in Western Europe during July 2021. *Climatic Change*, 176(7), 90.
24. Yin, C., Wang, J., Yu, X., Li, Y., Yan, D., & Jian, S. (2022). Definition of extreme rainfall events and design of rainfall based on the copula function. *Water Resources Management*, 36(10), 3759-3778.
25. Zhao, W., Kinouchi, T., Ang, R., & Zhuang, Q. (2022). A framework for quantifying climate-informed heavy rainfall change: Implications for adaptation strategies. *Science of the Total Environment*, 835, 155553.
26. Zhao, Z., Huo, A., Liu, Q., Yang, L., Luo, C., Ahmed, A., & Elbeltagi, A. (2024). Assessment of urban inundation and prediction of combined flood disaster in the middle reaches of Yellow river basin under extreme precipitation. *Journal of Hydrology*, 640, 131707.
27. Zhu, W., Wang, S., Luo, P., Zha, X., Cao, Z., Lyu, J., ... & Nover, D. (2022). A quantitative analysis of the influence of temperature change on the extreme precipitation. *Atmosphere*, 13(4), 612.