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Future precipitation characteristics of eight Tier I Urban Conglomerates amongst designated smart cities of India under selected Shared Socio-economic Pathways

Monomoy Goswami
Central Institute of Technology Kokrajhar
Avijit Paul
engr.avijit.paul@gmail.com

Central Institute of Technology Kokrajhar
Meghraj Goswami
Birla Institute of Technology and Science - Hyderabad Campus

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Abstract

Increased incidences of pluvial floods from rainfall affect key economic and cultural hubs of many countries of the world. Future-proofing India's 100 designated smart cities against pluvial flooding through Integrated Urban Water Management (IUWM) is an important requirement that calls for assessments of the future characteristics of rainfall in these cities and the likely impacts of alterations of these characteristics under Shared Socio-economic Pathways (SSPs) of the Sixth Assessment Report (2021) of the Intergovernmental Panel on Climate Change. In this study, potential future alterations in Intensity-Duration-Frequency (IDF) characteristics of precipitation were explored by using reanalysis outputs of hourly precipitation of the period 1955–2014 from a selected Global Climate Model (GCM), namely MIROC6. In this study, the MIROC6-simulated precipitation data of three future periods, namely 2015–2040, 2041–2070 and 2071–2100, under four SSPs, namely SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5, at a 0.25°×0.25° grid over India were used. It emerged from the analyses that, generally, for all four SSPs, the north-central, eastern and western parts of the country encompassing 69 smart city locations and the southern peninsular region containing 29 locations would have high future precipitation intensities. The number of smart cities having significant positive trends of 1-hour annual maximum precipitation was found to increase from 35 under SSP2-4.5 to 68 and 72 under SSP3-7.0 and SSP5-8.5 respectively. The historical 1-hr precipitations of 100-year return period and their % deviations in the three future periods under four SSPs showed that the aerial extents of positive deviations generally increase from SSP1-2.6 to SSP4-8.5, particularly during 2041-70 and 2071–2100, and that 81 smart city locations exhibit high positive deviations under SSP5-8.5 during 2071–2100. These results indicate that future precipitation intensities, and hence pluvial floods, are likely to increase over the designated smart cities, and accounting for the increasing vulnerabilities of these cities to urban pluvial flooding due to increased short-duration rainfall would be vital for effective IUWMs.

1. Introduction

Increased incidences of pluvial floods caused by precipitation in the form of rainfall coupled with inadequate infrastructure and shortfall in management practices affect key economic and cultural hubs in urban areas of many countries of the world. Generally, these floods occur from the accumulation of water from rain over urbanized surfaces and the inadequacies of conveyance systems to carry the accumulated water out of the urban catchments. In India, the effects of pluvial floods in urban areas include inundation of densely inhabited areas, disruption of infrastructures and economic activities, impacts on civic amenities, peoples' exposure to water borne diseases, psychological trauma, sufferings and other health risks, and in some cases, loss of lives. The National Disaster Management Authority of the Government of India, in describing the difference of urban flooding from rural flooding (NDMA, 2010), stated that high intensity rainfall increases the flood peaks to 1.8 to 8 times and flood volumes up to 6 times in urban areas in comparison with those in rural areas. India has 100 designated smart cities, hereinafter referred to as DSCs, including eight Tier I Urban Conglomerates (UCs) that are Ahmedabad, Bengaluru, Chennai, Delhi, Hyderabad, Kolkata, Mumbai and Pune. Many of the DSCs are historically flood-prone, and many experience increased incidences of flooding, primarily due to the impacts of (i)

increased occurrences of small-duration rainfall under a changing climate (Westra et al., 2014), (ii) the 'new and intensified phase of urbanization during 2001–2011 coupled with spatial expansion of urban extents' (MoUD, 2017), and (iii) the 'urbanization signature' on 'rainfall climatology' (Kishtawal et al., 2010). Recent notable floods in some of the DSCs are the floods of Bengaluru in 2022 and 2024, Hyderabad in 2000, 2020 and 2021, Ahmedabad in 2001 and 2020, Delhi in 2002, 2003, 2009, 2010 and 2023, Chennai in 2004, 2015 and 2021, Mumbai in 2005, 2020 and 2023, Surat in 2006, Jamshedpur in 2008, Pune in 2019, Guwahati in 2010 and Srinagar in 2014 (MoUD, 2017), besides the floods of Kolkata in 2007, 2017 and 2023 and of Ahmedabad in 2017. These observations on increased frequency of occurrence of flood in India are generally similar to the observations of increased occurrences of small duration precipitations, such as those lasting for less than a day, under a changing climate (Goswami et al., 2006).

Future-proofing the DSCs of India against pluvial flooding is an important requirement for ensuring that the benefits of implementing the National Smart Cities Mission of 2015 of the Government of India and the resulting contributions to the nation's economy and well-being are accrued in the desired pace and level as envisaged without hindrance from urban floods. Steps to achieve this call for adoption of (a) structural measures of constructing new and upgrading existing storm water drainage systems, flood-protection infrastructures, etc. (b) non-structural measures of operationalizing early warning systems, creating resilience, etc. and (c) Integrated Urban Water Management (IUWM) practices. Essentially, these require reliable inputs of intensity, duration and frequency (IDF) of future precipitation, particularly short-duration rainfall, in the focus areas.

There are several mathematical frameworks for deriving IDF relationships ((Koutsoyiannis et al., 1998)), and several studies exploring the impacts on future IDF characteristics in different regions of the world under a changing climate. (Zhao et al., 2021) used multi-model simulations for projecting the IDF characteristics of two Vietnamese cities by considering a near future period from 2026 to 2045 and a far one from 2066 to 2085. They found that the intensity of rarer rainfall events is likely to increase, particularly for longer durations, in the future, and recommended the updating of the existing urban drainage systems in these two cities. (Cheng and AghaKouchak, 2014) presented a generalized framework to account for non-stationarity of IDF characteristics for designing infrastructure under a changing climate. Applying IDF analysis on historical and climate projection data of three cities, one each in Ethiopia, Tanzania and Cameroon in Africa, (De Paola et al., 2014) found that, although future rainfall intensities in a study area might decrease or increase depending on the location of the area, frequencies of intense rainfalls would increase in the future. Simulating future precipitations using Canadian Regional Climate Model (Mailhot et al., 2007) estimated that the frequencies of 12- and 24-hour precipitations would increase three times and those of 2- and 6-hour precipitations would increase two times over the Southern Quebec region during the future period of 2041–2070. A 16–27% increase of IDF ordinates for different return periods over Europe was found by (Hosseinzadehtalaei et al., 2020) from a study of Climate change impacts on short-duration extreme precipitation and IDF characteristics. Using record of daily rainfall, (Choi et al., 2019) derived future IDF curves over South Korea, and concluded that the intensity of design rainfall is likely to increase in the future in most areas excluding

east coastal region. Increasing trends of precipitation intensities were also found over selected regions in China (Zhang et al., 2022), Brazil (De Souza Costa et al., 2020), Turkey (Şen and Kahya, 2021), Malaysia (Kuok et al., 2016; Shukor et al., 2020), and several other countries. In the case of India, the future IDF characteristics were studied individually for several cities including three DSCs, namely Bengaluru (Chandra et al., 2015), Hyderabad (Agilan and Umamahesh, 2016) and Chennai (Andimuthu et al., 2019), Roorkee (Singh et al., 2016), etc., and an extensive study of changes in future precipitation intensities across the whole country under different climate change scenarios was carried out by (Maity and Maity, 2022).

Noting the dearth of literature on studies of IDF characteristics involving the DSCs distributed across India, the objective of this study was set to investigate the trend and deviations of future IDF characteristics under different climate change scenarios that would have potential to aggravate the future pluvial flooding scenarios in the DSCs.

2. Study Area and Data

Noting that there are 7933 urban settlements across India (MoUD, 2017) and that regional attributes of rainfall are relevant for comprehending the dynamics of location-specific rainfall characteristics, this study was conducted by exploring the future IDF characteristics of rainfall at grid points over mainland India in a 0.25°×0.25° geographic grid into which the country is conventionally divided for climate related research. An outline of mainland India showing the major grids of latitudes and longitudes is provided in Fig. 1(a). The locations of the 100 DSCs including the locations, names and populations as per 2011 Census of the eight UCs amongst these DSCs are also included in this map in order to show the spread of the DSCs across India. The names of the DSCs are not given for the clarity of the map. Readers may find details of the DSCs in the official webpages of the Smart Cities Mission of the Government of India (smartcities.gov.in). Since precipitation of a region is influenced, *inter alia*, by the region's physiography, hence, the elevation map showing the Indo-Gangetic-Brahmaputra plains spreading across the north-central, eastern and western parts of the country, and the country's southern peninsular region is shown in Fig. 1(b).

Meaningful studies of IDF characteristics require short-duration, preferably hourly, data of precipitation. However, the unavailability of long records of historical data of observed hourly precipitation in many parts of the world including India compels researchers either to apply statistical techniques, such as temporal downscaling, scale invariance method, Equidistance Quantile Matching Method etc., to daily data of precipitation for producing data of sub-daily temporal resolutions, or to use a reference set of data in lieu of recorded data. Because the use of statistical techniques imparts increased uncertainty to the assessment of future IDF characteristics, and records of hourly observed data are not readily available for the study area, the current study was undertaken by using a set of hourly reanalysis precipitation data of the fifth generation produced by the European Centre for Medium-Range Weather Forecasts (ECMWF), called ECMWF Re-Analysis 5, i.e. ERA5, as reference data. As described in the Climate Data Guide of the National Center for Atmospheric Research of the USA (NCAR, 2023), these

reanalysis data were produced by assimilating multiple observational data of the atmosphere, land and ocean are assimilated into a forecast model and yielding a ‘dynamically consistent estimate’ of the state of climate. The adoption of ERA5 hourly data of precipitation as reference data for this study is supported by the observations from an earlier study (Mahto and Mishra, 2019) in which the authors found the ERA5 data as being the best amongst five different reanalysis datasets in representing the monsoon precipitation of India. Accordingly, ERA5 reanalysis outputs for a historical 60-year period from 1955 to 2014 were used for determining the observed IDF characteristics at grid points across the study area. For producing IDF characteristics of future precipitations, the hourly precipitation outputs from one General Circulation Model, also called a Global Climate Model (GCM), namely MIROC6 of the Coupled Model Intercomparison Project phase 6, were taken for an 86-year projection divided into three periods, namely 2015–2040 for immediate-future, 2041–2070 for near-future and 2071–2100 for far-future. The choice of MIROC6 was because of it being the only GCM that provided hourly output of precipitation for all SSPs considered in this study. The future MIROC6-simulated data were obtained for four of the five climate change and greenhouse gas emission scenarios under Shared Socio-economic Pathways (SSPs), namely SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5 of the variant level r1i1p1f1 as defined in the Sixth Assessment Report of the Intergovernmental Panel on Climate Change of the UN. These SSPs represent future climate change scenarios with SSP1-2.6 representing a sustainability-focused low greenhouse gas emission scenario, SSP2-4.5 corresponding to a ‘middle-of-the-road’ moderate emission scenario, SSP3-7.0 indicating a high emissions scenario with regional rivalries, and SSP5-8.5 representing a worst-case scenario of a ‘business as usual’ world with heavy reliance on fossil fuels and absence of any future climate policy.

3. Methodology

Due to the fact that GCM outputs often exhibit large systematic errors or biases arising out of inadequate comprehension of physical processes, inaccurate input data, limitations of computing resources, etc. in regional scales (Chen et al., 2021), and that the use of these outputs for the assessment of future impacts of climate change on hydro-climatological variables is likely to yield less reliable results (Kotlarski et al., 2014; Maraun and Widmann, 2018), it becomes pertinent to correct the bias of the GCM outputs for aligning the statistical characteristics of these outputs with those of the observed data (Maraun, 2013). For the study described herein, the Quantile Delta Mapping (QDM) for bias correction (Cannon et al., 2015) through matching of Cumulative Distribution Functions (Panofsky and Brier, 1968) was applied to the GCM outputs of hourly precipitation data. The mathematical formulation of this method is described by Eq. (1)

$$x_i^{maf} = x_i^{mf} + F_{x^{oh}}^{-1}\left(F_{x^{mf}}\left(x^{mf}\right)\right) - F_{x^{mh}}^{-1}\left(F_{x^{mf}}\left(x^{mf}\right)\right)$$

1

where *i* denotes a grid point, superscripts mf denotes GCM model outputs of the future, *maf* denotes bias-corrected GCM outputs of the future, *mh* denotes GCM-simulated historical values, and *oh* denotes

observed historical values or reference data of precipitation.

The Annual Maximum (AM) Series of precipitation intensities of durations 1-, 2-, 6-, 12-, 24- and 48-hours for the historical data period as well as for each future period were produced from the respective time series data of precipitation by using moving windows of the selected durations across the data series. The AM series of precipitation of different durations for different periods were thus generated for each grid point over the mainland India. The intensities of AM precipitation for different durations were then estimated for each of 5-, 10-, 25-, 50- and 100-year return periods by employing Gumbel's extreme value distribution (Gumbel, 1958). Having obtained these probabilistically derived data of precipitation, the IDF curves of the form of an empirical equation of Bernard (Bernard, 1932) as given by Eq. (2) were fitted to the data at each grid point.

$$I = \frac{aT^b}{d^c}$$

2

where *I* is the precipitation intensity, *d* is the duration, *T* is the return period, and *a*, *b*, and *c* are parameters. Accordingly, the precipitation intensity of a given duration and a given return period would increase with increase of *a* and *b*, and decrease of *c*. For the AMS at each grid point, the values of the three IDF parameters were estimated for 1-, 2-, 6-, 12-, 24- and 48-hr durations for 5-, 10-, 25-, 50- and 100-year return periods. The parameters of the equation were evaluated by Ordinary Least Squares estimation method by employing the Generalized Reduced Gradient search algorithm for automatic optimization.

Mann-Kendall trend test (Mann, 1945) was performed and Sen's slope (Sen, 1968) was estimated at each grid point by using 60 years of historical data from 1955 to 2014 and an 86-year projection into the future from 2015 to 2100, focusing on AMS of 1-hour duration across all four SSPs. Subsequent to trend analyses, the precipitation intensities of the selected durations and return periods were estimated at all grid points and their percentage (%) deviations under each of the four selected SSPs from the corresponding historical values were assessed. Inferences were then drawn from the values of trends, magnitudes of intensities and the deviations of short-duration precipitations at all grid points for three future periods under four climate change scenarios with particular references to the observations pertaining to the DSCs of India.

4. Results and Discussions

It was found from the analyses of Bernard's parameters that, generally for all four SSPs, the plains in the north-central, eastern and western parts of India encompassing 69 DSCs show relatively high values of *a* and *b*, and the southern peninsular region containing 29 DSCs exhibits relatively low values of *c* in the three future periods under all four SSPs. For brevity, representative graphical results for only one SSP, namely SSP1-2.6, for each of the three parameters and each of the three periods are exhibited in Fig. 2.

The sampled values of the parameters at the locations of the eight Tier I UCs for SSP1-2.6 are also provided in this figure using the same legends for the UCs as provided in Fig. 1(a) for visual assessment of the relative values of these parameters in the regions around the respective UCs, and across the whole country. Since the higher values of *a* and *b* and lower values of *c* indicate larger precipitation intensities, hence the results of the analyses of Bernard's parameters indicate that higher precipitation intensities would be likely in almost all DSCs in the future relative to the corresponding historical values under all greenhouse gas emission scenarios. It was also found from the comparison of values of the three IDF parameters for different SSP scenarios across the grid points that, generally, the magnitudes of the precipitation intensities would increase with the increase of severity of greenhouse gas emission from the low emission scenario SSP1-2.6 to the very high emission scenario SSP5-8.5. The above observations are similar to those made in respect of the whole of India by (Maity and Maity, 2022) who found that future precipitation intensities would increase by about 17–21% in areas covering about 70–90% area under SSP2-4.5 and by about 40–48% in areas covering almost the whole country, and that the increase in precipitation intensity is likely to be more in the Central and northeastern parts of the country and the mountainous and Terai regions of the Gangetic basin on the north, and moderate in the alluvial plains of the north, the southern peninsula and the desert region.

The historical 1-hour intensities of AM precipitations of 100-year return period and their deviations in the three periods under four SSPs from the corresponding historical values are presented in Fig. 3. These figures show that the aerial extents of positive deviations generally increase with the increase of severity of greenhouse gas emissions from the sustainability-focused scenario SSP1-2.6 to the business-as-usual scenario SSP4-8.5, particularly, in the near-future and far-future periods of 2041-70 and 2071–2100 respectively. It was found from the results of the deviation analysis that 85 of the 100 DSCs exhibit high positive deviations under SSP5-8.5 during 2071–2100 implying large increase in short-duration precipitation intensities in most of the DSCs of India. These observations further substantiate that the impacts of precipitation on pluvial floods in the DSCs are likely to increase in the future due to increase in the volume of short-duration precipitation.

The analysis of trends of the AM precipitation of 1-hour duration at 95% significance level at all grid points revealed that the trends in terms of both the Sen's slope and the Mann-Kendall test statistic worked out as being insignificant for the historical and the SSP1-2.6-projected future periods in considerably large expanse of the country. These observations are also reflected in the maps showing the trends of Sen's slope in Fig. 4(a) and 4(b). However, from a look at the significant trends of the AM precipitation of 1-hour duration for different SSPs as presented in Fig. 4 (b-e), it may be seen that increasing numbers of grid points exhibit significant positive trends from SSP1-2.6 to SSP5-8.5. From the results of trend analyses, it was also found that the number of DSCs having significant positive trends of AM precipitation intensities of 1-hour duration increases from 35 under SSP2-4.5 to 68 and 72 under SSP3-7.0 and SSP5-8.5 respectively. As regards the UCs in particular, the values of the trend indicator, i.e. the Sen's slope, provided on the maps of Fig. 4 reveal that the trends of the AM precipitation of 1-hour duration at 95% significance level are insignificant under the sustainability-focused low greenhouse gas emission scenario SSP1-2.6 in seven of the eight UCs, and negative in the UC of Mumbai on the western

coast. However, the trends change to significantly positive in two relatively closely located UCs of Mumbai and Pune under the moderate emission scenario SSP2-4.5. As the scenario turns to high emission, five UCs, namely Delhi, Hyderabad, Kolkata, Ahmedabad and Chennai, exhibit significant positive trends, whereas the UCs of Delhi, Bengaluru, Hyderabad, Mumbai and Pune show significantly positive trends under the very high emission scenario SSP5-8.5.

Although the above results from trend analysis of the AM precipitation of 1-hour duration over the DSCs and the whole country generally indicate increasing trends of short-duration AM precipitations, the results in respect of the UCs in particular reveal that the impacts of greenhouse gas emissions of increasing severities might not always translate to significantly increasing trends of short-duration AM precipitations in some DSCs. Similar results were found by (Mirhosseini et al., 2013) in a study of the impacts of climate change on rainfall IDF curves in Alabama in the US who observed that the patterns of future precipitation of Alabama are likely to be less intense for short-duration events, and that the results were not consistent for precipitations of relatively longer duration of more than four hours. The reasons for the apparent inconsistencies that could be found from the above trend analysis results for some of the UCs of India are likely to be (i) the impacts of greenhouse gas emissions and the resulting rise in temperature on a large variety of physical processes that complexly and non-linearly influence the pattern of occurrence of precipitation, (ii) the uncertainties in the GCM-projected values of future precipitations, and (iii) consideration of reanalysis products of precipitation instead of observed shot-duration precipitations as reference sets of historical data. The differences in the values of trend indicators, e.g. in the case of the UC of Mumbai as exhibited on the maps in Fig. 3., indicate the necessity of undertaking scenario-specific analysis for determining the expected IDF characteristics for efficient design of urban pluvial flood control structures and IUWM. However, although this approach would be idealistic, the practical problem would be to assess the likely severity of the greenhouse gas emission of the future that would help identify an appropriate SSP scenario. A way of overcoming this difficulty of adopting an SSP scenario for design in absence of better estimates of precipitation intensity would be that suggested for urban stormwater infrastructure design in Toronto-Niagara Region of Canada by (Watt et al., 2003) to adopt a design storm 15% larger than the present estimate.

5. Conclusions

In this study, the trends and deviations of future IDF characteristics, particularly of short-duration annual maximum precipitation, that are likely to aggravate the future pluvial flooding scenarios of 100 DSCs of India were studied at grid points of a 0.25°×0.25° grid covering mainland India. By using hourly data of AM precipitations of the historical past from the year 1955 to 2014 and the bias-corrected GCM-projected future values of 1-hour AM precipitations under four Shared Socioeconomic Pathways (SSPs) during three periods from 2015–2040, 2041–2070 and 2071 to 2100, it was found that

Intensity wise, the plains in the north-central, eastern and western parts of the country in which 69 DSCs are located and the southern peninsular region containing 29 DSCs are likely to experience intensities of

short-duration precipitation higher than the corresponding historical values in the three future periods under all four SSPs

Magnitude wise, the aerial extents of positive deviations of short-duration AM precipitation from the corresponding historical values would generally increase from SSP1-2.6 to SSP4-8.5, particularly, during 2041–2100, and 85 of the 100 DSCs are likely to experience high positive deviations under SSP5-8.5 during 2071–2100.

Trend wise, the number of DSCs having significant positive trends of AM precipitation intensities of 1-hour duration increases from 35 under SSP2-4.5 to 68 and 72 under SSP3-7.0 and SSP5-8.5 respectively.

In the case of some DSCs, the impacts of greenhouse gas emissions of increasing severities might not always indicate significantly increasing trends of short-duration AM precipitations. Whereas such an apparent inconsistency is possible, it would necessitate the consideration of a realistic future greenhouse gas emission scenario for each DSC for designing efficient urban pluvial flood protection structures and undertaking effective IUWM practices for the DSC. However, this approach of adopting DSC-specific and climate change scenario specific values of future IDF values of precipitations for design would be impractical, and the suggestion of (Watt et al., 2003) to adopt a design storm 15% larger than the present estimate for design appear as being pragmatic.

Generally, however, the results of this study show that most of the DSCs are expected to experience larger volumes of short-duration precipitation, and hence increased incidences of pluvial flooding, in the future. These findings would facilitate the assessment of the increasing vulnerabilities of the 100 DSCs located across India to urban pluvial floods, and provide an objective basis for efficient planning and design of urban stormwater drainage systems and flood protection infrastructures. The results of this study would also contribute to the framing of effective IUWM practices for sustainable, citizen-friendly developments of these DSCs.

Declarations

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ORCID

Monomoy Goswami: 0000-0003-1380-6276; Avijit Paul: 0000-0001-9388-9571; Meghraj Goswami: 0009-0007-4895-2747

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Author Contributions

The first author suggested improvements on the methodology and presentation of results, and prepared the manuscript. The second and third author conceptualized, analysed, and prepared graphical outputs of the research.

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Figures

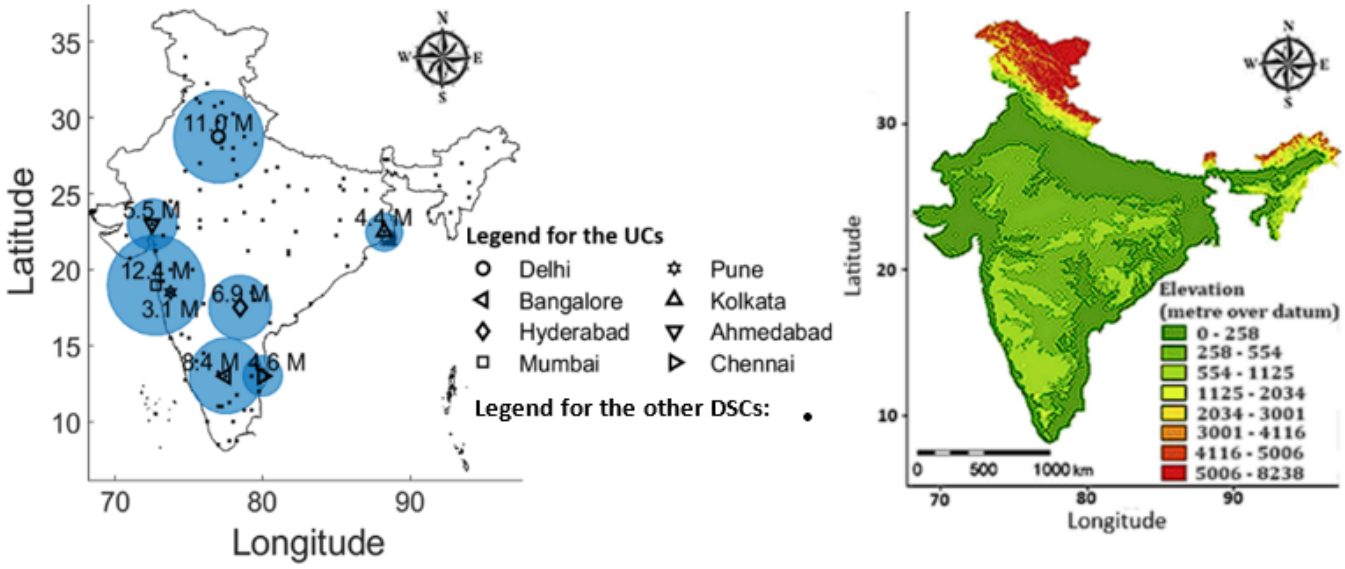


Figure 1

Map of mainland India: (a) Country outline showing the locations of 100 DSCs, and the locations and bubble plots of population in Million (as per Census 2011) of eight Tier I UCs, and (b) Elevation map (Paul and Goswami, 2024)

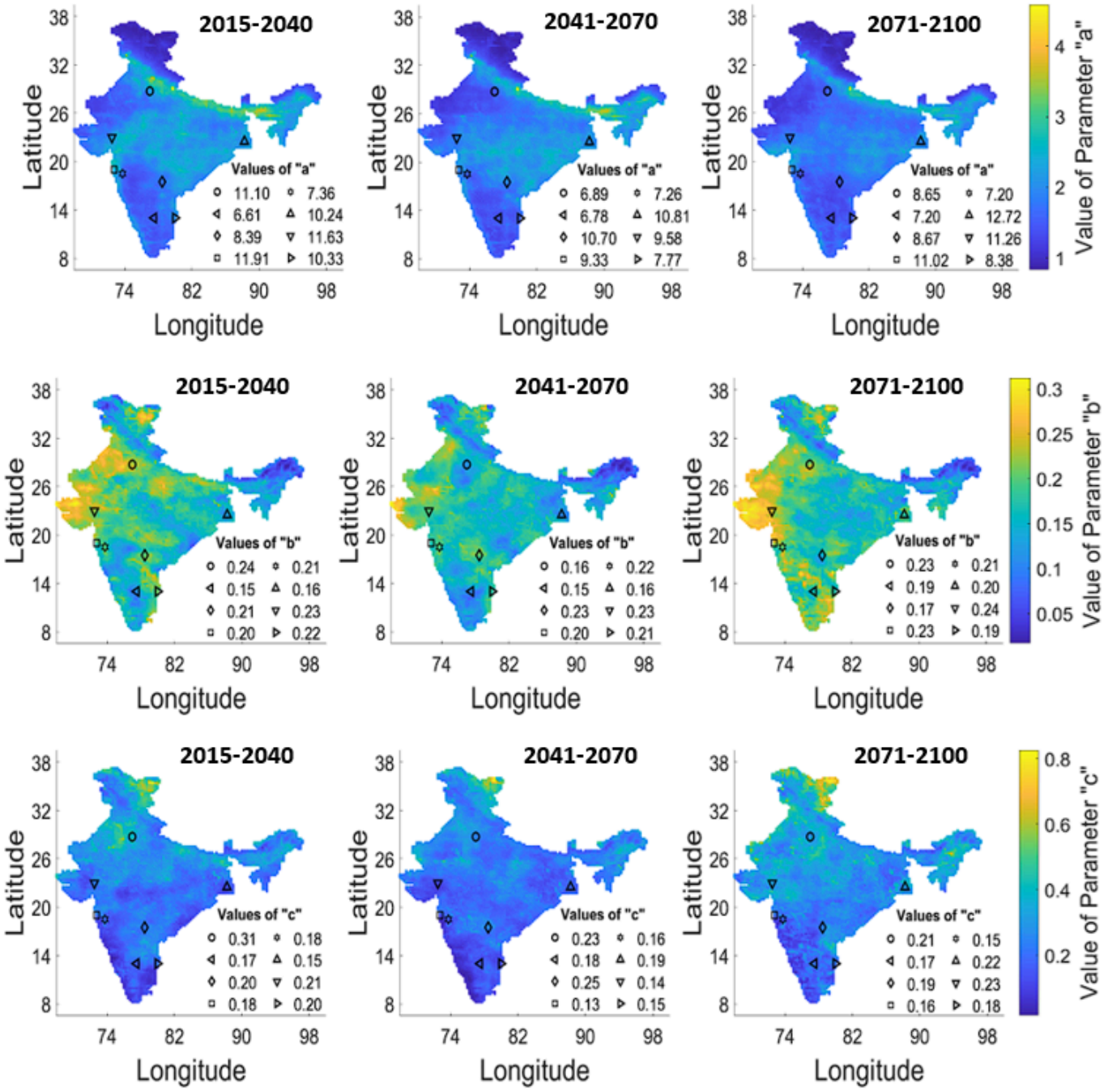


Figure 2

Spatial Distribution of Bernard's Parameters *a*, *b* and *c* in three 3 consecutive future periods under one of the SSPs, namely SSP1-2.6



Figure 3

Precipitation (a) in the historical period, and (b)-(m) the percentage deviations in three future periods under the four SSPs

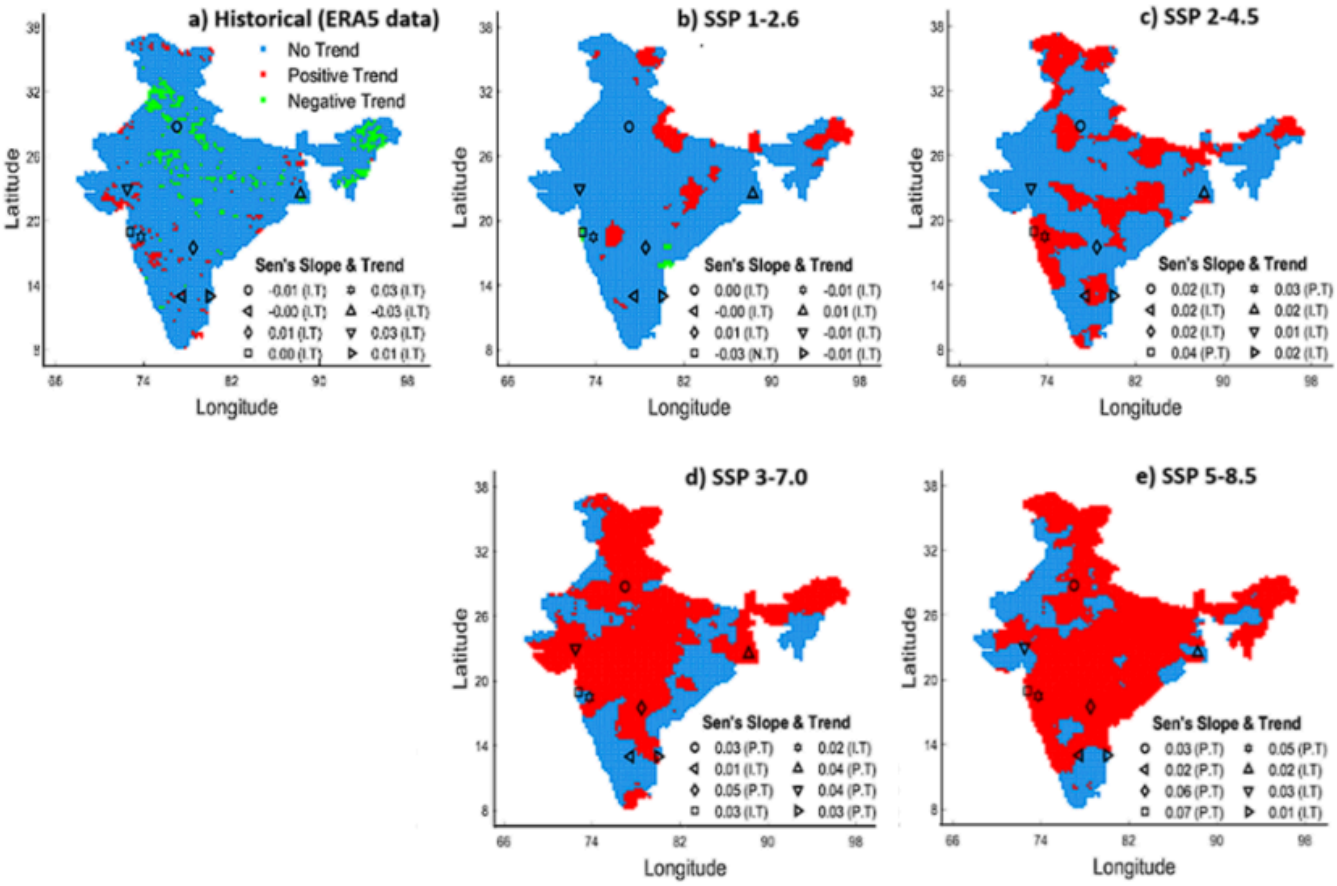


Figure 4

Trend Analysis of (a) historical and (b-e) future precipitation under four SSPs. Color indices indicating no trend (blue), positive trend (red) and negative trend (green) in Fig. (a) apply in Figs. (b-e), and I.T, P.T and N.T. in legends on all figures indicate Insignificant, Positive and Negative trends of the Sen's slope respectively.