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Lack of uniform trends but increasing spatial variability in observed Indian rainfall extremes

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Recent studies disagree on how rainfall extremes over India have changed in space and time over the past half century[1–4], as well as on whether the changes observed are due to global warming[5,6] or regional urbanization[7]. Although a uniform and consistent decrease in moderate rainfall has been reported[1,3], a lack of agreement about trends in heavy rainfall may be due in part to differences in the characterization and spatial averaging of extremes. Here we use extreme value theory[8–15] to examine trends in Indian rainfall over the past half century in the context of long-term, low-frequency variability. We show that when generalized extreme value theory[8,16–18] is applied to annual maximum rainfall over India, no statistically significant spatially uniform trends are observed, in agreement with previous studies using different approaches[2–4]. Furthermore, our space–time regression analysis of the return levels points to increasing spatial variability of rainfall extremes over India. Our findings highlight the need for systematic examination of global versus regional drivers of trends in Indian rainfall extremes, and may help to inform flood hazard preparedness and water resource management in the region.

There is considerable debate in the recent literature about the nature of space–time trends in extreme rainfall over India[1–3] and their attribution to aspects of global change, specifically, global climate change[5,6] versus regional urbanization patterns[7]. Previous researchers have drawn a variety of conclusions[1–4] about trends in rainfall extremes during the Indian monsoon from a regular $1^\circ \times 1^\circ$ (or similar) gridded daily rainfall dataset over India for 1951–2003. The differences can probably be attributed to the corresponding definitions of extremes, levels of spatial aggregation and areas of coverage. The use of fixed thresholds over a $12^\circ \times 10^\circ$ box labelled as Central India suggested an increasing trend in rainfall extremes concurrent with decreasing moderate rainfall, resulting in no discernible net trends[1]. However, the use of variable percentile-based thresholds over each individual $1^\circ \times 1^\circ$ grid[2], analysis based on homogeneous regions[3] and analysis with a percentile-based definition of the frequency and intensity of rainfall extremes[4] showed no discernible spatially uniform trends in rainfall extremes over India. Field significance tests do not statistically support the hypothesis of increasing trends in heavy rain events[2,3], and the region labelled as Central India in ref. 1 may not be meteorologically homogeneous[19]. However, the use of additional data (1901–2004; ref. 5) confirmed the findings of ref. 1 when identical definitions of extremes, aggregations and coverage were used. The often conflicting insights about Indian rainfall extremes in the recent literature point to the importance of effective characterization of extremes, especially for understanding and communicating their relevance to impacts and policy.

Here we show that rainfall extremes over India do not exhibit a spatially uniform trend, in agreement with a few studies[2–4] but in contrast to other published literature[1]. Instead, they seem to show a significant increasing trend in terms of their spatial heterogeneity. The insights presented here follow from extreme value theory (EVT). EVT methods[20] are means to infer the tail behaviour of a population (that is, the 'true' distribution), for example 100-year return levels (or, 1% probability storms), on the basis of well-grounded statistical theory. The approach used here, specifically, estimating the parameters of generalized extreme value (GEV) distribution from annual maxima, as well as their corresponding return levels from 30-year (climate timescale) moving windows, followed by calculating trends in these return levels, has been widely used in climate applications[17,21]. Although other EVT-based approaches, such as peak-over-threshold (POT) or covariates (that is, GEV parameters are expressed as functions of covariates, which in turn could include time or auxiliary variables) have been developed in the literature[11,12], they are not considered in this study. Rather, based on precedence in the literature[17], a flexible moving window approach is used in this study.

First we examine trends in 'all-India monsoon rainfall' (AIMR; see Methods for definition) over the past half century in the context of slowly varying trends and low-frequency variability. The dataset used for this analysis is the India Meteorological Department product of 1° resolution rainfall data[22], which is based on 1,803 stations that have at least 90% data availability during the analysis period (1951–2003; see Supplementary Note on datasets). (Data source: Indian Institute of Tropical Meteorology, Pune, India, Data Archive.)

The AIMR mean time series over the past 150 years shows a low-frequency cyclical pattern, which becomes apparent on filtering through a 30-year moving average (Fig. 1a). This cyclical pattern was also investigated in ref. 23 and observed to be teleconnected with the Atlantic multidecadal oscillation. The mean time series of 30-year moving-averaged AIMR decreases over the past half century, but needs to be interpreted in view of the longer-term trend and periodicity.

The spatial average of the annual maxima (Fig. 1b), calculated on the basis of all grids over India, shows a statistically significant increasing trend (defined as a 1% significance level, computed using the confidence intervals of regression parameters when the data are regressed on time), whereas the grid-based temporal mean of the annual maxima (Fig. 1c) shows geographical heterogeneity. The annual maxima rainfall patterns over each grid (Fig. 1e) show no discernible increasing or decreasing trends anywhere in India other than for a few isolated grids. The 30-year moving temporal variance calculated from the spatial means (Fig. 1d) shows a statistically significant decreasing trend.

The 30-year and 100-year return levels calculated by EVT (Fig. 2a,b) show geographically coherent patterns, although spatial heterogeneities are visually apparent. In the Deccan peninsula,

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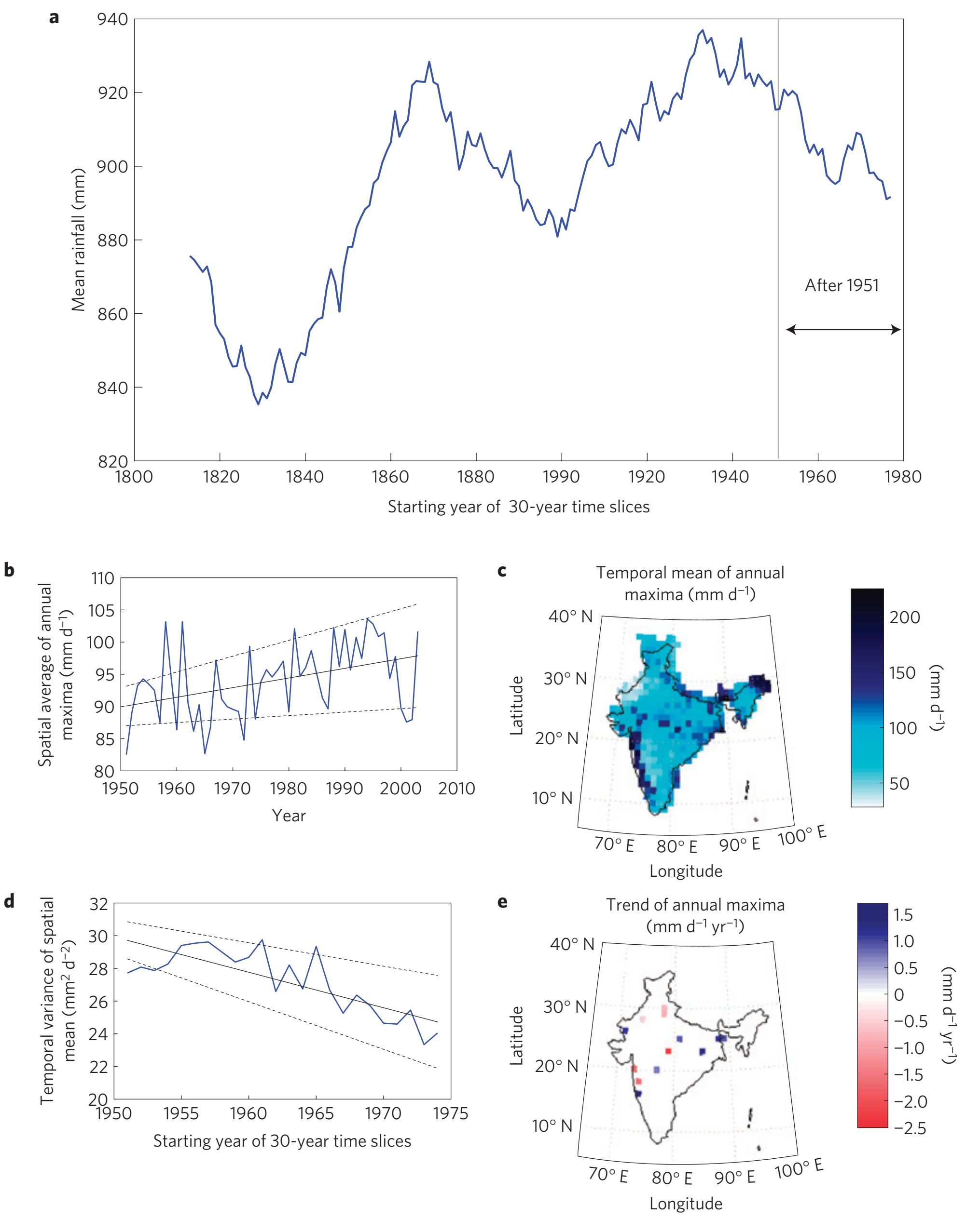

Figure 1 | Spatiotemporal trends and variability in all-India monsoon rainfall (AIMR) with 30-year overlapping time windows. a, AIMR time series (30-year moving average) from 1813 to 2006, suggesting that the decreasing mean trends over the past half century may need to be put in the context of low-frequency variability. **b**, Spatial average of the annual maximum rainfall. **c**, Spatial distribution of the temporal mean of the annual maximum rainfall. **d**, Temporal variance of the spatial mean. In **b** and **d** the bold lines are the trend lines and the dotted lines are their bounds at the 1% significance level. The spatial average (**b**) shows an increasing trend, whereas the temporal variance of the spatial mean (**d**) shows a decreasing trend, both of which are statistically significant at the 1% level. **e**, Spatial distribution of the trends in the annual maximum, indicating that only a few stations have trends that are statistically significant at the 1% level. The data for all plots, except **a**, cover the period 1951–2003 and the spatial distributions are based on a 1° grid.

larger values are observed to the west of the Western Ghats than in the region between the Eastern and Western Ghats. The return level values are relatively larger in the regions adjoining Bangladesh and parts of the northeast and Gujarat than in the rest of India. The uncertainties associated with these return levels are computed using bootstrap methodology[17,21,24] (Supplementary Methods and Figs S7–S9). The geographical correspondence of the return levels with the annual maxima is noticeable, also as expected. No spatially uniform or coherent trends emerge in the 30-year or 100-year return levels (Fig. 2c,d) when the trends are examined through 30-year moving windows. However, where there are visual trends, they seem to be slightly positive rather than negative, along with scattered grids (with occasional spatial coherence) showing positive trends. Nevertheless, the trends, if any, seem small, and spatial heterogeneity dominates across all subregions in India. Incidentally, the coefficient of determination, although spatially heterogeneous, seems fairly large over several grids (Supplementary Fig. S1). The coefficient of determination is a statistical measure of how well the linear trend line approximates the real data points. The spatial heterogeneity of the trend (the values range from zero to unity; Supplementary Fig. S1) possibly reflects the inherent spatial variability and randomness of rainfall, with the high values in several grids reflecting some degree of confidence in the trends of the return level calculations.

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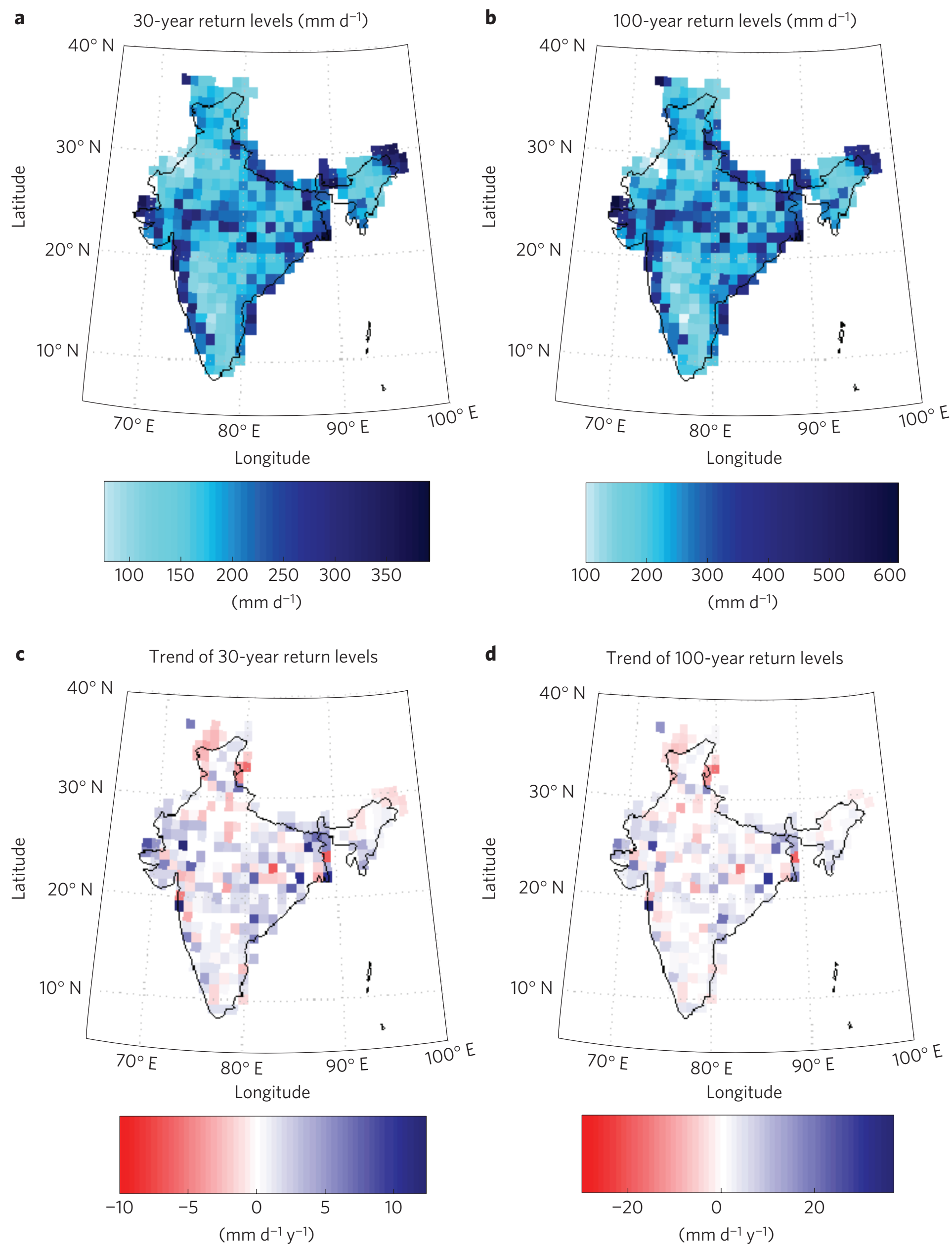

Figure 2 | Return periods and volatility of rainfall extremes in India and their 30-year moving trends. a,b, 1° spatial grid-based 30-year (**a**) and 100-year (**b**) return levels, using 1951–2003 data. Each of these maps exhibits spatial variability. The 30-year and 100-year return levels are interpreted as the expected intensity of 3.3% and 1% probability storms respectively. **c**,**d**, Grid-based trends in 30-year (**c**) and 100-year (**d**) return levels. No uniform trends in rainfall extremes are evident and spatial heterogeneities seem to dominate.

The spatial variances of rainfall extremes are calculated with 30-year overlapping windows for 30-year and 100-year return levels. The spatial variances of the annual maximum rainfall (Fig. 3a), as well as the 30-year and 100-year return levels (Fig. 3b,c), show statistically significant increasing trends. However, the trends in spatial variances are not similar in different meteorologically homogeneous regions[3] (Supplementary Fig. S2). The trends in the spatial variance of the return levels are especially large, indicating the rapid increase in geographical heterogeneity of rainfall extremes over the past half century. When combined with the fact that there are no significant uniform trends, or even any spatially coherent trends, the rapid increase in spatial heterogeneity of return levels suggests regional drivers for changes in the frequency and intensity of rainfall extremes. The widening of the box-plots (Fig. 3d–f) further confirms the spatial heterogeneity, especially for return levels. Furthermore, although outlying values are present, the generic insight of significant increasing trends in spatial variability of the return levels does not seem to be an artefact of outlying values alone (Supplementary Methods). We also note that the station density over India during the past half century did not change significantly and is unlikely to have caused the growth in spatial heterogeneity. A global increase in extreme rainfall events has been suggested in the literature as a consequence of anthropogenic greenhouse-gas emissions leading to atmospheric and oceanic warming[25,26]. However, the increase in spatial heterogeneity of rainfall extremes in India may result from local influences[7], such as topography, non-uniform population growth and urbanization (Supplementary Discussion).

We use EVT as our tool of choice based on its statistical rigour. We have shown that data used by previous researchers yield

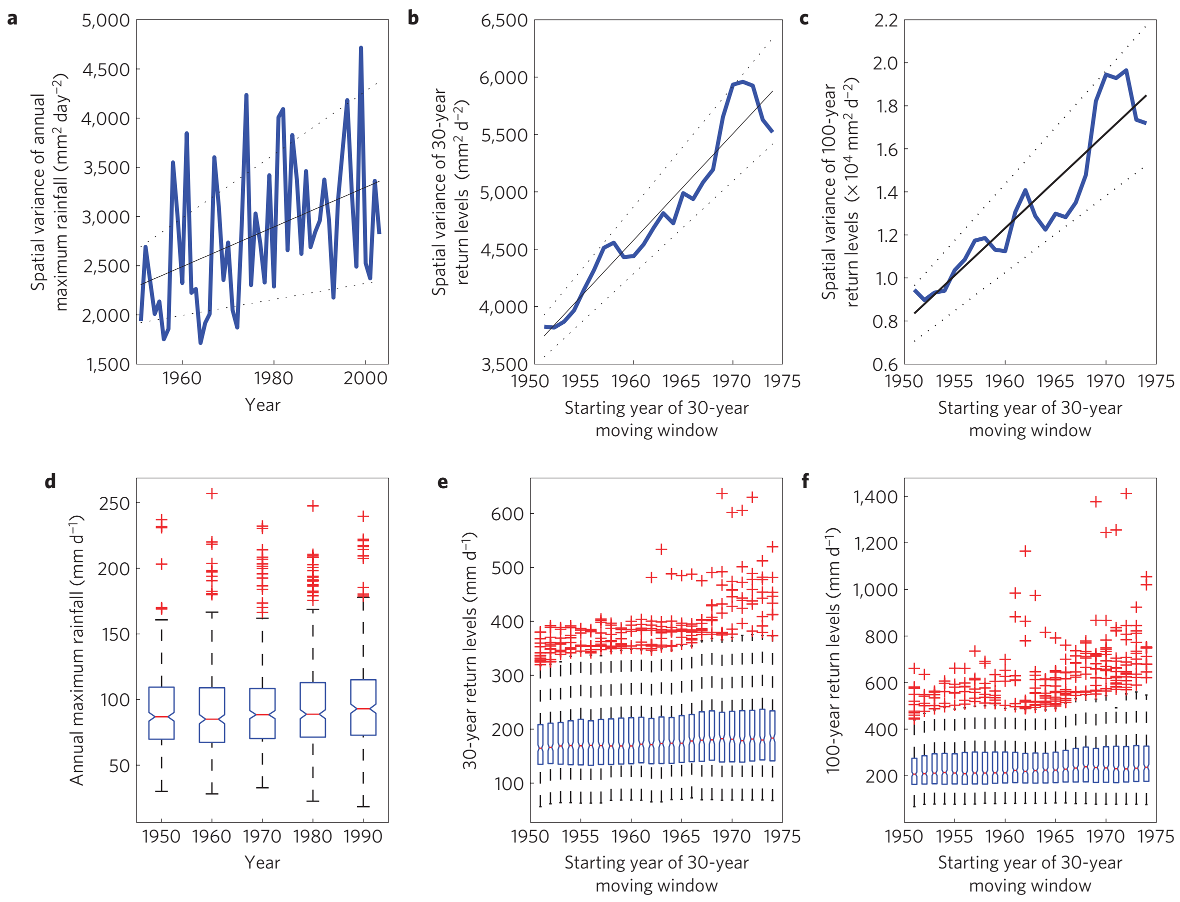

Figure 3 | Trends in spatial variance of rainfall extremes calculated with 30-year overlapping time windows. a–c, Trends in the spatial variability based on all grids over India with 1951–2003 data for annual maximum rainfall (**a**), and 30-year (**b**) and 100-year (**c**) return levels. **d–f**, Box plots corresponding respectively to **a–c**. Statistically significant increasing trends are noted for all the plots. In **a–c**, the bold lines are the trend lines and the dotted lines are their bounds at the 1% significance level. In the box plots, the bottom and top of each box indicate the 25th and 75th percentile (the lower and upper quartiles) respectively, and the band near the middle of a box is always the 50th percentile (the median). The ends of the whiskers (fences) represent the lowest datum still within 1.5 times the Interquartile Range (IQR, the range between the 25th and 75th percentiles of the data) of the lower quartile and the highest datum still within 1.5 IQR of the upper quartile. The outliers are denoted by the red plus signs ('+'). Given the proposed underlying GEV distribution, with a heavy upper tail, many of these apparent outliers may actually be systematic features of the underlying extreme precipitation distribution and not true outliers in the sense of unexpectedness.

different insights when analysed using EVT. We also note that the insights obtained about rainfall extremes can vary significantly depending on the way extremes are characterized. For instance, the percentage of grids in all-India (Fig. 4a–f (top panels)) and Central India[1] (Fig. 4a–f (bottom panels)) showing increasing, decreasing or no trends in rainfall extremes differs significantly depending on the choice of the metric: annual maxima, fixed threshold, variable threshold, or 30-year and 100-year return levels based on EVT. However, we note that in most cases either a majority of the grids show no significant trends or there is an even balance of grids showing increasing versus non-increasing trends. In Fig. 4c, 50% of the grid points show an increasing trend, 30% show a decreasing trend and 20% show no significant trends of 30-year return levels, at 1% significance. This variability in the trends also points to geographical heterogeneity and partially supports our conclusion, from Fig. 3, about a lack of spatially uniform trends but changes in the spatial heterogeneity of rainfall extremes over India during the past half century. The bootstrap confidence bounds in Fig. 3(a–c) suggest that these results were not a product of chance.

Our examination of regions in India considered meteorologically homogeneous[3] further supports the growing trends in the geographical heterogeneity of rainfall extremes. The application of GEV leads to considerably larger areas with significant trends, emphasizing the fact that the application of the appropriate statistical model in this case brings out the components that behave in a theoretically constrained manner and actually reveals significant trends. The random components, on the other hand, are less likely to exhibit significant trends.

Our results suggest that policymakers need to be aware of the different characterizations of extremes, and that characterization of extremes requires both interpretability and statistical rigour. For India specifically: (1) the decrease in mean rainfall over the past half century needs to be put in the context of low-frequency natural variability, and (2) significant increasing trends in spatial heterogeneity of the return levels of rainfall extremes, together with a lack of spatially uniform trends, suggest the predominance of regional rather than global drivers. Flood hazard and water resources management[27] in India may be better positioned by adapting to growing regional variability in rainfall extremes rather than a uniformly increasing trend. Mitigation strategies may need to focus on regional issues such as urbanization and land-use change[28–30] as well as global warming and greenhouse-gas emissions. Our finding regarding the increase in geographical heterogeneity of rainfall extremes over India during the second half of the twentieth century motivates a deeper analysis into the root causes thereof. The increase in the spatial variance of return levels may also be

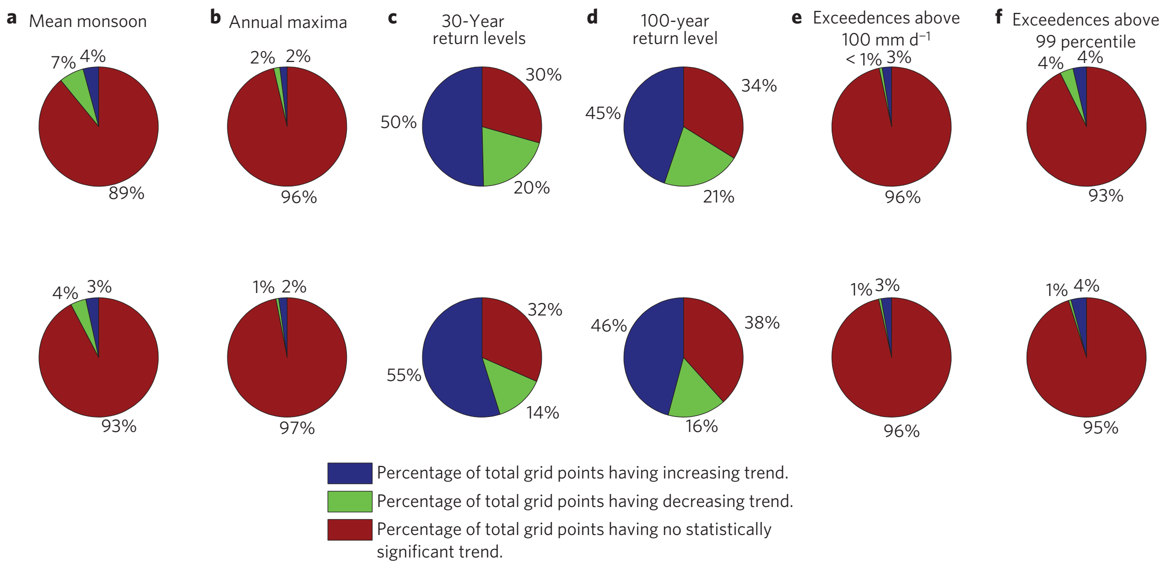

Figure 4 | Multi-metric examination of average and severe rainfall trends over Central India as defined in ref. 1 and over 'all-India'. Number of grids showing increasing, decreasing, or no significant trends in a range of metrics, based on 30-year moving windows over the past half century for all-India (top panels) and Central India (bottom panels). The metrics are mean monsoon rainfall (**a**), annual maximum rainfall (**b**), 30-year (**c**) and 100-year (**d**) return levels, exceedances above a fixed (100 mm d^{-1}) threshold (**e**) and exceedances above a variable (99th percentile) threshold (**f**). The choice of metric strongly affects the insights concerning trends in severe rainfall. The results compare results from extreme value theoretic definitions with other metrics that have been commonly used by previous researchers to characterize severe rainfall over India and its trends. The trends over Central India show strong visual similarities with all-India trends. The calculations are based on 1951–2003 data.

correlated with the evolution of the spatial maxima; a possibility that should be analysed in future research. Global warming and associated oceanic and atmospheric warming may lead to an overall trend in Indian summer monsoon rainfall[1], whereas trends in spatial heterogeneity may result from changes in factors such as urbanization, deforestation, or other land-use considerations (Supplementary Discussion). Hypothesis-guided research, perhaps based on a combination of climate-model simulations and analysis of observations, may enhance an understanding of the possible contributions of anthropogenic climate change, with associated atmospheric and oceanic warming, versus, or in addition to, regional changes in land-use and urbanization patterns. The results of a root cause analysis to further explain our findings may be helpful to guide emissions policies and regional planning decisions, as well as informing national-scale adaptation and regional preparedness.

Methods

'All-India monsoon rainfall' refers to the areal average of rainfall amounts over India during the monsoon months of June, July, August and September, calculated from 29 subdivisions, where rainfalls for each subdivision are the areal averages of the constituent district rainfalls, and the district rainfalls are in turn calculated by averaging all stations in the district.

The GEV distribution is used for annual maxima of daily rainfall to obtain 30-year and 100-year return levels at each grid. The details of fitting the GEV distribution for annual maxima time series has been described generally in ref. 8, while ref. 17 provides an application to grid-based time series of temperature and precipitation from climate models. Ref. 16 describes the GEV distribution along with the location, scale and shape parameters. Positive, zero or negative values of the shape parameter lead to three special cases of the GEV distribution used in classical EVT, specifically, the Frechet, Weibull and Gumbel distributions, respectively. The n-year return level is calculated as a function of the shape and scale parameters and represents the $(1/n)$% probability of exceedance. Thus, the 30- and 100-year return levels are interpreted as the expected intensity of 3.3% and 1% probability storms. In other words, we would expect at least one storm of equal or greater intensity to occur with 3.3% or 1% probability in any given year.

Trends in n-year return levels can be interpreted as trends in $(1/n)$% extremes. Linear trends are calculated here at each grid point, for both 30-year and 100-year return levels, by fitting GEV distributions on moving (30-year in this study) time windows and calculating return levels corresponding to each window, followed by fitting trend lines with confidence bounds, to the return levels. The method for computing spatiotemporal trends in extreme rainfall is similar to that in ref. 10, even though the latter used a different EVT approach to compute the return levels.

Trends of return levels were calculated at each grid cell. Also, trends in the spatial variance of annual maxima and the return levels were calculated and tested for statistical significance.

The other characterizations of rainfall extremes used in earlier studies[1–4] are either based on exceedances above fixed or variable thresholds, or by fitting gamma distributions to threshold exceeded values, rather than the EVT. The primary purpose of using these non-EVT characterizations here is for comparative purposes.

The raw data are available for a processing fee from the website of the India Meteorological Department (IMD): http://www.imd.gov.in/nccraindata.htm. The analysis and visual presentations, including the maps of India and corresponding political boundaries, were generated using the MATLAB software from The MathWorks.

The MATLAB codes, processed data, information on raw data, and a readme file are provided as online Supplementary Information.

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Author contributions
S.G. developed codes and performed the analysis, apart from EVT. D.D. performed the EVT analysis and S-C.K. and D.D. developed the EVT codes. S.G. and A.R.G. designed the problem and interpreted the analysis results. A.R.G. wrote the paper, primarily with inputs from S.G., as well as with comments from D.D. and S-C.K.

Additional information
The authors declare no competing financial interests. Supplementary information accompanies this paper on www.nature.com/natureclimatechange. Reprints and permissions information is available online at http://www.nature.com/reprints. Correspondence and requests for materials should be addressed to A.R.G.