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Trends in rainfall extremes over Bangladesh, 1989–2023: a quality- controlled station analysis with field significance testing

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Abstract

Station-based evidence on changing rainfall extremes in Bangladesh is fragmented, and earlier studies seldom report how data gaps were treated or how multiple tests were controlled. We analysed daily rainfall from 31 Bangladesh Meteorological Department stations for 1989–2023. Parts of the record had been gap-filled by copying earlier years or by entering missing months as zero; after these values were removed, 29 stations met a 30-year completeness criterion. Eleven indices of the Expert Team on Climate Change Detection and Indices and four seasonal totals were tested with a modified Mann–Kendall test and Theil–Sen slopes, with false discovery rate control and permutation-based field significance. Only 25 of 434 station trends were significant at $P < 0.05$, close to the 22 expected by chance, and no index had a field-significant regional trend. Regional trends in rainfall intensity and in maximum 1-day and 5-day totals were near zero, and their confidence intervals exclude increases larger than 0.2 standard deviations per decade. The most consistent change was a longer dry-season dry spell. Consecutive dry days had positive trend statistics at all 29 stations and were significant at two (regional $P = 0.041$), but the signal was not field significant ($P = 0.099$) and weakened under stricter quality control. Over 35 years, rainfall extremes in Bangladesh show no detectable intensification, and claims of change based on counts of significant stations need explicit control of multiple testing.

1 Introduction

Bangladesh receives most of its rain in four months, and the timing and intensity of that rain govern dry-season rice production, river flooding and slope failure (Mirza 2002; Ahmed 2015; Mainuddin et al. 2022). Physical reasoning and global station networks point to heavier daily extremes as the atmosphere warms (Trenberth 2011; Westra et al. 2013; Dunn et al. 2020), and the IPCC Sixth Assessment Report assessed with medium confidence that heavy precipitation has increased over South Asia (Seneviratne et al. 2021). The regional picture is less tidy. Over central India, extreme rain events became more frequent while mean monsoon rainfall weakened (Goswami et al. 2006; Roxy et al. 2015, 2017), dry spells in the core monsoon zone became more frequent (Singh et al. 2014), and station trends across South Asia are mixed, with consistent signals only over small areas (Sheikh et al. 2015). Episodes of intense moisture transport that produce flood-causing rainfall over Meghalaya and coastal Bangladesh have become more frequent since 1950 (Fahad et al. 2024).

Station studies within Bangladesh disagree. Analyses ending in the 2000s reported rising annual and pre-monsoon rainfall with fewer consecutive dry days (Shahid 2011), or increases carried mainly by light rain with no clear change in heavy rain (Endo et al. 2015). Later work found drier winters (Mullick et al. 2019), declining extreme indices in the northeast (Basher et al. 2018), falling but mostly non-significant annual totals (Khan et al. 2019) and increasing consecutive dry days at every station analysed for 1987–2017 (Ezaz et al. 2022). For 1980–2017, Islam et al. (2024) found the opposite pattern, with longer wet spells and shorter dry spells. Annual maximum daily rainfall has been reported to be decreasing at most stations (Das and Islam 2023). Differences in period, station selection and method explain part of this spread.

Two further issues have received little attention. Few studies state how gaps in the national record were treated, although several infilling methods have been applied to Bangladesh Meteorological Department (BMD) rainfall (Jahan et al. 2019), and infilled values can create or remove trends. Testing many station–index combinations at $P < 0.05$ also guarantees some false positives, yet field significance is seldom assessed (Wilks 2016).

In this study we examine rainfall amount, intensity, heavy-rain frequency, extreme 1-day and 5-day totals, and dry and wet spells at 31 BMD stations over 1989–2023. We use the index framework of the Expert Team on Climate Change

Detection and Indices (ETCCDI) (Zhang et al. 2011), as recent country-scale studies of Pakistan and Nepal have done (Ghanim et al. 2023; Maharjan et al. 2023), and combine it with systematic screening for infilled data, a modified Mann–Kendall test, false discovery rate control and permutation-based field significance. We ask which changes in Bangladesh rainfall are coherent enough across the network to be distinguished from station noise, and we document the data problems that have to be removed before such trends can be estimated.

2 Study area and data

2.1 Study area

Bangladesh (20.6–26.6°N, 88.0–92.7°E) occupies most of the Ganges–Brahmaputra–Meghna delta. Most of the country is low-lying floodplain, and hill ranges rise in the southeast and along the northeastern border. Rainfall is dominated by the South Asian monsoon. At the stations analysed, the June–September monsoon supplies a median of 70% of annual rainfall (range 59–83%), March–May 17%, October–November 10% and December–February less than 2%. Mean annual rainfall increases from 1,367 mm at Rajshahi in the west to 4,274 mm at Teknaf on the southeast coast, with a second maximum of 4,048 mm at Sylhet, below the Meghalaya Plateau, one of the rainiest places in the world (Fig. 1; Islam and Uyeda 2007; Murata et al. 2007).

2.2 Station data

Daily rainfall totals (mm) for 31 BMD stations from 1 January 1989 to 31 December 2023 were supplied as station files, together with station latitude and longitude. Each series contained all 12,783 calendar days and no missing-value codes, and values were recorded in whole millimetres. The files also held sunshine, relative humidity and air temperature, which were not used. National boundaries were taken from Natural Earth 1:10m Admin 0, version 5.1.1 (Natural Earth n.d.). Supplementary tables and figures are given in Online Resource 1, and station coordinates, completeness and quality-control results are listed in Table S1.

2.3 Quality control

Date checks found no duplicated, missing or invalid dates and no negative values. Because a gap-free record is implausible for this network, we searched each station for repeated sequences. We flagged whole calendar years whose 365 daily values matched another year at the same station, and calendar months with at least three wet days (≥ 1 mm) whose first 28 daily values matched the same month in another year. The earliest occurrence was kept and later copies were set to missing. A strict alternative removed every member of a duplicate group. A month with 0 mm was treated as a zero-filled gap when the median of the four nearest stations was at least 100 mm.

Spatial consistency was checked first at the annual and then at the daily scale. Station-years whose annual total departed from the four-neighbour mean by more than five robust standard deviations (median and median absolute deviation of the log ratio across years) were set to missing. Daily values above the station's 99.9th wet-day percentile were also set to missing when no neighbour recorded ≥ 50 mm within ± 1 day. Following climdex.pcic (Bronaugh 2020), a month was invalid when more than 3 days were missing, and a year was invalid when more than 15 days were missing or any month was invalid. Stations with at least 30 valid years were retained.

2.4 Homogeneity testing

Annual wet-day totals and annual wet-day counts were tested with the Pettitt (Pettitt 1979), standard normal homogeneity (SNHT; Alexandersson 1986), Buishand range (Buishand 1982) and von Neumann ratio (von Neumann 1941) tests. P values came from the asymptotic approximation for the Pettitt test and from 20,000 Monte Carlo

simulations for the other tests. Each test was applied to the station series and to its ratio with the mean of the four nearest stations. Series were classed as useful, doubtful or suspect when 0–1, 2 or 3–4 tests rejected homogeneity at the 1% level (Wijngaard et al. 2003). Station histories were not available, so no adjustments were made; suspect stations were retained and examined in the sensitivity analyses.

3 Methods

3.1 Rainfall indices

Eleven indices were computed from daily data following the ETCCDI definitions implemented in climdex.pcic (Zhang et al. 2011; Bronaugh 2020) (Table 1). A wet day has at least 1 mm. The dry season spans the calendar-year boundary, so CDD and CWD were computed with spells allowed to cross 31 December, and each year takes the longest spell ending in that year (climdex.pcic option spells.can.span.years = TRUE). A 1989 value whose longest spell began on 1 January 1989 was set to missing because the start of that spell is unobserved. R95p and R99p used the 95th and 99th percentiles of wet-day rainfall in 1991–2020, the current climatological standard normal (WMO 2017), estimated with Hyndman–Fan type 8 quantiles (Hyndman and Fan 1996). Bootstrap resampling, which climdex.pcic applies only to temperature percentile indices, was not required.

We retained R50 rather than R25 as the higher fixed threshold. Annual R25 and R20 counts were nearly interchangeable (median station correlation 0.93, range 0.89–0.96), whereas 50 mm lies close to the 95th wet-day percentile (median 64 mm, range 51–116 mm), and days of at least 50 mm supply a median of 38% of wet-day rainfall. R50 occurred in every station-year, whereas a 100 mm threshold would give zero counts in 18% of station-years (Table S2). Seasonal totals were summed for winter (December–February, with December assigned to the following year), pre-monsoon (March–May), monsoon (June–September) and post-monsoon (October–November). A season was valid only when all its months were valid.

Table 1
Rainfall indices used in this study

Index	Definition	Unit
PRCPTOT	Annual total rainfall on wet days	mm
SDII	PRCPTOT divided by the number of wet days	mm day^{-1}
R10	Annual count of days with RR ≥ 10 mm	days
R20	Annual count of days with RR ≥ 20 mm	days
R50	Annual count of days with RR ≥ 50 mm	days
R95p	Annual total of RR on days above the 95th percentile	mm
R99p	Annual total of RR on days above the 99th percentile	mm
RX1day	Annual maximum 1-day rainfall	mm
RX5day	Annual maximum consecutive 5-day rainfall	mm
CDD	Longest run of consecutive days with RR < 1 mm	days
CWD	Longest run of consecutive days with RR ≥ 1 mm	days
Seasonal totals	Total rainfall in DJF, MAM, JJAS and ON	mm

RR, daily rainfall. A wet day has RR ≥ 1 mm. Percentile thresholds are station-specific wet-day percentiles for 1991–2020. CDD and CWD spells may cross 31 December

3.2 Trend detection

Trends were tested with the Mann–Kendall test (Mann 1945; Kendall 1975) and quantified with the Theil–Sen slope (Theil 1950; Sen 1968). Slopes were computed against calendar year so that missing years are handled correctly, with rank-based 95% confidence intervals (Sen 1968). Serial dependence was treated with the Hamed–Rao variance correction (Hamed and Rao 1998), based on autocorrelations of the ranks of the detrended series at lags significant at the 5% level. Negative autocorrelation makes the original test conservative (Yue et al. 2002), and correction factors below one estimated from 30–35 values are unstable, so the correction was applied only when it increased the variance. After detrending, 7.6% of series had significant lag-1 autocorrelation and the correction was active in 5.1%. Series with fewer than 30 valid values were not tested. Slopes are reported per year and as a percentage of the station mean per decade, and significance was assessed at $P < 0.05$.

3.3 Multiple testing and field significance

For each index, station P values were adjusted with the Benjamini–Hochberg false discovery rate (FDR) procedure (Benjamini and Hochberg 1995) at $\alpha_{FDR} = 0.10$, which approximates a global level of 0.05 under moderate to strong spatial correlation (Wilks 2016). Field significance was assessed by permuting the order of years 1,000 times, identically at all stations, so that inter-station correlation was preserved. Two statistics were compared with their permutation distributions: the number of stations with $P < 0.05$, and the regional mean of the station Mann–Kendall Z statistics, a regional average Kendall statistic (Douglas et al. 2000). The regional mean statistic tests for a coherent regional trend and was used as the primary field test. The count statistic tests whether local significance is more frequent than expected, regardless of sign. A regional series was also formed for each index by averaging station standardised anomalies in years with at least 14 contributing stations, and this series was tested in the same way as the station series.

3.4 Sensitivity analyses and computation

All trends were recomputed with the strict duplicate rule (24 stations retained), without spatial screening (29 stations), excluding the five stations classed suspect by any relative homogeneity test (24 stations), and for 1989–2016, before the concentration of copied months in 2019 and 2023. The analysis was coded in Python with NumPy, pandas, SciPy, statsmodels and GeoPandas. The index code follows the climdex.pcic definitions, and the trend code reproduced pymannkendall results on complete series. Figure 2 summarises the workflow.

4 Results

4.1 Data quality and station selection

The raw record contained repeated sequences and zero-filled months that cannot be genuine observations. Seven groups of identical calendar years occurred at six stations, including seven identical years (2001–2007) at Chittagong and five (1994–1998) at Hatiya. A further 81 station-months matched earlier months exactly. These month-level copies were concentrated in 2019 (62 months at 19 stations, mostly repeating 2017 or 2018) and 2023 (14 months at 9 stations, chiefly June 2023 repeating June 2022) (Fig. S1; Table S3). Eleven months at five stations were zero-filled, including seven months at Hatiya in 1990 and 1993.

Spatial screening removed two station-years: Faridpur 2020, whose July–September totals were three to four times the neighbour median, and Sandwip 2001 (6,135 mm against a neighbour mean of 3,217 mm). It also removed five isolated daily values. In total, 2.4% of station-days were set to missing. Chittagong (27 valid years) and Hatiya (28) failed the completeness criterion. The other 29 stations had 31–35 valid years, and 96.2% of their station-years were valid.

All 29 series of annual totals were classed useful by the absolute homogeneity tests. The relative tests classed Chandpur and Patuakhali as suspect for annual totals, and Cox's Bazar, Kutubdia and Maijdee Court as suspect for wet-day counts (Table S1).

4.2 Spatial pattern of rainfall extremes

Rainfall extremes followed the mean climate (Figs. 1 and 3). The western stations (Rajshahi, Ishurdi, Jessore and Satkhira) were among the least intense (SDII 14–15 mm day^{-1}) and had the fewest R50 days (5–7 per year) and the smallest RX1day (105–118 mm). The southeast coast and the northeast were the wettest. Teknaf averaged 34 mm per wet day, 30 R50 days and an RX5day of 575 mm, and Sylhet had the longest wet spells (CWD 27 days). CDD was long everywhere (70–100 days). It was longest at Teknaf and shortest at Jessore and at the northeastern stations of Srimangal and Sylhet, where pre-monsoon rain supplies 26–30% of the annual total. Rain on days above the 95th percentile supplied 22–28% of the annual total. Interannual variability of annual totals was modest (coefficient of variation 14–24%), whereas the coefficient of variation of winter totals was 83–157% (Table S4; Fig. S2).

4.3 Station trends

CDD had a positive Mann–Kendall statistic at all 29 stations, whereas the other indices showed no coherent direction of change (Table 2; Fig. 4). The CDD increases (Fig. 4h) had a median slope of 8.0% per decade (6.9 days per decade) and a maximum of 22.3% per decade, but the increase was individually significant only at Patuakhali and Sitakunda. The longest dry spell ended between December and March in 88% of station-years. Winter rainfall

declined at all 28 stations with enough valid winters (median − 13.6% per decade), significantly at Patuakhali and Rangpur (Figs. S3 and S4).

Most other indices leaned towards drier conditions without a coherent signal. Annual totals declined at 22 of 29 stations (median − 68 mm, or − 2.8%, per decade), but the decline was significant only at Maijdee Court. R10 and R20 declined at 22 and 20 stations, pre-monsoon totals at 21 (three significant) and monsoon totals at 19 (two significant, Dinajpur and Rajshahi in the northwest). The intensity indices had no preferred direction: SDII increased at 16 stations and decreased at 12, RX1day at 15 and 14, and RX5day at 13 and 16, with a few significant trends of both signs (Fig. 4b, f, g). CWD showed no consistent change (Fig. S4).

Only 25 of 434 station–index tests (5.8%) were significant at $P < 0.05$, against 22 expected by chance. One trend passed the FDR criterion: an increase in R99p at Chandpur (48% per decade), a station whose annual totals failed the relative homogeneity tests.

Table 2
Summary of station and regional trends, 1989–2023

Index	Unit	Mean	Inc. (sig.)	Dec. (sig.)	Slope (yr^{-1})	% $dec.^{-1}$	Regional, SD $dec.^{-1}$ (95% CI)	Regional P	Field P (count)	Field P (Kendall)
PRCPTOT	mm	2150	7 (0)	22 (1)	−6.78	−2.8	−0.18 (−0.44, +0.08)	0.146	0.520	0.331
SDII	mm day^{-1}	17.9	16 (0)	12 (1)	0.004	0.2	−0.05 (−0.23, +0.18)	0.678	0.623	0.926
R10	days	57.4	7 (0)	22 (2)	−0.125	−2.7	−0.22 (−0.46, +0.08)	0.091	0.281	0.221
R20	days	34.6	9 (0)	20 (1)	−0.056	−1.4	−0.18 (−0.43, +0.11)	0.192	0.563	0.382
R50	days	9.9	10 (0)	19 (0)	0.000	0.0	−0.11 (−0.31, +0.09)	0.328	1.000	0.594
R95p	mm	577	10 (1)	19 (1)	−1.20	−2.7	−0.09 (−0.26, +0.11)	0.343	0.357	0.676
R99p	mm	188	19 (1)	9 (1)	0.00	0.0	−0.01 (−0.12, +0.17)	0.906	0.352	0.439
RX1day	mm	148	15 (3)	14 (1)	0.11	0.8	+ 0.03 (−0.07, +0.16)	0.635	0.047	0.323
RX5day	mm	271	13 (1)	16 (0)	−0.24	−1.2	+ 0.00 (−0.13, +0.17)	0.976	0.686	0.702
CDD	days	78.1	29 (2)	0 (0)	0.69	8.0	+ 0.27 (+0.02, +0.50)	0.041	0.254	0.099
CWD	days	14.2	12 (1)	16 (0)	0.000	0.0	+ 0.00 (−0.16, +0.13)	0.976	0.667	0.748
Winter	mm	39	0 (0)	28 (2)	−0.57	−13.6	−0.22 (−0.43, +0.07)	0.131	0.205	0.107

Mean: median across stations of the station mean. Inc./Dec.: number of stations with positive/negative Mann–Kendall statistics, with the number significant at $P < 0.05$ in parentheses (winter: 28 stations with ≥ 30 valid seasons). Slope: median station Theil–Sen slope in index units per year; % $dec.^{-1}$: median slope as a percentage of the station mean per decade. Regional: Theil–Sen slope of the regional standardised anomaly series in SD per decade with 95% confidence interval. Field P: permutation P for the number of locally significant stations (count) and for the regional mean Kendall statistic (Kendall). One station trend (R99p, Chandpur) passed the false discovery rate criterion

Index	Unit	Mean	Inc. (sig.)	Dec. (sig.)	Slope (yr^{-1})	% $dec.^{-1}$	Regional, SD $dec.^{-1}$ (95% CI)	Regional P	Field P (count)	Field P (Kendall)
Pre-monsoon	mm	402	8 (0)	21 (3)	−2.40	−6.6	−0.13 (−0.36, +0.11)	0.280	0.173	0.387
Monsoon	mm	1428	10 (0)	19 (2)	−2.64	−1.3	−0.09 (−0.34, +0.15)	0.495	0.284	0.603
Post-monsoon	mm	216	12 (0)	16 (1)	−0.32	−1.4	−0.07 (−0.26, +0.19)	0.553	0.460	0.792

Mean: median across stations of the station mean. Inc./Dec.: number of stations with positive/negative Mann–Kendall statistics, with the number significant at $P < 0.05$ in parentheses (winter: 28 stations with ≥ 30 valid seasons). Slope: median station Theil–Sen slope in index units per year; % $dec.^{-1}$: median slope as a percentage of the station mean per decade. Regional: Theil–Sen slope of the regional standardised anomaly series in SD per decade with 95% confidence interval. Field P: permutation P for the number of locally significant stations (count) and for the regional mean Kendall statistic (Kendall). One station trend (R99p, Chandpur) passed the false discovery rate criterion

4.4 Regional signal and field significance

No index had a field-significant regional trend by the regional mean Kendall statistic (Table 2). The regional CDD series increased by 0.27 standard deviations (SD) per decade (95% confidence interval 0.02 to 0.50; P = 0.041), but the regional mean Kendall statistic did not exceed its permutation distribution at the 5% level (P = 0.099). The mean inter-station correlation of annual CDD was 0.56. Regional annual totals (− 0.18 SD per decade, 95% confidence interval − 0.44 to + 0.08; P = 0.146), R20 (− 0.18 SD per decade, − 0.43 to + 0.11; P = 0.192) and winter rainfall (− 0.22 SD per decade, − 0.43 to + 0.07; P = 0.131) declined without reaching significance. Regional SDII, RX1day, RX5day and R99p changed by no more than 0.05 SD per decade in either direction, and their upper 95% confidence limits were at most + 0.18 SD per decade (Fig. 5). The count of stations with significant RX1day trends was field significant (P = 0.047), but the four trends were of mixed sign (three increases and one decrease), and the regional mean statistic was not significant (P = 0.323).

4.5 Robustness

Under all three alternative quality-control and station sets, CDD increased at 23–29 stations with no decreases, and regional P ranged from 0.035 to 0.077. The signal was least significant with the strict duplicate rule (Table S5). For 1989–2016, CDD increased at 27 of 29 stations (regional P = 0.072), and winter rainfall declined at all 28 stations, six of them significantly, with a significant regional decline of 0.38 SD per decade (P = 0.024). The significance class of station trends changed in 2.2% of cases under the strict duplicate rule, in 0.5% without spatial screening and in none when the relative-suspect stations were excluded. Applying the Hamed–Rao correction without restriction would have made regional CDD (P < 0.001), annual totals (P = 0.018) and R20 (P = 0.023) significant. Because these results depend on correction factors below one, they are not interpreted further (Table S6).

5 Discussion

Across 29 stations and 35 years we find no detectable intensification of rainfall extremes in Bangladesh. Regional trends in intensity and in extreme 1-day and 5-day totals are close to zero with narrow confidence intervals, and the declines in annual totals and heavy-rain days seen at most stations do not rise above interannual variability. The only

change shared by the whole network is a longer dry-season dry spell, together with lower winter rainfall, and neither is field significant.

5.1 Longer dry-season dry spells

The CDD tendency agrees with increases at all 28 stations analysed for 1987–2017 (Ezaz et al. 2022), with longer dry-season dry spells and lower dry-season rainfall for 1980–2014 (Mainuddin et al. 2022) and with drier winters over 1966–2015 (Mullick et al. 2019). It contrasts with shorter dry spells reported for 1958–2007 (Shahid 2011) and 1980–2017 (Islam et al. 2024). Period explains part of the difference, and computation explains more. Counting CDD within calendar years splits the dry season at 31 December and changes 84% of the station-year values in our data, so studies that do not state this choice cannot be compared directly. Because the longest dry spell almost always ends between December and March, CDD tracks winter and early pre-monsoon rainfall and says little about monsoon breaks.

Winter rain is less than 2% of the annual total and matters little for the annual water balance. If the tendency of about a week per decade persists, however, it would matter for dry-season rice and irrigation demand, particularly in the drought-prone northwest (Mainuddin et al. 2022). The evidence for it should be read with care. Agreement in sign at every station carried less weight than it seems, because annual CDD is strongly correlated between stations (mean correlation 0.56) and the 29 stations therefore do not provide 29 independent pieces of evidence. The permutation test, which preserves that correlation, did not reject the null hypothesis of no regional trend.

5.2 No regional intensification of extremes

The absence of intensification contrasts with global and South Asian evidence for heavier extremes (Westra et al. 2013; Dunn et al. 2020; Seneviratne et al. 2021) and with the rise of widespread extreme events over central India (Goswami et al. 2006; Roxy et al. 2017). It is consistent with declining extreme indices in northeast Bangladesh (Basher et al. 2018), lower annual maxima at most stations (Das and Islam 2023), mostly non-significant changes in national totals (Khan et al. 2019) and the mixed station trends across South Asia (Sheikh et al. 2015).

Low statistical power does not explain the regional result. Station maxima are nearly independent (mean inter-station correlation of RX1day 0.07), so the regional series averages out much of the local noise, and its trend of + 0.03 SD per decade (95% confidence interval − 0.07 to + 0.16) excludes a large regional increase. Individual stations, by contrast, have little power to detect changes of a few percent per decade in 35 years. Increases in intense moisture transport over Meghalaya and the coast (Fahad et al. 2024) may be expressed at scales finer than the gauge network, and a weakening monsoon over the Ganges–Brahmaputra basins (Roxy et al. 2015) would oppose thermodynamic intensification (Trenberth 2011).

5.3 Comparison with neighbouring regions

Bangladesh shares neither the increase in extremes reported for Nepal between 1976–1995 and 1996–2015 (Maharjan et al. 2023) nor the widespread decreases in total, intensity and frequency and the shorter dry spells reported for the northern highlands of Pakistan over 1990–2020 (Ghanim et al. 2023). It does share the tendency towards longer dry spells found in Nepal. The rainfall regimes differ, from a monsoon delta to mountain regions with stronger westerly influence, but the treatment of multiple tests also matters. In our network the share of locally significant trends was close to the chance level, and counts of significant stations alone would have overstated the evidence for change.

5.4 Data quality and implications for hazard assessment

Copied years repeat extreme events, and the zero-filled months at Hatiya would have produced dry spells of 109 and 154 days spanning the monsoon. The copies in 2019 and 2023 sit at the end of the record, where they have the greatest leverage on trends. Infilled values should be flagged in distributed records (Jahan et al. 2019) and screened out before trend analysis. For hazards, stable heavy-rain frequency at gauges does not imply lower flood risk, because river floods in Bangladesh are governed by flows from the wider Ganges–Brahmaputra–Meghna basins (Mirza 2002), and single extreme events continue to trigger landslides in the southeastern hills (Ahmed 2015).

5.5 Limitations

The main limitations are the modest station density, particularly in the hills, the absence of station histories, whole-millimetre recording near the wet-day threshold and the assumption that the first occurrence of each copied sequence is genuine. The sensitivity analyses indicate that these choices do not alter the conclusions on rainfall extremes, although they affect the strength of the CDD tendency.

6 Conclusions

Between 1989 and 2023, rainfall extremes in Bangladesh did not intensify detectably. Regional trends in rainfall intensity and in extreme 1-day and 5-day totals were close to zero, and declines in annual totals and heavy-rain days were not significant across the network. Trend statistics were positive for dry-season dry spells and negative for winter rainfall at every station, but neither change was field significant, and both are best treated as tendencies to monitor. Few station trends survive correction for multiple testing, and the national record contains infilled values that must be removed before trends are estimated. Statements about changing rainfall extremes in Bangladesh therefore need longer, better-documented records and explicit control of multiple testing.

Declarations

Competing interests

The authors have no relevant financial or non-financial interests to disclose.

Ethics approval

Not applicable. The study uses archived meteorological observations and involves no human participants or animals.

Consent to participate

Not applicable.

Consent for publication

Not applicable.

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Author Contribution

B.G. conceived the study, curated the data, carried out the formal analysis and wrote the original draft of the manuscript. A.K.D. developed the methodology, prepared all figures (Figs. 1–5 and Supplementary Figs. S1–S4), and reviewed and edited the manuscript. S.S. supervised the study and reviewed and edited the manuscript. All authors reviewed and approved the final manuscript.

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Data availability

The daily station rainfall data used in this study were obtained from the Bangladesh Meteorological Department (BMD). The data are available from the corresponding author on request.

Code availability

The Python code used for quality control, index calculation and trend analysis is available from the corresponding author on reasonable request.

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Figures

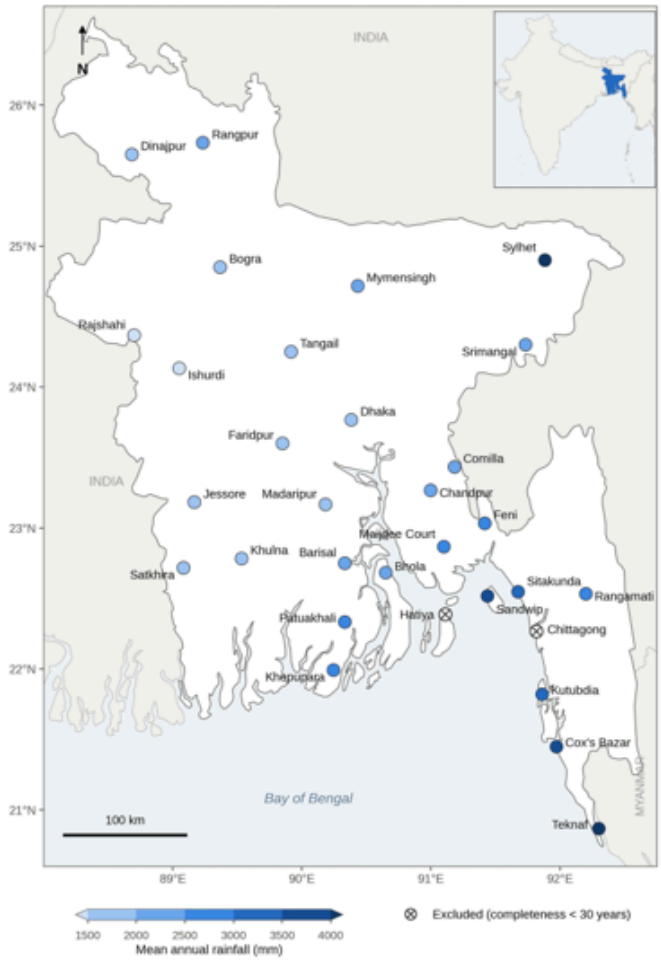


Figure 1

Study area and station network. Circles show the 31 Bangladesh Meteorological Department stations, shaded by mean annual rainfall for 1989–2023 at the 29 stations retained after quality control. Crossed circles mark the two stations excluded for incompleteness. The inset shows the location of Bangladesh

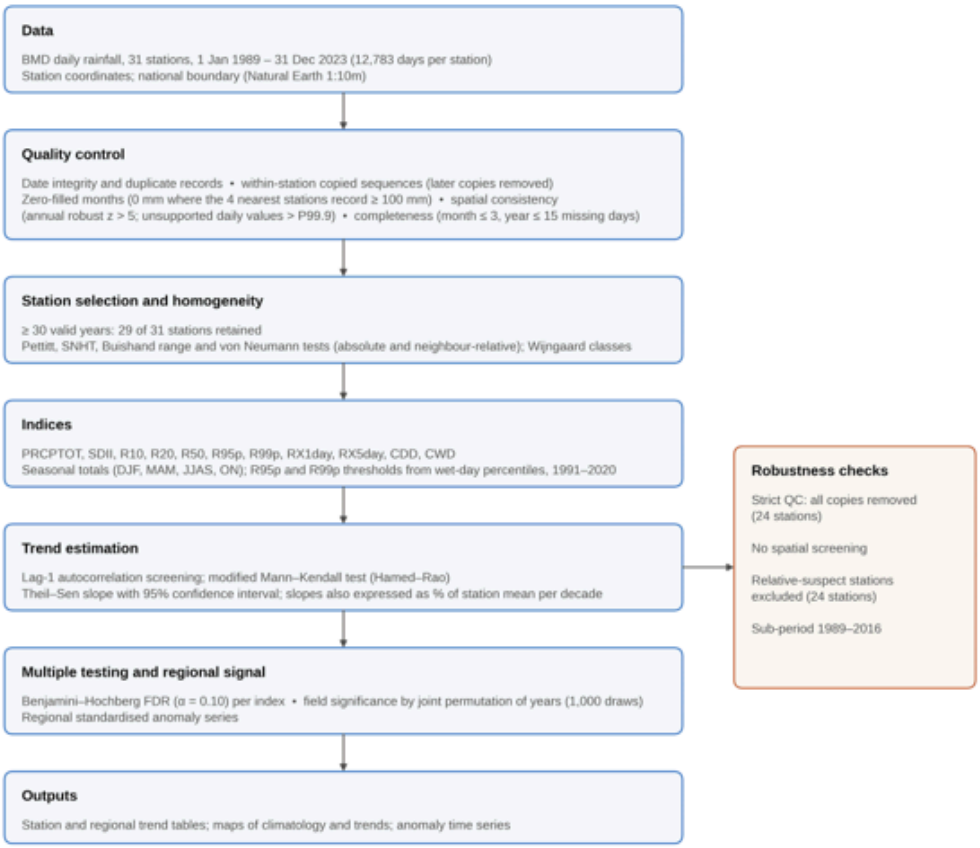


Figure 2

Analysis workflow, from the raw station records to the reported outputs. The box on the right lists the sensitivity analyses applied to the trend results

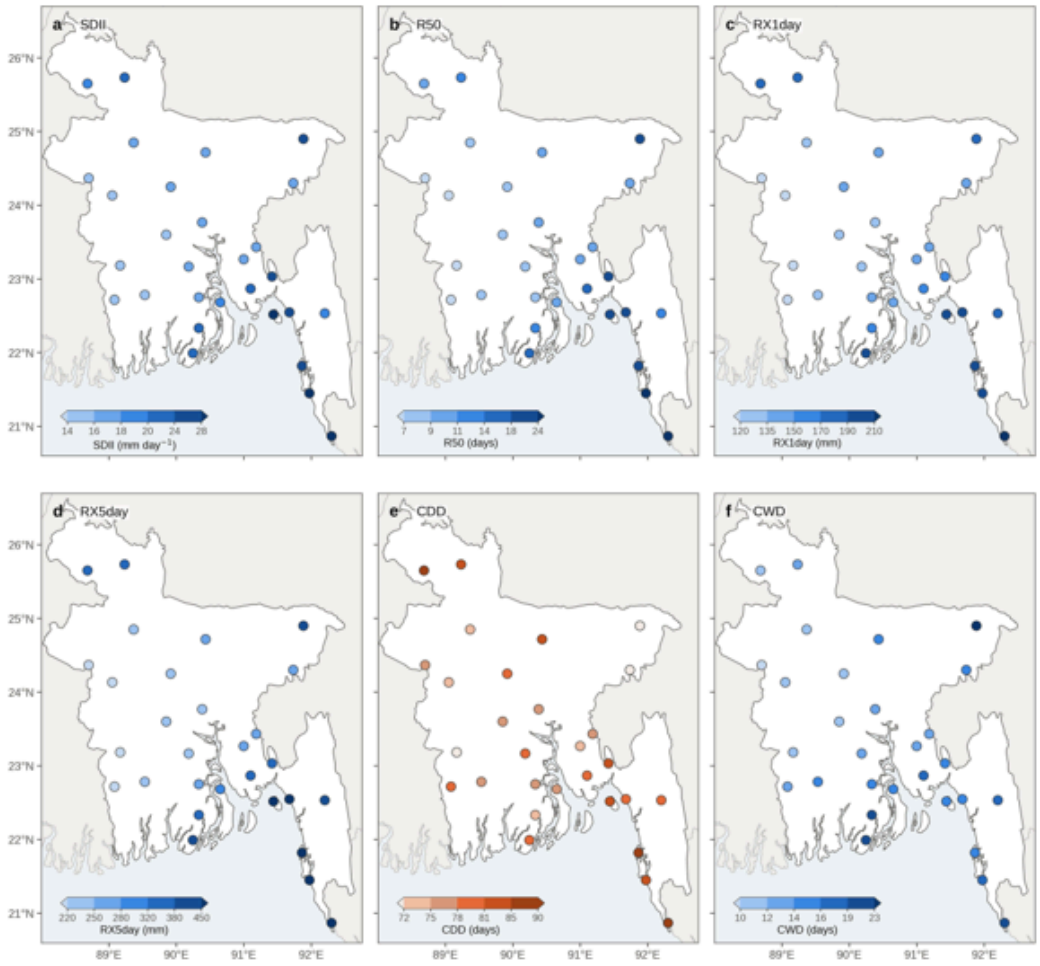


Figure 3

Mean rainfall extremes, 1989–2023: (a) SDII, (b) R50, (c) RX1day, (d) RX5day, (e) CDD and (f) CWD at the 29 retained stations

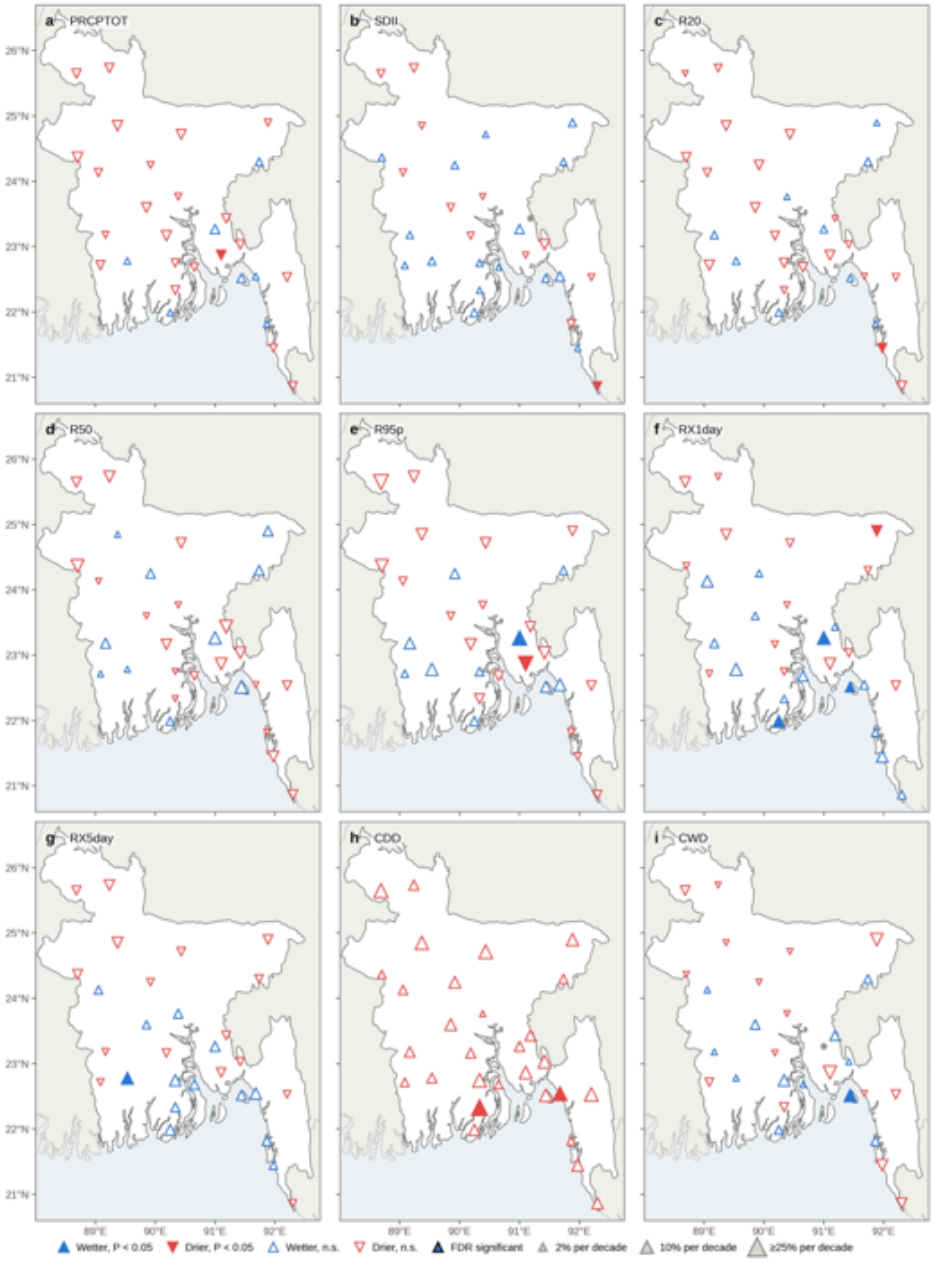


Figure 4

Station trends in annual rainfall indices, 1989–2023. Triangles point up for increases and down for decreases, and symbol size is the Theil–Sen slope as a percentage of the station mean per decade. Filled symbols are significant at $P < 0.05$ (modified Mann–Kendall test), and a black outline marks trends that pass the false discovery rate criterion. Colour gives the hydroclimatic sense of the change (blue wetter, red drier; for CDD an increase is drier). Grey dots mark stations with no change ($Z = 0$), and grey crosses mark excluded stations

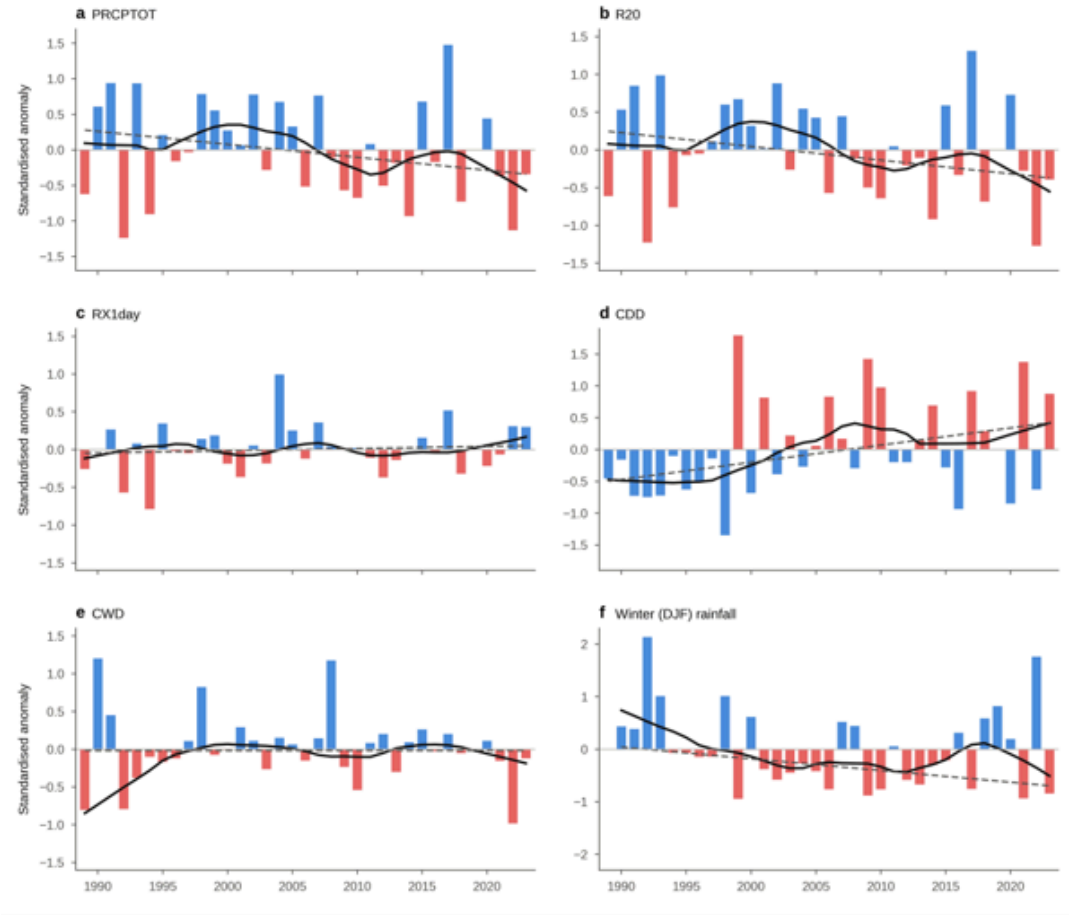


Figure 5

Regional standardised anomalies, 1989–2023. Bars show the mean of station standardised anomalies of (a) PRCPTOT, (b) R20, (c) RX1day, (d) CDD, (e) CWD and (f) winter rainfall; blue indicates wetter and red drier than average. Black curves are LOWESS fits (span 0.35), and dashed lines are Theil–Sen trends. Trend magnitudes and P values are given in Table 2. In (a)–(e), 2019 is omitted because only 12 of 29 stations had a valid year; the winter series (f) begins in 1990

Supplementary Files

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