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Long-term spatio-temporal variability and trends in rainfall and temperature extremes and their potential risk to rice production in Bangladesh

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Abstract

Understanding the historical and future spatio-temporal changes in climate extremes and their potential risk to rice production is crucial for achieving food security in Bangladesh. This paper presents results from a study on trend analysis for 13 climate metrics that significantly influence rice production. The analysis was conducted using the non-parametric Mann-Kendall test and the Theil-Sen slope estimator methods. The study included data from all available weather stations in Bangladesh and the assessment was done for both the wet (May to October) and dry (November to April) seasons, which cover the growing seasons of the country's three types of rice: Aus, Aman and Boro. Results show significant decreasing trends for wet season rainfall (>12 mm/season/year in some stations) in the central and north regions. In addition, dry season rainfall is decreasing significantly in many areas, whilst dry season dry spells are increasing throughout Bangladesh. Decrease in rainfall in some of these areas are of concern because of its impacts on rainfed Aus rice and in the sowing/planting of rainfed Aman rice and irrigated dry season Boro rice. The maximum temperatures in the wet season are increasing throughout the country at 0.5˚C every ten years, significantly at most of the climate stations. The analysis shows that the number of days with temperature >36˚C has significantly increased in 18 stations over the last three decades, which implies a serious risk to Aman rice yield. The current maximum temperatures (both in the wet and dry seasons) are higher than the optimum temperature ranges for rice production, and this will have likely adverse effects on yield in the face of climate change with increasing temperatures. The results herein have practical implications for planning appropriate adaptation policies to ensure food security in the country.

related to overseas activities are considered as Australian Aid. All authors worked in this project. So it is not only me though I lead the project.

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Introduction

Climate variables like rainfall, temperature, solar radiation, wind speed and humidity have key impacts on agriculture [1–4]. Extreme variability in rainfall and temperature regimes often stress agricultural systems in many regions worldwide [5–7]. For example, agricultural production in India on a year-to-year basis has been strongly linked to monsoonal rainfall characteristics [8–10] and El-Niño Southern Oscillation ENSO [11]. Bangladesh, a predominantly agricultural country, has a monsoonal climate with an intense wet season associated with almost regular flooding [12, 13], and a dry season in which crop production relies on groundwater feed irrigation. Currently, about 79% of irrigation water comes from groundwater [14].

Bangladesh produces about 34.7 million metric tons of rice annually (4th largest in the world), with almost 80% of the total cropped area (11.7 million ha) planted with rice [15]. Rice accounts for 91% of the total food grain production [16] and 60% of the total agricultural output [17]. Regardless of technological advancements like improved crop varieties and irrigation methods that have made the country almost food secure [18], climatic factors still add uncertainty in agricultural productivity [18, 19]. Inter-annual and intra-seasonal features of the monsoon predominantly control crop production both during the wet May to October and dry November to April seasons [20, 21].Climate variability has been identified as a major cause of changes in crop yield in the country, while increasing temperature and changing rainfall patterns have a deleterious impact on crop production [22]. In recent decades, expansion of groundwater irrigation for dry season crops, particularly Boro rice, has led to concerns of declining groundwater depth in some parts of the country, especially in the northwest region [19, 23]. The groundwater tables are declining due to a combination of factors, which, aside from extraction of groundwater, also depend on climate characteristics like declining rainfall [16, 24]. The declining rainfall reduces infiltration to groundwater [25] and runoff supply to wetlands and seasonally flooded areas [24], which reduce recharge to the underlying aquifers, resulting in a decline in groundwater tables.

Studies of historical temperature trends in Bangladesh reveal continuously increasing temperature across the country (Table 1); the increase in annual temperature is generally true for different metrics, such as the average, maximum and minimum temperatures, and also for different hydro-climatic seasons in a year. In contrast, findings on rainfall trends are mixed, some studies show increasing trends [26], some show decreasing trends [23, 24] and some show no significant trends [27] in rainfall over the past several decades (Table 1).

However, most studies agree that rainfall has increased in the south [26, 30], and possibly also in the north [28, 36], but decreased in central areas [34]. It is important to note that some differences between studies may have been because of differences in the extents of the periods and areas studied and the inherent variability in the rainfall data.

Crop production is partly controlled by rainfall and temperature and partly by non-climatic factors, such as areas of irrigated crops, development of new crop varieties, crop prices, access to markets and labour among others. Many studies [e.g., 38–43] have assessed the impacts of climate variability on rice production in Bangladesh. It is important to note that previous studies have focused either on the yield of Boro rice, or their assessment was regardless of the country's representative climatic characteristics [44]. For example, although Aman rice has the largest acreage (48.4%) with a production of 38% rice grain [45], studies on impacts of climate variability for Aman yield have been limited [43].

This study focused on assessing the inter-seasonal changes in rainfall and temperature. Unlike previous studies that evaluated changes in mean climate metrics or extremes, our focus is on climate metrics with potential impacts on rice production, both temporally and spatially. Historical trends in rainfall and temperature and the associated agriculturally relevant metrics

Table 1. List of studies assessing rainfall and temperature trends in Bangladesh. The studies are grouped by geographic domain.

Study area	Data period	Main findings	Reference
Western Bangladesh	1961–2011	Non-significant rainfall increases in most stations, but significant increases at three stations in the northwest.	Rahman et al. [28]
		Temperature increases in most stations.	
Northern Bangladesh	1964–2013	Non-significant rainfall decreases except in Rajshahi with significant decrease.	Bari et al. [27]
Northwest Bangladesh	1984–2014	Significant rainfall decreases up to 26%.	Dey et al. [24]
Northwest Bangladesh (Barind area)	1980–2006	Rainfall increases in southern Barind.	Jahan et al. [29]
		Rainfall decreases in northern Barind.	
Northwest Bangladesh	1985–2015	Rainfall decreases at a rate of 9.2 mm/year.	Mojid et al. [23]
Southwest coastal area	1948–2010	Rainfall increases both in magnitude and number of rainy days.	Mondal et al. [26]
		Temperature increases.	
Southwest coastal area	1948–2007	Rainfall increases.	Hossain et al. [30]
Southeast Bangladesh	1980–2013	There is no change in rainfall trends.	Raihan et al. [31]
		Temperature increases.	
Whole of Bangladesh	1966–2015	Rainfall increases/decreases during the wet/dry season.	Mullick et al. [32]
		Temperature increases/decreases during the wet/dry season.	
Whole of Bangladesh	1958–2007	Annual and pre-monsoon rainfall increases. Number of wet months increases.	Shahid [33]
Whole of Bangladesh	1969–2003	Rainfall increases in coastal zone and northwest Bangladesh but decreases in central regions.	Shahid and Khairulmaini [34]
Whole of Bangladesh	1954–2013	Non-significant trend in rainfall, with rainfall increases in coastal regions and decreases in northeast.	Rahman et al. [2]
Whole of Bangladesh	1975–2014	Rainfall decreases and shifts to post-monsoon.	Hossain et al. [35]
Whole of Bangladesh	1958–2007	Rainfall increases in the north.	Shahid et al. [36]
		Temperature increases.	
Whole of Bangladesh	1961–2008	Temperature increases in the southeast but decreases in the north.	Shahid et al. [37]

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are assessed for two cropping seasons: May to October and November to April, representing wet and dry season crops respectively. Dry season covers the cultivation period of Boro rice and wet season covers the cultivation period of Aus and Aman rice. We qualitatively link the trends in the derived climate metrics to discuss known risk to rice production based on the literature, and similarly remark on the likely impacts of climate change. In achieving these objectives, this study seeks to inform the debate on the impacts of likely climate change on rice production in Bangladesh.

Materials and methods

Study area

Bangladesh is about 147,500 km^2 and is bounded by India in the west, north and east and the Bay of Bengal in the south (Fig 1). The country is located overlying the delta of three large rivers of south Asia: the Padma (name of the Ganges in Bangladesh), Jamuna (name of the Brahmaputra in Bangladesh) and Meghna (name of the Meghna upstream and after the confluence with the Padma and Jamuna rivers). The topography of the country is relatively flat, except for the hilly north- and southeast, and gently rolling northeast and northwest [46]. The country is divided into eight administrative regions known as divisions: Barisal, Chittagong, Dhaka, Khulna, Mymensingh, Rajshahi, Rangpur and Sylhet (Fig 1).

The climate of Bangladesh is characterized by four hydro-climatic seasons. These include: dry winter from December to February, hot summer from March to May, monsoon from June

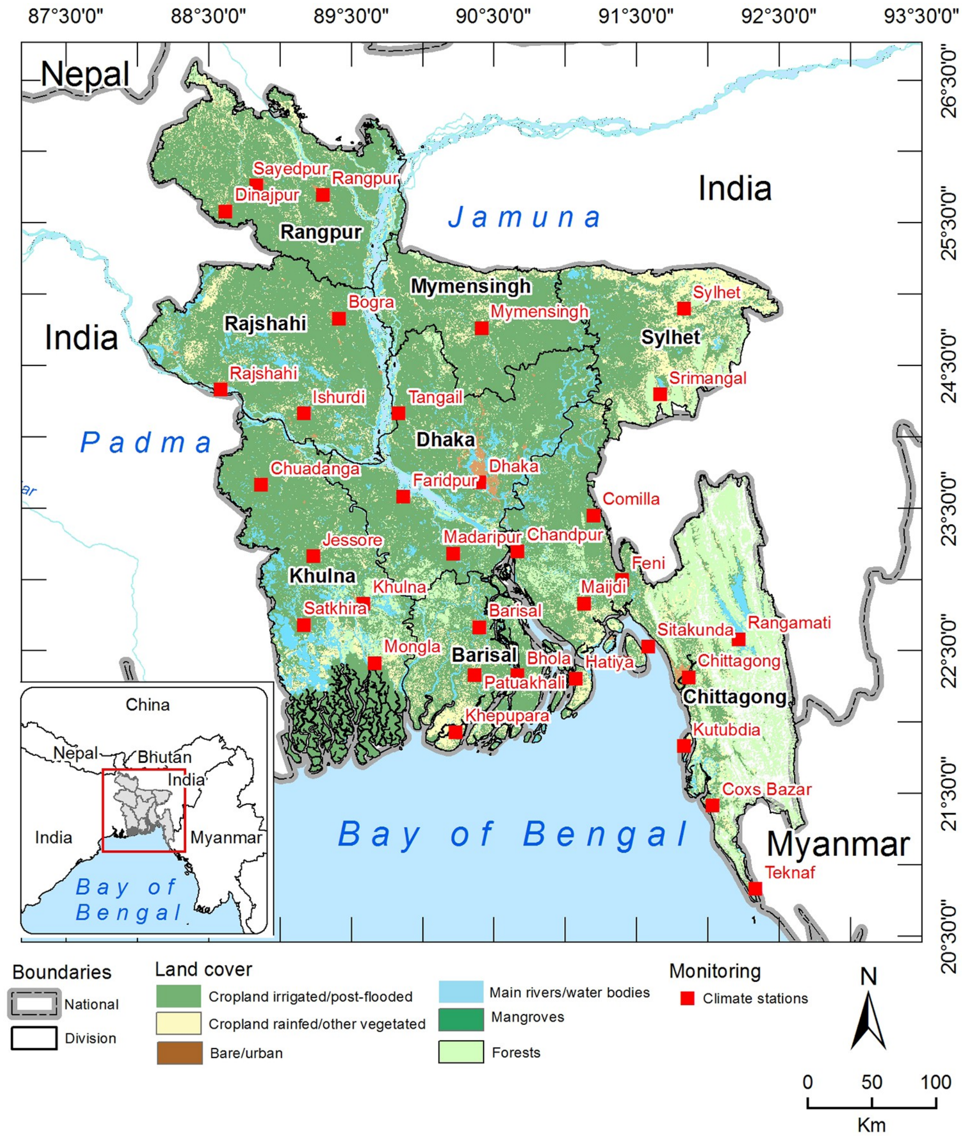

Fig 1. Divisional administrative boundary (black bold font), land cover and location of the 34 climate stations in Bangladesh (red bold font). Source of administrative boundary shapefile: https://data.humdata.org/dataset/administrative-boundaries-of-bangladesh-as-of-2015.

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to September, and autumn in October and November [28, 47]. During the winter months, the mean temperature of the country varies from 18˚C to 21˚C, and during the summer months the mean temperature varies from 27˚C to 29˚C. Winter is characterized by relatively cool and sunny days followed by cool nights. January is the coldest month in Bangladesh, and the country's northern districts (e.g., Rangpur; Fig 1) experience the lowest temperatures. Winter temperatures are higher in the central areas (e.g., Dhaka) than in the northern areas, with much higher temperatures along the southern coastal areas due to the influence of the Bay of Bengal. A southerly wind is prominent during winter, and very often brings cool temperatures in the north (3–6˚C), central and central-south areas (8–10˚C). In February, the temperature rises and continues rising during March to May. The temperature in March to May varies from 30 to 35˚C [31, 47].

The monsoon season, characterised with frequent rains, starts between late May and early June and ends in late September or early October, with July being the peak monsoon month. In some years, it continues until November, especially in the south-eastern region of the country. The north-eastern part of the country receives the highest annual rainfall (up to 4200 mm) and the western part receives the lowest rainfall (about 1500 mm). The rainfall in Bangladesh is seasonal, with 72% of the total annual rainfall occurring during the monsoon period [27, 33, 35].

Bangladesh is predominantly an agricultural country, characterized by rice paddy agriculture-dominated landscapes. About 21% of the national Gross Domestic Product comes from agriculture [45, 48]. Rice dominates the major share (60%) of crop production [17]. There are three main rice crops in Bangladesh, two of them (Aus and Aman) are predominantly rainfed, and Boro rice, grown in the dry season requires irrigation. Aus is grown from March to July, Aman from July to November and Boro from December to May. Boro rice occupies about 59% of net cultivable area in the dry season and it contributes about 55% of the total rice production in Bangladesh [49, 50]. Aman rice occupies 69% of the net cultivable area in the wet season and produces 38% of total rice. The contribution of Aus rice to total rice production is relatively small at only about 7% [50].

Historical data

The Bangladesh Meteorological Department (BMD) is the main source of climate data in Bangladesh. This study used daily rainfall and temperature data from 34 climate stations managed by the BMD. The stations are spatially well-distributed across the country, with at least one station in each of the eight divisional units of the country (Fig 1). Out of 34 climate stations, 10 stations have been operational since 1948, 20 stations were progressively added to the BMD's network before 1980, while four stations were added to the network after 1980. So, considering continuity of the data and reliability of measurements, data from 1980 to 2014 were included in this study. Only the years having with at least 350 days with data were included in the analysis. The length of data in the final data set that were used for analysis, varies from 23 to 34 years between the stations. While longer the time series can capture variability better, data length of more than 20 years is considered sufficient for trend analysis in hydrological variables [51]. Fig 2 depicts the data period for each of the 34 climate stations with a demarcation for the duration of missing data. The mean, maximum and minimum data periods are 32, 34 and 23 years (at Mongla climate station), respectively over the assessment period.

The consistency of rainfall data was tested using double-mass analysis [52]. A detailed description and results of this analysis can be found in the (S1 Text), which shows that the double-mass curves in most climate stations essentially follow the same linear relationship throughout the study period ($r^2 > 0.99$), and thus are considered consistent and suitable for the analyses done herein. There was a notable exception, the insular station at Sandwip, which was impacted by cyclonic activity in 1999, had some daily rainfall totals exceeding 400 mm/day [53]. Besides these quality-control procedures, no other pre-processing was implemented as the rainfall and temperature data in Bangladesh largely show no serial autocorrelation as demonstrated by the recent work of Mullick et al. [32] for the 34 climate stations used in this study. The absence of serial correlation was confirmed by calculating the autocorrelations up to lag 10 (i.e., ten seasons) and plotting the sample autocorrelation function (ACF) for each metric (see next section) including bands for rejection testing each autocorrelation = 0 under the assumption of white noise. These are reported in the (S2 Text). Therefore, in any case, attempts to correct the data can result in degradation of the results of trend tests [54].

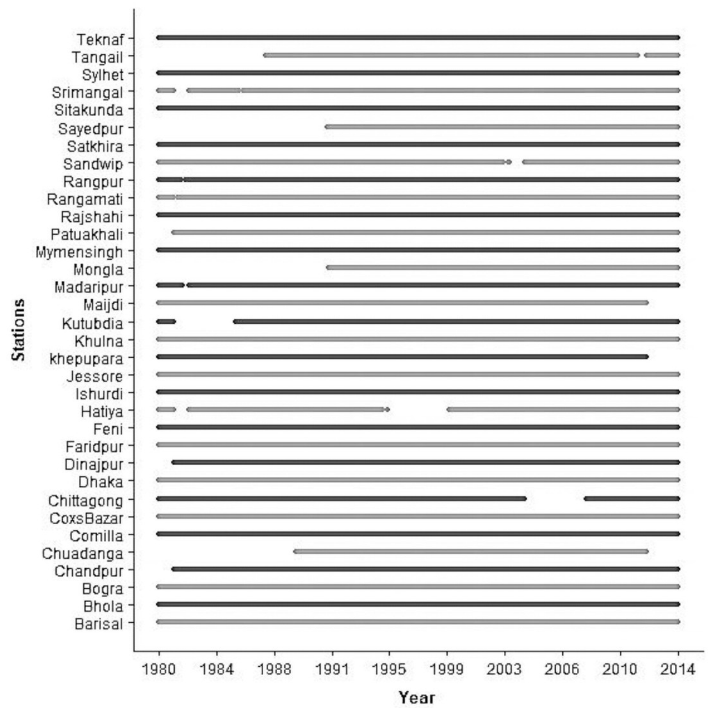

Fig 2. Data availability (black and grey bars) and gaps for the 34 climate stations across eight administrative divisions in Bangladesh.

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Seasonal climate metrics linked to crop production

Two cropping seasons (wet and dry) were considered here, these cover the main developmental stages for Aman and Boro and aggregate the four hydro-climatic seasons in wet and dry. Wet season crops (e.g., Aus and Aman rice) largely depend on the characteristics of the monsoon [55–57]. Changes in rainfall can have either positive or negative impacts on crop yield depending on timing, location and duration of the monsoon. The starting of monsoon determines the sowing/transplanting period of Aus and Aman rice. Any delay in transplanting from the optimum period reduces yield and exposes the crop, particularly Aman rice, to a period with lower rainfall, thus requiring supplementary irrigation [41, 56, 57]. Low rainfall and/or a long period with no rainfall during the wet season adversely affects the yield of both Aus and Aman rice [58, 59], and the impact is mostly statistically significant [41]. Also, extreme rainfall and floods, quite often encountered, can drastically reduce Aman rice yield [60, 61].

Boro rice is largely irrigated and sensitive to changes in temperature [62]. Rice for example, has an optimum temperature around 25˚C, minimum temperature limits around 10–12˚C and maximum temperature limits around 36–38˚C [5]. The optimum temperature range is crucially important for proper growth and development of the rice plants. A decrease or increase in temperature from the optimum limit will reduce crop yield [63].

Daily rainfall and temperature data were aggregated for the two cropping seasons described above: (i) May to October, which captures the growing season of Aus and Aman rice, and (ii) November to April, which captures the growing season of Boro rice. For each season, several climate metrics linked to agricultural production [64] were derived from the daily data. The

Table 2. List of climate metrics (linked to agricultural production) used for trend analyses in this study. The subscript 'wet' pertains to the wet season (May to October), the subscript 'dry' pertains to the dry season (November to April).

Variable name	Explanation of variable	Unit	Calculation method	Purpose
$RSEA_{wet,dry}$	Seasonal total rainfall	mm/ season	Seasonally per year, total rainfall in the period	Trend of seasonal rainfall
$RCDD_{wet,dry}$	Maximum number of consecutive dry days when daily precipitation goes below 1 mm	days/ season	Seasonally per year, longest spell of dry days (rainfall <1 mm) in the period	Trend of dry conditions
$RCWD_{wet,dry}$	Maximum number of consecutive wet days when daily precipitation goes above 1 mm	days/ season	Seasonally per year, longest spell of wet days (rainfall >1 mm) between all wet spells in the period	Trend of wet conditions
$RFDD10_{wet}$	Number of spells of consecutive 10 or more dry days when daily precipitation goes below 1 mm	spells/ season	Seasonally per year, number of spells of consecutive 10 or more dry days per period	
$Tmax_{wet,dry}$	Mean of daily maximum temperature	˚C/ season	Seasonally per year, mean value for daily maximum temperature in the period	Trend of maximum seasonal temperature
$Tmin_{wet,dry}$	Mean of daily minimum temperature	˚C/ season	Seasonally per year, mean value for daily minimum temperature in the period	Trend of minimum seasonal temperature
$T36_{wet,dry}$	Number of days with temperature >36˚C	days/ season	Seasonally per year, total number of days in a season where temperature is >36˚C	Trend of days above maximum temperature limits for rice
$T12_{dry}{}^{*}$	Number of days with temperature <12˚C	days/ season	Seasonally per year, total number of days in a year temperature <12˚C in the period	Trend of days below minimum temperature limits for rice

*T12wet is not considered as the temperature will rarely vary below 12˚C during May to October.

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climate metrics, based on rainfall and temperature characteristics, are described in Table 2 with their likely impacts on seasonal crop development and production.

Variability and trend assessment

The coefficients of variation (CV, the ratio of standard deviation to the mean, here expressed as a percentage) computed for 1980 to 2014 at the 34 climate stations were used to assess the temporal variability in the derived rainfall and temperature metrics.

The non-parametric Mann-Kendall (MK) test [65] was adopted to examine the existence of trends in rainfall and temperature metrics for the 1980 to 2014 period. The MK test is widely used in hydrology and climatology because of its advantages over parametric methods; for example, it can deal with missing data in the series [66, 67], which is characteristic of the climate data used in this study. The MK test does not require any assumption of normality, and it is less sensitive to non-homogeneous time series. The test considers two assumptions (null and test hypotheses) while analysing the existence of a trend: (i) that the data is independent and identically distributed (i.e., no trend exists), and (ii) that the data follows a monotonic trend. The MK statistic is computed as:

$$MK = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sign\left(x_j - x_i\right) \quad (1)$$

where x is a climate variable, i varies from 1 to n-1 and j varies from i+1 to n. Each of the data in x_i is taken as a reference point, which is compared with the rest of the data points in x_j by satisfying the condition:

$$sign\left(x_j - x_i\right) = \begin{cases} 1 & if \quad x_j - x_i > 0 \\ 0 & if \quad x_j - x_i = 0 \\ -1 & if \quad x_j - x_i < 0 \end{cases} \quad (2)$$

if $n \geq 10$, the statistic MK is approximately normally distributed with the mean of 0 and standard deviation of σ^2. The significance in the trend (Z_s) is calculated as:

$$Z_s = \begin{cases} \dfrac{MK - 1}{\sigma} & for\ MK > 0 \\ 0\ for\ MK = 0 \\ \dfrac{MK + 1}{\sigma} & for\ MK < 0 \end{cases} \tag{3}$$

A positive value of Z_s indicates upward (increasing) trend and a negative value indicates downward (decreasing) trend. A significance level α is also utilized for testing the upward and/or downward monotonic trend (a two-tailed test). For $|z_s| > {}^{z_\alpha}/_2$, the null hypothesis is rejected, and consequently, a significant trend in the variable is detected.

The Theil-Sen estimator, or Sen's slope estimator [68] was used to quantify the slopes of the linear trends in the rainfall and temperature metrics. The Sen's slope method is widely used in the analysis of climate data time-series and has been used in studies focusing on Bangladesh's climate [e.g., 32]. It is regarded as more robust than the least-squares estimator as it is insensitive to outliers and is more precise in the presence of skewed data [69]. The slope estimator S is the median over the pairs of points in the time series for all $i = 1$ to n

$$S = median\left(\frac{x_j - x_i}{j - i}\right) \tag{4}$$

where x_i and x_j are the data points with i varying from 1 to n-1 and j varying from i+1 to n.

Results

For brevity and clarity, the results reported here include 9 climate metrics that show a degree of spatial organisation and/or significant change ($p<0.1$) according to the MK test. The climate metrics are $RSEA_{wet}$, $RSEA_{dry}$, $RCDD_{dry}$, $Tmax_{wet}$, $Tmax_{dry}$, $Tmin_{wet}$, $Tmin_{dry}$, $T36_{wet}$ and $T12_{dry}$ (see Table 2). Tables 3 and 4 summarise the trend results of these climate matrices for eight administrative Divisions in Bangladesh. The remaining 5 climate metrics ($RCDD_{wet}$, $RCWD_{wet}$, $RCWD_{dry}$, $RFDD10_{wet}$ and $T36_{dry}$), are presented in the (S3 Text).

Variability and trends in rainfall metrics linked to rice production

The spatial and temporal variability and trends in the seasonal total rainfall in the wet season, $RSEA_{wet}$, at the 34 climate stations are illustrated in Fig 3. The mean $RSEA_{wet}$ is 2214 mm/sea (from 1323 mm/sea in Rajshahi to 4151 mm/sea in Teknaf), CV is 20% (from 12% in Teknaf to 28% in Chandpur), and S is 0.793 mm/sea/yr (from -14.889 mm/sea/yr in Mymensingh to 23.750 mm/sea/yr in Hatiya). $RSEA_{wet}$ is relatively high (>2000 mm/sea) at the climate stations located in the southeast and relatively low (<1900 mm/sea) at the climate stations located in the central and western areas of Bangladesh. The CV is relatively high (>19%) at the climate stations in the northwest and relatively low (<19%) at most of the climate stations in the coastal, southwest and northwest areas. Increasing trends in $RSEA_{wet}$ occur at the coastal and southwestern climate stations, while declining trends occur at the central and northern climate stations. There are 9 climate stations with significant ($p<0.1$) trends, with 4 declining (at the north, see Fig 3) and 5 increasing (at coastal areas, see Fig 3, Table 3).

Fig 4 shows the variability and trends in the seasonal total rainfall in the dry season, $RSEA_{dry}$, at the 34 climate stations.

The mean $RSEA_{dry}$ is 241 mm/sea (from 120 mm/sea in Dinajpur to 605 mm/sea in Sylhet), CV is 56% (from 35% in Sylhet to 75% in Sayedpur), and S is -5.33 mm/sea/yr (from

Table 3. Summary of trend results based on Mann-Kendall test and Sen's slope estimator for the 34 weather stations (arranged according to administrative division, in bold) for the wet season (May to October), ($p < 0.10$ = *, $p < 0.05$ = **, $p < 0.01$ = *,—sign indicates decreasing trend).**

Station	$RSEA_{wet}$	$Tmax_{wet}$	$Tmin_{wet}$	$T36_{wet}$
Rangpur				
Dinajpur	-10.408	0.037***	0.031***	0.067
Rangpur	-13.042*	0.033***	0.013***	0.059**
Sayedpur	-8.100	0.060***	0.023*	0.250
Rajshahi				
Bogra	-8.294	0.037***	0.024***	0.143**
Ishurdi	-5.455	0.039***	0.018***	0.353*
Rajshahi	-8.833*	0.038***	0.019***	0.428**
Khulna				
Chuadanga	-4.583	0.011	-0.009	0.226
Jessore	7.529	0.050***	0.014**	0.643***
Khulna	9.169	0.037***	0.016***	0.500***
Mongla	8.222	0.032***	0.011**	0.452***
Satkhira	2.265	0.006	0.022***	0.000
Mymensingh	-14.889*	0.020***	0.013**	0.000
Dhaka				
Dhaka	-5.077	0.027**	0.014**	0.045
Faridpur	-11.100	0.035***	0.016**	0.182**
Madaripur	-10.547*	0.006	0.023***	0.049
Tangail	-1.091	0.055***	0.007	0.400***
Barisal				
Barisal	-1.440	0.029***	0.024***	0.056***
Bhola	-8.833	0.014**	0.011**	0.000
Khepupara	15.879**	0.037***	0.015**	0.000
Patuakhali	-1.217	0.048***	0.010	0.146***
Sylhet				
Srimangal	-1.308	0.024**	0.003	-0.045
Sylhet	-9.857	0.045***	0.030***	0.143***
Chittagong				
Chandpur	-8.322	0.035***	0.010**	0.000***
Chittagong	9.793	0.006	0.024***	0.000
Comilla	-1.250	0.034***	0.017***	0.000
Cox Bazar	18.666*	0.050***	0.009*	0.000
Feni	-7.395	0.009*	0.017***	0.000
Hatiya	23.750**	0.019***	0.007	0.000
Kutubdia	17.900	0.025**	0.014*	0.000
Maijdi	-2.600	0.057***	0.027***	0.125***
Rangamati	6.350	0.043***	-0.008	0.059*
Sandwip	22.156**	0.057***	-0.005	0.000**
Sitakunda	7.283	0.053***	0.005	0.087***
Teknaf	21.623**	0.015**	0.026***	0.000

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-9.368 mm/sea/yr in Chittagong to 0.169 mm/sea/yr in Dinajpur). $RSEA_{dry}$ is relatively high (>200 mm/sea) at most of the climate stations located at the east and southeast areas (with the exception of Teknaf, station number 34 that is situated further south) and relatively low (<200 mm/sea) at the climate stations located at the west and northwest areas. The CV does not

Table 4. Summary of trend results based on Mann-Kendall test and Sen's slope estimator for the 34 weather stations (arranged according to administrative division, in bold) for the dry season (November to April) ($p < 0.10$ = *, $p < 0.05$ = **, $p < 0.01$ = *,—sign indicates decreasing trend).**

Station	$RSEA_{dry}$	$RCDD_{dry}$	$Tmax_{dry}$	$Tmin_{dry}$	$T12_{dry}$
Rangpur					
Dinajpur	0.169	0.623	-0.022*	0.039***	-0.429
Rangpur	-0.093	1.200**	-0.013	0.045***	-0.658***
Sayedpur	-2.154	0.857	0.011	0.026	0.155
Rajshahi					
Bogra	-2.042	1.429***	-0.009	0.029***	0.185
Ishurdi	-2.375**	0.654	-0.004	0.028**	0.000
Rajshahi	-1.722	1.080**	-0.013	0.022	0.057
Khulna					
Chuadanga	-3.000*	0.765	-0.028	-0.006	0.389
Jessore	-5.110**	0.705*	0.019	-0.009	0.333**
Khulna	-5.652***	0.763	0.010	0.055***	-0.483***
Mongla	-7.125*	0.467	0.030	-0.001	0.444**
Satkhira	-3.121*	1.057*	-0.035*	0.020**	-0.045
Mymensingh	-1.739	0.748	-0.019*	0.017	-0.220
Dhaka					
Dhaka	-6.447***	1.118***	-0.004	0.040***	-0.051
Faridpur	-7.816***	1.134**	0.012	0.021**	0.200
Madaripur	-5.932**	0.924	-0.009	0.031**	-0.100
Tangail	-7.071***	1.690**	0.007	0.006	0.286
Barisal					
Barisal	-3.975*	0.511	0.020*	0.025**	-0.143
Bhola	-6.857***	0.617	0.003	0.010	0.208
Khepupara	-4.775*	0.659	0.032**	0.000	0.036***
Patuakhali	-6.878***	1.419**	0.039***	-0.018**	0.500***
Sylhet					
Srimangal	-9.258**	1.127*	0.014	-0.009	0.121
Sylhet	-4.867	1.000**	0.045***	0.049***	-0.176
Chittagong					
Chandpur	-7.171**	0.828	0.017	0.040***	-0.308*
Chittagong	-9.368***	1.400***	0.023	0.035**	0.000
Comilla	-6.364**	1.257**	-0.003	0.022*	-0.022
Cox Bazar	-6.916**	0.577	0.053***	0.028***	0.000
Feni	-6.167***	1.444***	0.000	0.011	0.167
Hatiya	-6.432**	1.095*	0.029**	-0.027*	0.052***
Kutubdia	-7.216***	0.523	0.025	0.009	0.000
Maijdi	-8.129**	0.333	0.025**	0.047***	-0.250
Rangamati	-5.441*	0.232	0.062***	-0.042**	0.571***
Sandwip	-7.792***	1.043*	0.057***	-0.048**	0.636***
Sitakunda	-8.729**	1.394***	0.070***	-0.024**	0.500***
Teknaf	-3.667**	0.577	0.021**	-0.008	0.042

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reveal any discernible spatial pattern. All but one (Dinajpur, station number 10, in the north-west) climate stations exhibit decreasing trends in $RSEA_{dry}$. There are 27 climate stations with significant (p<0.1) decreasing trends, mostly located in the central, southwest and southeast areas of the country (Table 4).

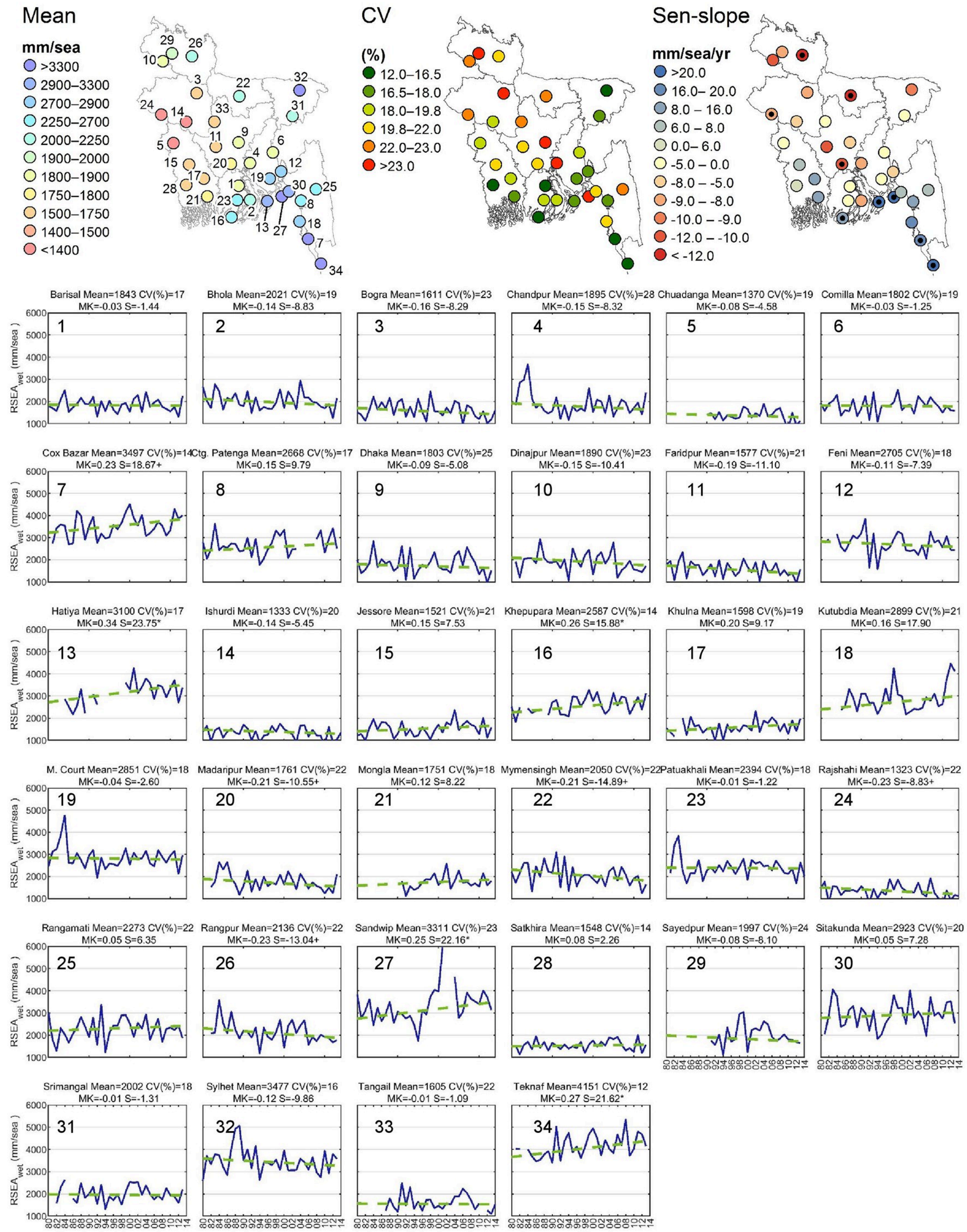

Fig 3. Variability and trends for the wet season total rainfall (RSEAwet). The top row depicts the geographical locations of the 34 climate stations showing the mean (in mm per season, left map), coefficient of variation (CV in %, middle map) and Sen-slope (S, in mm per season per year, right map) in circles with graduated colours and significant S values ($p<0.1$) shown with a smaller black interior dot. In the rest of rows, time-series (blue lines) of $RSEA_{wet}$ for the 34 climate stations (sorted in alphabetical order) and S (green lines) are shown. Summary information in each plot includes the mean, CV, MK statistic and S.

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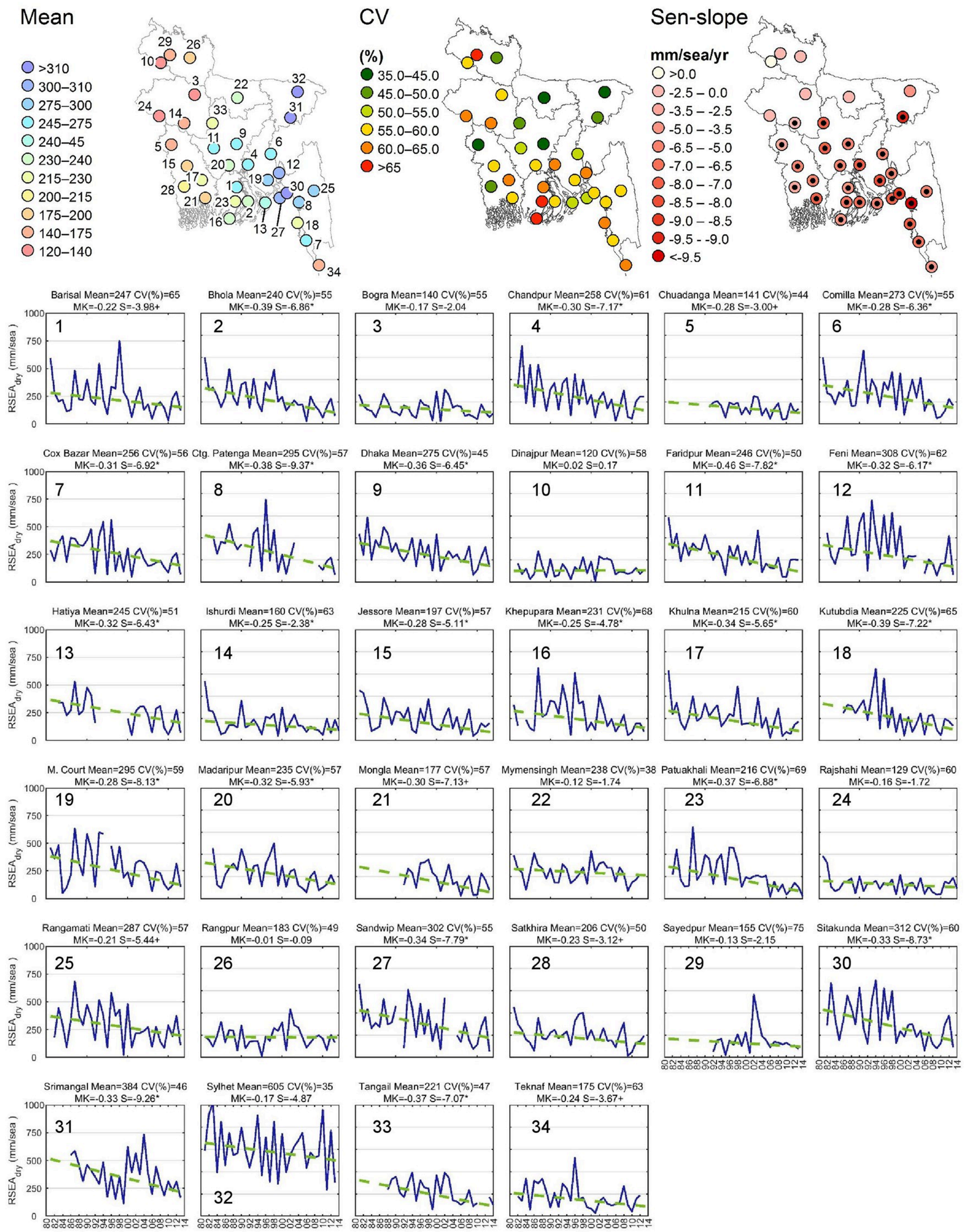

Fig 4. Variability and trends for the seasonal total rainfall for the dry season (RSEA$_{dry}$). The top row depicts the geographical locations of the 34 climate stations showing the mean (in mm per season, left map), coefficient of variation (CV in %, middle map) and Sen-slope (S, in mm per season per year, right map) in circles with graduated colours and significant S values (p<0.1) shown with a smaller black interior dot. In the rest of rows, time-series (blue lines) of RSEA$_{dry}$ for the 34 climate stations (sorted in alphabetical order) and S (green lines) are shown. Summary information in each plot includes the mean, CV, MK statistic and S.

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The spatial and temporal variability and trends in the maximum number of consecutive dry days, $RCDD_{dry}$, for the 34 climate stations are shown in Fig 5. The mean $RCDD_{dry}$ is 81 days/sea (from 71 days/sea in Sylhet to 100 days/sea in Teknaf), CV is 36% (from 30% in Teknaf to 43% in Dinajpur), and S is 0.919 days/sea/yr (from 0.232 days/sea/yr in Rangamati to 1.690 days/sea/yr in Tangail). The climate stations in the north (numbers 10, 29 and 26 in Fig 5) and the southeast areas have generally longer $RCDD_{dry}$ (>81 days/sea) compared to most climate stations in the central and western areas (<79 days/sea). The CV is relatively high at the mentioned stations in the north, but there are no clear patterns in CVs in the other areas. All 34 climate stations have increasing trends in $RCDD_{dry}$, 18 with significant ($p<0.1$) trends (Table 4).

Variability and trends in temperature metrics linked to crop production

The spatial and temporal variability and trends in $Tmax_{wet}$ and $Tmax_{dry}$ for the 34 climate stations are illustrated in Figs 6 and 7.

The mean $Tmax_{dry}$ is 29˚C/sea (from 27˚C/sea in Rangpur to 30˚C/sea in Jessore), CV is 2% (from 2% in Teknaf to 3% in Sitakunda), and S is 0.014˚C/sea/yr (from -0.035˚C/sea/yr in Satkhira to 0.070˚C/sea/yr in Sitakunda). There are 14 climate stations with significant ($p<0.1$) trends in $Tmax_{dry}$, 3 with declining and 11 with increasing trends. The climate stations located in the northwest area are slightly cooler (<28˚C/sea, numbers 10, 26 and 29) than elsewhere. The CV is low and does not exceed 3% in any climate stations. The climate stations with significant ($p<0.1$) increasing trends are mostly located in the coastal areas (Tables 3 and 4).

The spatial and temporal variability and trends in mean daily minimum temperature for the wet season, $Tmin_{wet}$, for the 34 climate stations are shown in Fig 8.

$Tmin_{wet}$ is 25˚C/sea (from 24˚C/sea in Srimangal to 26˚C/sea in Mongla), CV is 2% (from 1% in Sitakunda to 4% in Dinajpur), and S is 0.015˚C/sea/yr (from -0.009˚C/sea/yr in Chuadanga to 0.031˚C/sea/yr in Dinajpur). There are 26 climate stations with significant ($p<0.1$) increasing trends and only three have insignificant declining trends. The CV is low (<2%) in most stations.

The spatial and temporal variability and trends in mean daily minimum temperature for the dry season, $Tmin_{dry}$, for the 34 climate stations are depicted in Fig 9. $Tmin_{dry}$ is 17˚C/sea (from 15˚C/sea in Srimangal to 19˚C/sea in Cox's Bazar), CV is 3% (from 2% in Khepupara to 5% in Rangamati), and S is 0.014˚C/sea/yr (from -0.048˚C/sea/yr in Sandwip to 0.055˚C/sea/yr in Khulna). The CV is slightly higher (>4%) at the stations located in the northwest area. There are 21 climate stations with significant ($p<0.1$) trends, 5 with declining and 16 with increasing trends (Table 4). Most of the climate stations with increasing $Tmin_{dry}$ trends are located in the central and northern areas, and the 5 stations with declining trends are located in the coastal areas.

The spatial and temporal variability and trends in the number of days with temperature >36˚C for the wet season, $T36_{wet}$, for the 34 climate stations are shown in Fig 10. The mean $T36_{wet}$ is 5 days/sea (from 0 days/sea in Teknaf to 21 days/sea in Chuadanga), CV is 124% (from 46% in Chuadanga to 316% in Teknaf), and S is 0.128 days/sea/yr (from -0.045 days/sea/yr in Srimangal to 0.643 days/sea/yr in Jessore). There are 17 climate stations with significant ($p<0.1$) increasing $T36_{wet}$ trends; the rate of increase is 0.52˚C per year (Table 3). $T36_{wet}$ is higher at the climate stations in the west and northwest areas (>5 days/sea), while it is lower at the stations in the western and coastal areas (<3 days/sea). $T36_{wet}$ follows a noticeable east-west gradient, with 1 to 3 days in the east to 10 to 21 days in some locations in the west. The CV is lower (<50%) at all climate stations (>100%) in the west and northwest areas than at the stations in the northeast and coastal areas. The large number of days with $T36_{wet}$ is quite

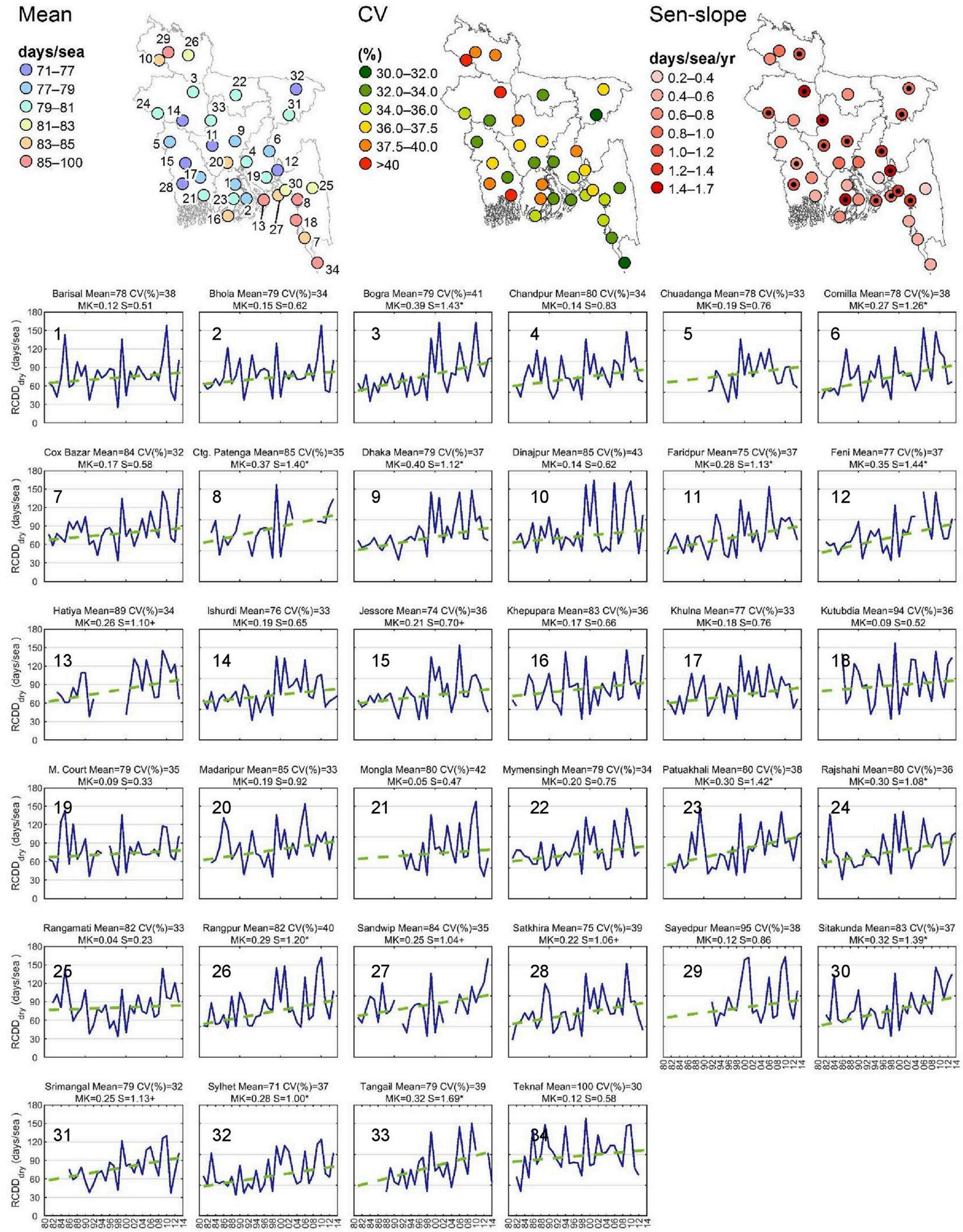

Fig 5. Variability and trends for the maximum number of consecutive dry days when daily precipitation goes below 1 mm for the dry season (November to April, RCDD$_{dry}$). The top row depicts the geographical locations of the 34 climate stations showing the mean (in mm per season, left map), coefficient of variation (CV in %, middle map) and Sen-slope (S, in mm per season per year, right map) in circles with graduated colours and significant S values ($p<0.1$) shown with a smaller black interior dot. In the rest of rows, time-series (blue lines) of RCDD$_{dry}$ for the 34 climate stations (sorted in alphabetical order) and S (green lines) are shown. Summary information in each plot includes the mean, CV, MK statistic and S.

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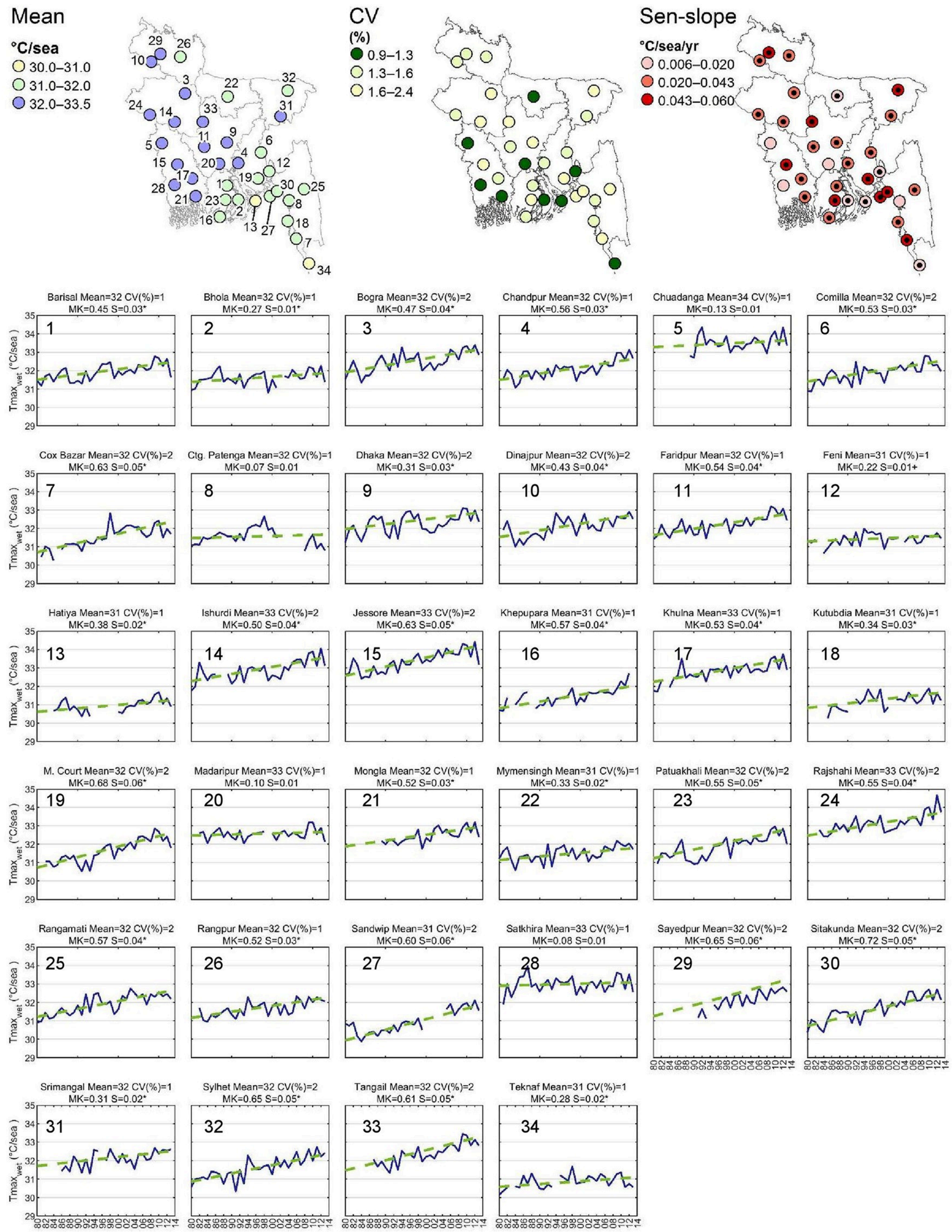

Fig 6. Variability and trends for the mean daily maximum temperature for the wet season (April to October, $Tmax_{wet}$). The top row depicts the geographical locations of the 34 climate stations showing the mean (in mm per season, left map), coefficient of variation (CV in %, middle map) and Sen-slope (S, in mm per season per year, right map) in circles with graduated colours and significant S values ($p<0.1$) shown with a smaller black interior dot. In the rest of rows, time-series (blue lines) of $Tmax_{wet}$ for the 34 climate stations (sorted in alphabetical order) and S (green lines) are shown. Summary information in each plot includes the mean, CV, MK statistic and S.

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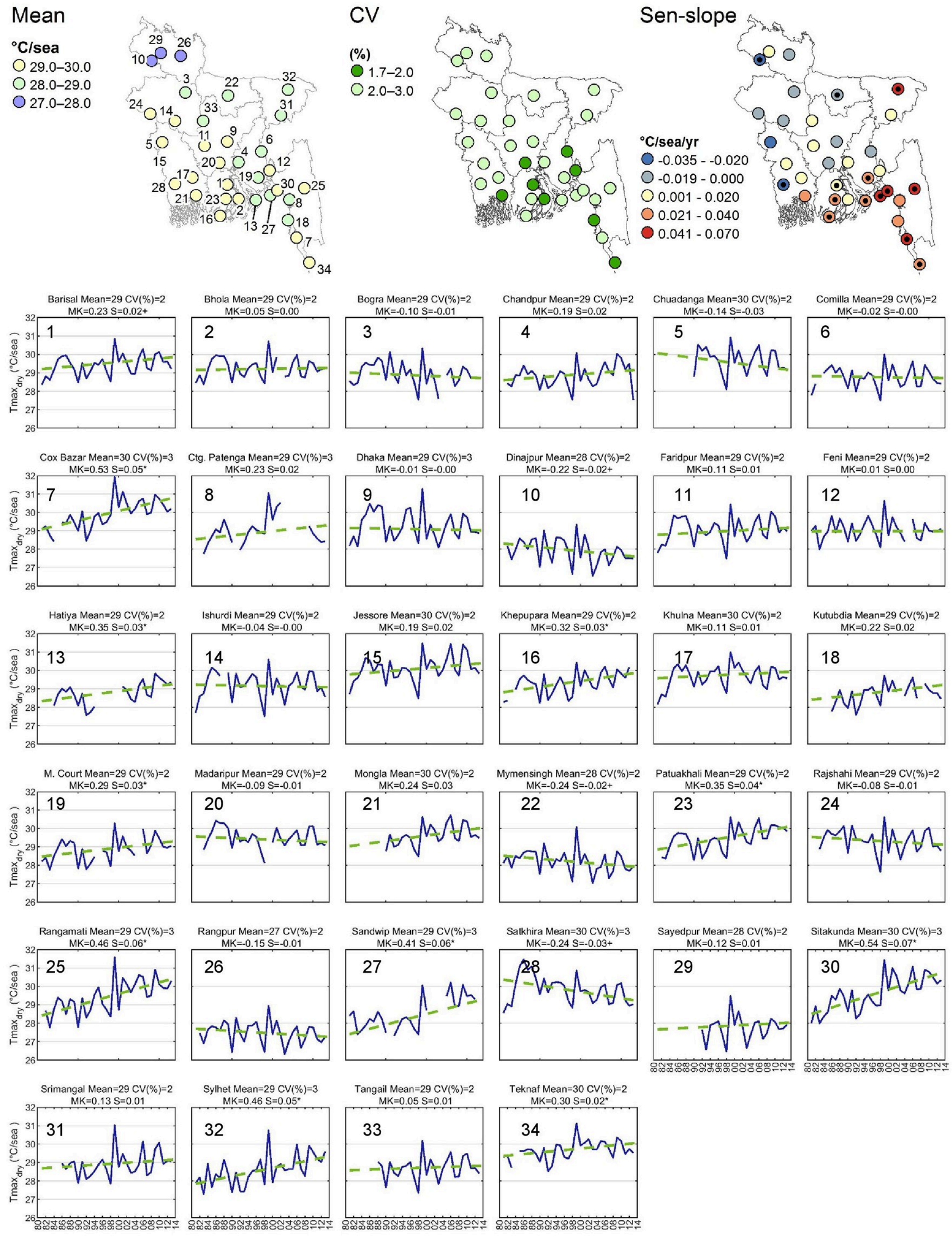

Fig 7. Variability and trends for the mean daily maximum temperature for the dry season (October to March, $Tmax_{dry}$). The top row depicts the geographical locations of the 34 climate stations showing the mean (in mm per season, left map), coefficient of variation (CV in %, middle map) and Sen-slope (S, in mm per season per year, right map) in circles with graduated colours and significant S values ($p<0.1$) shown with a smaller black interior dot. In the rest of rows, time-series (blue lines) of $Tmax_{dry}$ for the 34 climate stations (sorted in alphabetical order) and S (green lines) are shown. Summary information in each plot includes the mean, CV, MK statistic and S.

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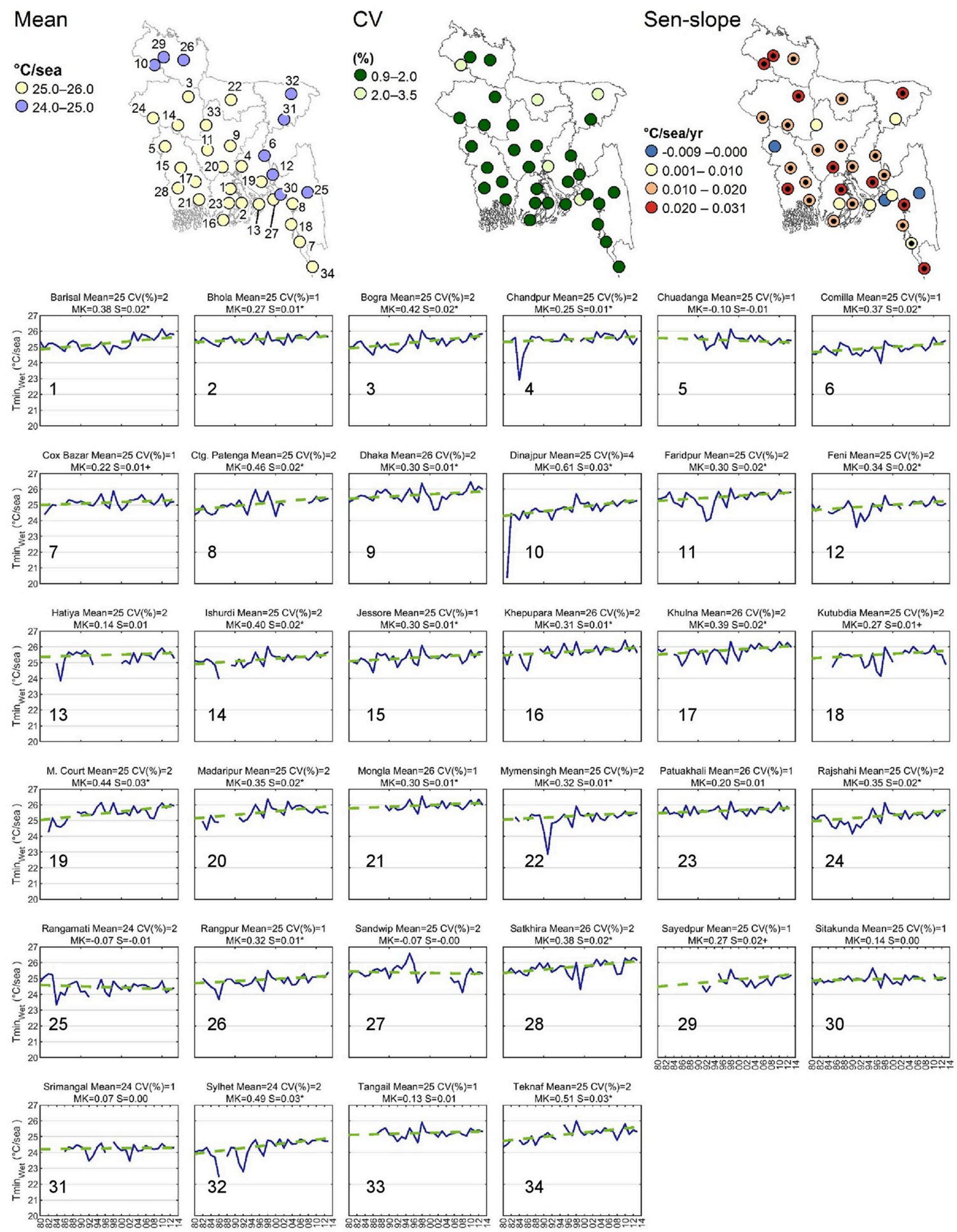

Fig 8. **Variability and trends for the mean daily minimum temperature for the wet season (April to October, $Tmin_{wet}$).** The top row depicts the geographical locations of the 34 climate stations showing the mean (in mm per season, left map), coefficient of variation (CV in %, middle map) and Sen-slope (S, in mm per season per year, right map) in circles with graduated colours and significant S values ($p<0.1$) shown with a smaller black interior dot. In the rest of rows, time-series (blue lines) of $Tmin_{wet}$ for the 34 climate stations (sorted in alphabetical order) and S (green lines) are shown. Summary information in each plot includes the mean, CV, MK statistic and S.

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regular over the years in the west, but highly variable in the southeast. Significantly increasing trends ($p<0.1$) in $T36_{wet}$ occur mostly at the climate stations in the western area, the rate being 5 days in every ten years (see station number 28, Satkhira), while the declining trends in $T36_{wet}$ occur mostly in the coastal areas.

The spatial and temporal variability and trends in the number of days with temperature <12˚C for the dry season, $T12_{dry}$, for the 34 climate stations are shown in Fig 11. The mean

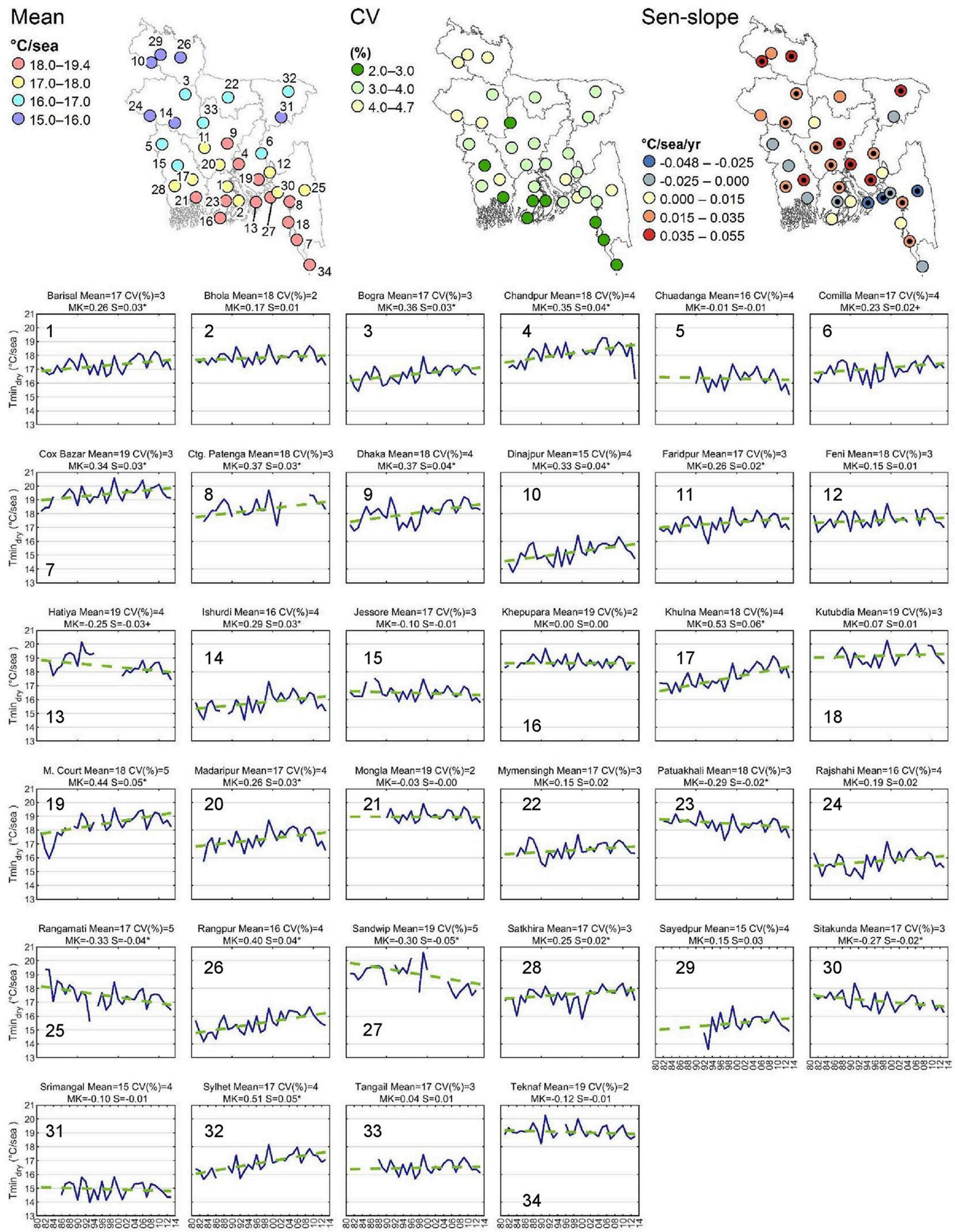

Fig 9. Variability and trends for the mean daily minimum temperature for the dry season (November to March, Tmin$_{dry}$). The top row depicts the geographical locations of the 34 climate stations showing the mean (in mm per season, left map), coefficient of variation (CV in %, middle map) and Sen-slope (S, in mm per season per year, right map) in circles with graduated colours and significant S values ($p<0.1$) shown with a smaller black interior dot. In the rest of rows, time-series (blue lines) of Tmin$_{dry}$ for the 34 climate stations (sorted in alphabetical order) and S (green lines) are shown. Summary information in each plot includes the mean, CV, MK statistic and S.

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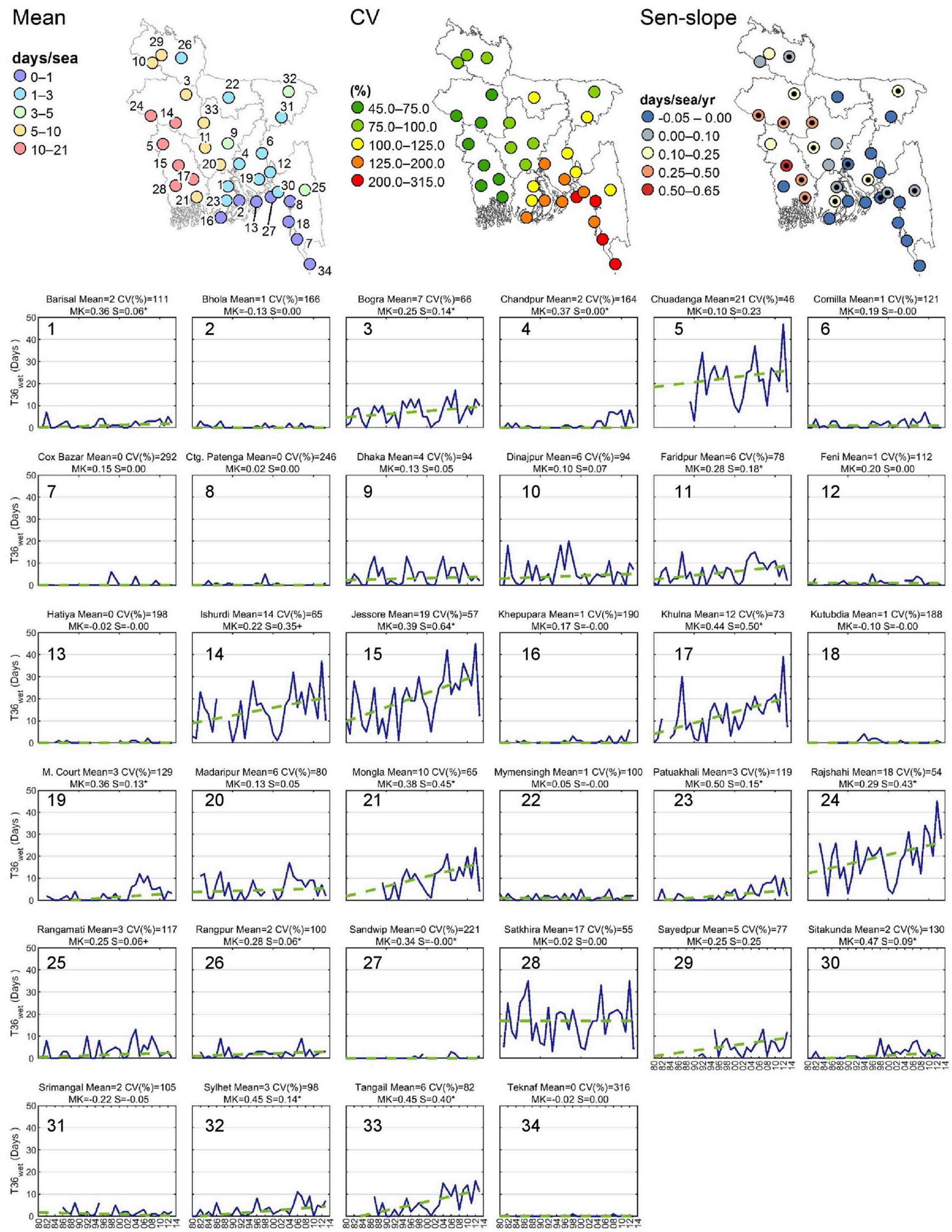

Fig 10. Variability and trends for the number of days with temperature >36˚C for the wet season (April to October, $T36_{wet}$). The top row depicts the geographical locations of the 34 climate stations showing the mean (in mm per season, left map), coefficient of variation (CV in %, middle map) and Sen-slope (S, in mm per season per year, right map) in circles with graduated colours and significant S values ($p<0.1$) shown with a smaller black interior dot. In the rest of rows, time-series (blue lines) of $T36_{wet}$ for the 34 climate stations (sorted in alphabetical order) and S (green lines) are shown. Summary information in each plot includes the mean, CV, MK statistic and S.

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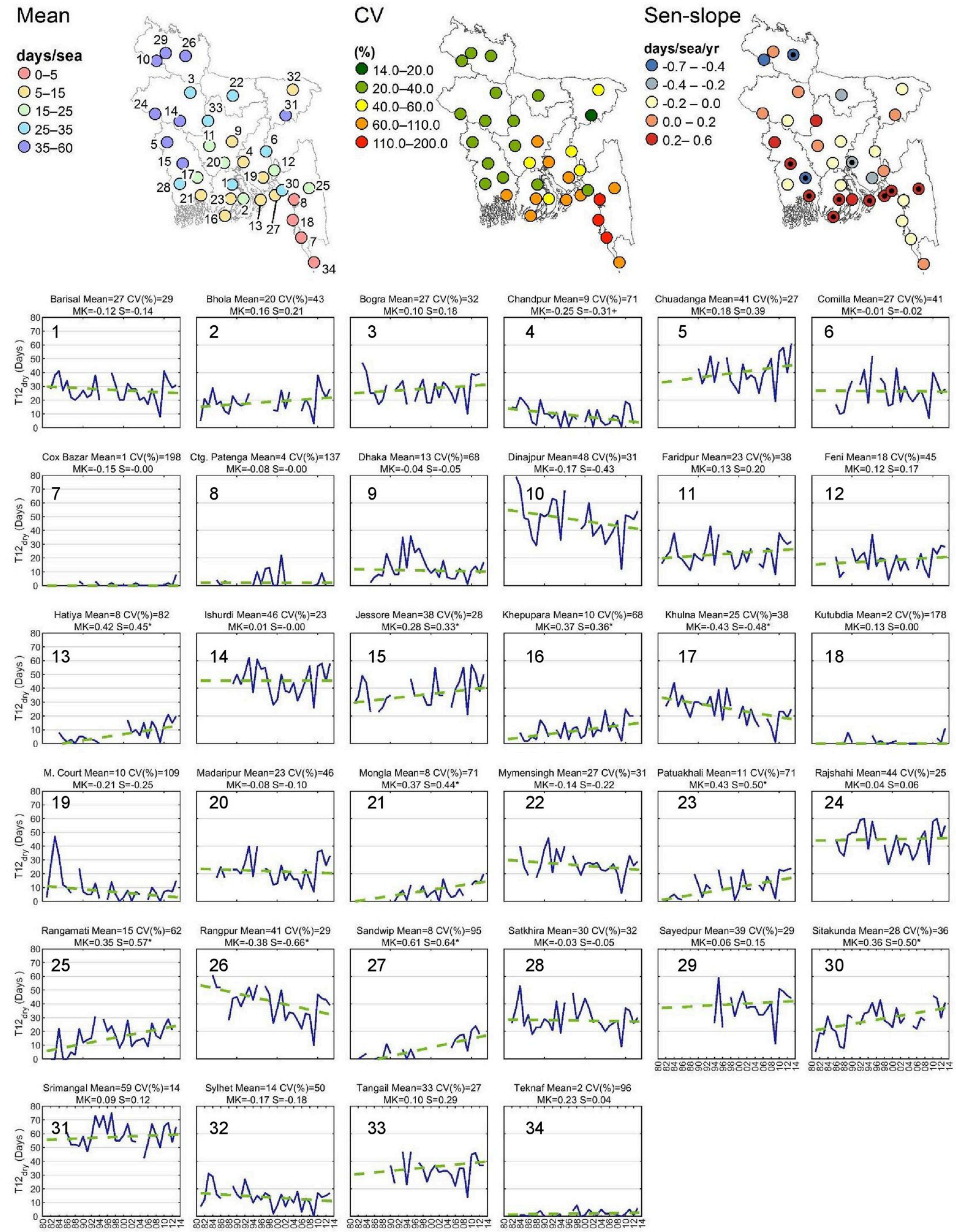

Fig 11. Variability and trends for the number of days with temperature <12˚C for the dry season (November to March, $T12_{dry}$). The top row depicts the geographical locations of the 34 climate stations showing the mean (in mm per season, left map), coefficient of variation (CV in %, middle map) and Sen-slope (S, in mm per season per year, right map) in circles with graduated colours and significant S values ($p<0.1$) shown with a smaller black interior dot. In the rest of rows, time-series (blue lines) of $T12_{dry}$ for the 34 climate stations (sorted in alphabetical order) and S (green lines) are shown. Summary information in each plot includes the mean, CV, MK statistic and S.

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$T12_{dry}$ is 23 days/sea (from 1 days/sea in Cox's Bazar to 59 days/sea in Srimangal), CV is 59% (from 14% in Srimangal to 198% in Cox's Bazar), and S is 0.080 days/sea/yr (from -0.658 days/sea/yr in Rangpur to 0.636days/sea/year in Sandwip). Similar to $T36_{wet}$, $T12_{dry}$ also follows a visible east-west gradient, with generally 0 to 15 days in the east to 35 to 60 days in some locations in the west. Also, the large number of days with $T12_{dry}$ is quite regular over the years in the west, but highly variable in the southeast. There are 11 climate stations with significant ($p<0.1$) trends, 3 with declining and 8 (mostly in the coastal areas) with increasing trends (Table 4). The results elsewhere are mixed.

Discussion

Variability and trends in rainfall metrics linked to rice production

The seasonal total rainfall for the wet season, $RSEA_{wet}$, is highly variable spatially, with an approximate east-west gradient, and is more variable in time in the northwest and central areas (Fig 3, Table 3). $RSEA_{wet}$ is increasing, generally significantly, in the coastal area (>20 mm/sea/yr in some stations, e.g. Hatiya and Sandwip) and the southwest (e.g. Khepupara) area, but decreasing significantly in some central (such as Mymensigh, Madaripur) and northwest areas (>12 mm/sea/yr in some stations, e.g. Rangpur and Rajshahi). These results agree with those of Mullick et al. [32] who reported generally increasing monsoon and post-monsoon rainfall trends during 1966 to 2015 in the southwest and coastal areas, and mixed trends in the northwest and central areas. Mojid et al. [23, their Fig 2], for a similar study period as in this paper (1985–2015) but at annual scale, reported that the overall average annual rainfall of six climate stations in the northwest region decreased significantly, and at a similar rate (~9.2 mm/year) of the seasonal results reported here. In addition, the results of Nishat and Mukherjee [70] and Shahid [33] on the maximum seasonal rainfall during the pre-monsoon and monsoon seasons with prominent increasing trend in the coastal regions are similar to the results reported herein. However, Rahman et al. [21, their Fig 7], for a longer study period (1954–2013), found similar patterns on an annual scale except for increasing trends in the northwest areas, while Mullick et al. [32] did not find significant rainfall trends during the monsoon in northwest Bangladesh for the last 50 years (1966–2015). The increasing trends in the annual total rainfall observed by Rahman et al. [21, their Fig 7] in the northwest areas that are in contrast to the results of the other investigators might be due to data limitation in their study since some of the currently available climate stations in that region were installed during 1980s or later. Inter-decadal variations in the Indian Monsoon have been reported in Krishnamurthy and Goswami [71], suggesting epochs of 30 years with below and above mean rainfall. Krishnamurthy and Goswami [71] showed that selected Indian stations reported below mean rainfall during 1959 to 1988 and above mean rainfall conditions during 1989 to 1998 (their analyses ended in 1998). These observations lead to the general agreement that the seasonal total rainfall for the wet season has decreased significantly in some central and northwest areas of Bangladesh that are major rice-growing areas. The decreasing rainfall, often causing droughts, drastically reduces yields of the rainfed Aus and Aman rice in these areas leading to increased requirement of supplemental irrigation with eventual stress on available water resources. To cope with the wet season droughts, use of supplemental irrigation is gradually increasing in these areas. However, the supplemental irrigation may be less important or not required at all if wet season rainfall increases in the future as the climate change rainfall projections of Hasan et al. [72], Kamruzzaman et al. [73] and Karim et al. [74] indicate that the annual total rainfall will increase in the drought-prone northern region, and regionally with an increase in the Indian Monsoon rainfall [75].

The seasonal total rainfall for the dry season, $RSEA_{dry}$, follows a similar spatial pattern as $RSEA_{wet}$ (i.e., an approximate east-west gradient), but is generally more variable in time in the southeast (Fig 4, Table 4). $RSEA_{dry}$ is decreasing throughout Bangladesh, significantly in many areas, more so in the central and southeast areas (>9 mm/sea/yr). These results agree with those of Mullick et al. [32], who also reported decreasing trends of $RSEA_{dry}$ at most of the climate stations across the country during winter (December to February). Decreasing trends of $RSEA_{dry}$ during winter and pre-monsoon seasons were also reported by Basak et al. [76] and Rahman et al. [21]. Although the rainfall projections of Karim et al. [74] suggest a moderate increase (~10 mm/year/season) during the dry season in northwest Bangladesh the observed past trend exposes the opposite. The dry season is the cultivation period of Boro rice, the irrigation requirement of which varies from season to season due to available rainfall in the dry season [55, 77]. So, if the current decreasing trend of dry season rainfall continues, it will increase the pressure on already stressed water resources of the country. In spite of decreasing $RSEA_{dry}$ irrigated Boro rice acreage continuously increased all over Bangladesh in the past 3–4 decades with associated increased groundwater abstraction. This practice caused decline in groundwater level in the recent past decades with eventual scarcity of dry season irrigation water, predominantly in most areas of the northwest region [50]. To cope with this, the government has put embargo on installing new irrigation wells and is vigorously advocating crop diversification by replacing high water-demanding rice with low water-demanding crops. Farmers are also increasingly adopting crop diversification practices since they very often obtain more economic profit than they obtain from irrigated Boro cultivation [50].

Whilst most climate stations do not reveal significant trends for $RCDD_{wet}$, $RCWD_{wet}$ and $RCWD_{dry}$ (see S3 Text, Figs P-R), $RCDD_{dry}$ is increasing across the country (Fig 5, Table 4), quite dramatically (>1 days/sea/year) in some central and northern areas where dry spells are already long (>70 days). This observation demonstrates that the seasonal $RCDD_{dry}$ index exposes more specific and accurate climatic condition than would be obtained from its annual resolution. The increasing trends in $RCDD_{dry}$ at many climate stations (e.g. Rangpur, Bogra, Rajshahi, Dhaka and Faridpur) have occurred in relatively recent dry seasons; the time-series in Fig 5 show that at several stations (numbers 6, 7, 9, 10, 11, 15, 26, 27, 33 in Fig 5) $RCDD_{dry}$ is higher on average from the year 2000 onwards than the previous years. In addition to the decreased seasonal total rainfall in the dry season, the $RCDD_{dry}$ also contributed to increased irrigation requirement for Boro rice cultivation.

Variability and trends in temperature metrics linked to rice production

Both the maximum and minimum temperatures have increased significantly ($p<0.1$) across several climate stations over the period from 1980 to 2014. $Tmax_{wet}$ is spatially variable (Fig 6), approximately following an east-west gradient. The west, on average, is slightly cooler (~2˚C) than the east. $Tmax_{wet}$ is increasing significantly (Table 3) throughout the country by 0.5˚C in every ten years. If the trend continues, the increased $Tmax_{wet}$ will drastically affect Aman rice production by deteriorating grain formation. $Tmax_{dry}$ follows a similar pattern as $Tmax_{wet}$ but is cooler in the northern areas (~2˚C). It is significantly increasing in the coastal areas by 0.5˚C in every ten years. It is decreasing in the north and west, significantly at some locations (Table 3) thus revealing the opposing trends and more specific climate information for crop growth in the two seasons that would not be obtained from the analysis of data on annual resolution. $Tmin_{wet}$ follows an east-west gradient, with temperatures in the east being slightly cooler (~1˚C) than in the west. The minimum temperature shows seasonality; $Tmin_{wet}$ is generally increasing throughout the country, sometimes by 0.3˚C in every ten years. Although, $Tmin_{dry}$ follows a similar pattern as $Tmin_{wet}$ but is cooler in the northern areas (~3˚C) than in the other areas. It is significantly decreasing in some coastal areas (Table 4) by 0.5˚C in every ten years and increasing in the north, significantly at some locations in the northwest (Table 4), by 0.3˚C in every ten years.

Rahman et al. [2] also reported similar results, but with higher incremental rate of the minimum temperature, while Wassmann et al. [78] reported a gradual increase in temperature in most regions of the country. Similar to our findings, Rimi et al. [79] also reported an insignificant increasing trend of the annual maximum and minimum temperatures for the southern region (e.g., Satkhira district) over the period from 1950 to 2006. Basak et al. [76] estimated an increasing trend of 0.012˚C per year for the yearly average maximum temperature and 0.015˚C per year for the yearly average minimum temperature. In contrast, our analysis of the extensive data set provides higher increasing trend (0.024˚C per year) for the yearly average maximum temperature but lower increasing trend (0.012˚C per year) for the yearly average minimum temperature than the estimates of Basak et al. [76]. Further rise in average day temperature of 1.0˚C by 2030 and 1.4˚C by 2050 has been predicted [80]. All the climate stations in this study reveal an increasing trend in temperature during May to October. Nishat and Mukherjee [70] also reported an increasing trend in the mean seasonal temperature within the range of 0.40–0.65˚C during the period from 1967 to 2007.

We observed 0.52˚C per year increasing rate of the extreme high temperature (>36˚C), $T36_{wet}$, for the wet season (Table 3). But Nishat and Mukherjee [70] reported 0.87˚C increase in the maximum temperature during pre-monsoon (March-May) and 0.42˚C during post-monsoon (September-November) months. Based on the seasonal maximum values, these temperatures are in agreement with our results in terms of their timing of occurrence. In our analysis, the monthly low temperature, $T12_{dry}$, shows a decreasing trend in December (0.022˚C) and January (0.031˚C) but increasing trend (0.002 to 0.04˚C) in all other months of the year. Partially contrasting timing and magnitudes of occurrence of the dry season minimum temperature were also reported; for example, Nishat and Mukherjee [70] reported an increase in the minimum temperature during December to February (0.45˚C) and June to August (0.52˚C).

While the historical trend shows both the increase and decrease in temperature, climate change projections indicate that both seasonal and annual temperatures will increase in the future across Bangladesh [72, 81, 82]. For example, Agrawala et al. [83] predicted 1.1˚C, 1.6˚C and 2.7˚C increase in winter/dry season temperature for the year 2030, 2050 and 2070, respectively. Based on 11 GCMs, Fahad et al. [81] predicted mean temperature rise of 3.2˚C to 5.8˚C for Bangladesh at the end of the twenty-first century. Similarly, Hasan et al. [72] and Caesar et al. [82] predicted 2.0˚C to 4.5˚C and 2.6˚C to 4.8˚C rise in mean temperature, respectively by the end of the century. Thus, although the magnitudes may vary the results of all these studies lead to the general consensus that both the mean seasonal and annual temperatures will increase to a large extent in the future.

Risk of rainfall variability and trends to rice production

The success of Aus and Aman rice production largely depends on the monsoon, whereas Boro rice being largely irrigated is much more sensitive to changes in temperature than to changes in rainfall [62]. Depending on timing and magnitude, the changes in rainfall can have either positive or negative impacts, which are specifically significant to Aus and Aman rice production [41].

Changes in rainfall also affect recharge rates into aquifers that, can affect irrigated agriculture, particularly Boro rice, in the northwest and central regions of Bangladesh. These regions are the main crop production zones and considered the food bowl of the country [25, 84]. The northwest region, despite having only 31% of net cultivable area of the country, produces 37% of Aman rice, 35% of Boro rice, and 60% of wheat, maize and potato of the total production of the country [50]. In our analysis, most climate stations reveal decreasing rainfall trends (four significantly, Table 3, Fig 3) during the wet season in the northern parts of the country. This can have obvious adverse effects on crop production, specifically Aman rice production [85] that covers ~69% of the country's total cultivated land area for rice production [86]. The decrease in rainfall in the wet season (as shown by $RSEA_{wet}$) increased in-seasonal drought for Aman rice over the past decades [87]. Due to sub-humid and dry conditions, droughts occurred quite frequently in the northwest region during June/July to October/November [87, 88] and about 5.5 Mha of land have been classified as drought-affected [89]. The decreased rainfall in the wet season increased the need of supplementary irrigation for Aman rice in the drought-prone areas. Consequently, supplementary irrigation is increasingly being practiced in those areas over the past years. Without supplemental irrigation, rice production may fluctuate greatly on a year-to-year basis [41, 86] with the resulting adverse effects on food security in the country, particularly in dry years. This is likely to be exacerbated by climate change [90] since the future climate change in Bangladesh is anticipated to increase the variability in the production of all three cultivated rice types: Aus, Aman and Boro [18].

In addition, the wet season rainfall recharges groundwater, which is extracted and used in the dry season for irrigation. There is strong evidence [23, 24, 91, 92] that groundwater levels are declining in the northwest region, which is the most intensely groundwater-irrigated area in Bangladesh [14]. The reduction in rainfall in the future is likely to further exacerbate the situations as there will be less recharge to the aquifers from rainfall in the wet season [25] with the eventual adverse effects on the productivity of irrigated crops (e.g., Boro rice, wheat, maize) grown in the dry season. The effects of decreasing rainfall in the dry season, as shown by $RSEA_{dry}$, on groundwater are also of concern, particularly in the northwest region [93]. Boro rice is grown in the dry season using groundwater irrigation in the northwest and central regions. The decrease in dry season rainfall will increase irrigation requirements of the crops, thus exerting further pressure on groundwater for irrigation, particularly in the northwest region where irrigation is almost entirely dependent on groundwater. To cope with this situation, rice breeders are trying to develop short-duration varieties to reduce water requirement; but until now the success is limited [94]. As described before that until now restriction on installation of additional irrigation wells and advocating crop diversification have the government's policy to keep both groundwater usage and food production sustainable. However, this policy might not be adequate or even appropriate in future since irrigation requirements are also projected to increase due to climate change [55, 95]. The increasing irrigation amount and associated costs will greatly affect the livelihood of the farmers in groundwater-irrigated regions of Bangladesh. The declining groundwater table due to high extraction will also intensify water scarcity and lead to insufficient supply of freshwater in dry periods for the growing population in the urban areas [23]. In the face of climate change, declining groundwater levels, variable rainfall and irrigation will represent a challenge for Bangladesh and South Asia's food security [96, 97].

However, if climatic variability [71] and projected increases in the Indian Monsoon rainfall [75] are considered, the negative effects of declining rainfalls (particularly in the northwest region) may be reverted in the medium to long term [74]. On the other hand, floods due to extreme rainfall may become more prevalent in the region [98]. The poldered (large areas enclosed and protected from seawater flooding by man-made earth embankments) coastal areas (south and southwest regions) of Bangladesh are already prone to flooding and water logging due to high rainfall and limited drainage opportunities since the water levels in the surrounding rivers of the polders are high [99, 100]. Thus, water management remains a critical problem within the polders and appropriate water management method(s) is(are) yet to be developed. Aman rice is the main crop in the region grown in the wet season and famers usually cultivate low-yielding local varieties of Aman rice [101]. The Government of Bangladesh intends to increase the productivity of Aman rice in this region by introducing high yielding varieties to secure rice grain self-sufficiency and improve livelihood of the local people [99, 101]. The increasing trend in wet season rainfall ($RSEA_{wet}$) in this region may not only seriously hamper this effort but also make the current cropping practice difficult with eventual deleterious impact on the livelihood of millions of people.

The number of consecutive wet days, $RCWD_{wet}$, is the lowest (102 day) in the western region and highest (149 days) in the northeast region, the average wet days being 119 days. Seventy-nine per cent (79%) of the wet days occur within May to October. $RCWD_{wet}$ increases annually by 0.19 days and seasonally (May-October) by 0.12 days. These results demonstrate that rainfall has become increasingly variable with uneven temporal and spatial distributions. The erratic rainfall pattern often produces extreme events like floods and droughts, which have adverse effects on crop production, especially on rice production [85].

Risk of temperature variability and trends to rice production

The past increasing trends in $Tmax_{wet}$, $Tmax_{dry}$ and $T36_{wet}$ and further predicted increase in the extreme high temperature under climate change [102] are a serious concern for rice production in Bangladesh as they impact the period for flowering and grain formation of Aus, Aman and Boro rice. High temperature stress is a serious concern for crop production because of its manifold and often adverse impacts in plant growth, development, physiological processes and yield [103]. It adversely affects pollen growth which is one of the most sensitive phenological stages. Temperature extremes during pollen developmental stage have been reported to greatly affect crop production [5]. However, plants' response to high temperature varies with the degree and duration of exposure of the high temperature and types of plant [103]. The impacts of high temperature are highly heterogeneous across the crops and geographical areas, even with some positive impact estimates [22]. At the heat stress of 35˚C to 40˚C, Ahamed et al. [104] estimated reduction in 1000-grain weight by 3.4% to 4.4% in heat-tolerant rice varieties.

Twenty-one out of 34 climate stations in our study show increasing trend of the annual extreme low (<12˚C) temperature and 13 stations show decreasing trend; some of them are highly significant (Table 4). So, in some regions of the country the annual lowest temperature has been decreasing linearly since the past three decades, with the lowest temperature observed in the far north (e.g., Rangpur; Fig 1). January is the coldest month when Boro rice is at transplanting stage. Like the maximum temperature limit, all plants have also minimum temperature limits (e.g., 10˚C to 12˚C for rice plants). The minimum temperature in our data series varies from 3˚C to 10˚C that occurs during December to February, most often during January, which is the period of early stages of Boro rice growth. The northern part of the country experiences lower temperature compared to the south and southwest regions. Low temperature affects survival, water transport, growth and finally yield of rice. For example, the flowering stage of rice at 12˚C for 15 days' exposure has significant negative effects ($p<0.01$) on panicle number, panicle length and the number of full, empty and total grains [105]. This situation is more prevalent in the colder northern areas during the dry season, when Boro rice is at transplanting stage; but the observed trends do not suggest significant decreases in $Tmin_{dry}$ or increases in $T12_{dry}$. However, if the current trend of annual extreme low temperature continues for a long future period, it will force to delay transplanting of rice seedlings with eventual shifting of the ripening and perhaps also the grain formation stages to the period most likely affected by seasonal storm often with hails. Again, cultivation of short-duration rice varieties, when available, may be an option to save the harvest from adverse impacts.

The impact of climate change on the development phases of rice is one of the major concerns for yield reduction [76] since most of the rice crops are cultivated where temperatures are above the optimal limit for their growth and development [106]. High temperature is already one of the major environmental stresses limiting rice productivity. For example, Islam [3] reported decrease in grain yields with 35˚C at grain-filling stages. Therefore, further increase in mean temperature or incidents of high temperature in Bangladesh during the sensitive growth stages would reduce yields of Aman rice drastically. Rice production under various climatic stresses has been projected to decline by 8% to 17% by 2050 [80]. The increase in temperature will also increase the crop water requirements of rice [55]. Significant decreasing trend in dry season rainfall ($RSEA_{dry}$), as shown in Table 4, and increase in crop water requirements resulting from increase in maximum temperature will have additional stress on the groundwater resources in the country particularly in the northwest and central regions as discussed earlier. For Aus and Aman rice, increase in crop water requirements will increase the requirement of supplementary irrigation; and failure to provide such irrigation is likely to significantly reduce yield.

The increase in temperature is also likely to impact yield of rice all over Bangladesh [107]. For example, Karim et al. [40] predicted a 33% reduction of average rice yields due to climate change, whilst Yu et al. [17] predicted an overall reduction in rice production by an average of 7.4% every year over the period from 2005 to 2050. Management of high-temperature stress focuses on selection of early maturing and temperature-tolerant cultivars or sowing early to avoid high temperature stress during grain filling stage; however, the low temperature stress creates a dilemma in this case. But these measures could be insufficient due to more severe temperature stress (both high and low temperature stress) in the future. So, there are considerable risks for rice production due to temperature stress. The benefits from effective mitigation and/or adaptation options soon to be developed through rice research will be crucial to sustain the rice production systems in a warmer world [106], specifically in Bangladesh [108].

The rising temperature due to climate change intensifies the global water cycle and alters precipitation patterns [109], which affect surface runoff, evapotranspiration, groundwater recharge and irrigation demand. Many studies [e.g., 110–112] in different parts of the world indicated that rising temperature due to global warming enhances evapotranspiration, with a consequent increase in irrigation demand in most climate regions. Likewise, extraction of groundwater continues increasing over time with the ensuing accelerating rates of declining groundwater tables in many parts of Bangladesh [113]. Declining groundwater tables due to increasing temperature were also reported by Gunawardhana and Kazama [114]. However, Peña-Arancibia [25] show that declining groundwater tables are not solely a result of increasing groundwater pumping but also likely of other factor(s) like reduced recharge. Declining rainfall is clearly one possibility, and the results outlined in the previous section and in Mojid et al. [23] clearly demonstrate that the rainfall has decreased in the northwest region. Dey et al. [24] also reported a 25.6% decline of rainfall during 1984 to 2014 over parts of the northwest region. The projected rainfall pattern and its distribution in Bangladesh will have an adverse impact on the crop yields due to increasing water demands by 14% in the future [40]. So, there are multi-faceted impacts of rainfall and temperature trends on the rice production of Bangladesh.

The population of Bangladesh is expected to increase from the current 168 million to 202 million in 2050 [115] requiring about an additional 10 million tonnes of rice [18]. So, it is not only important to sustain the current production of rice but also necessary to increase from a land-area, that is declining at a rate of 1% per year due to urbanization and industrial development [116]. This essentially requires understanding the climate risk to rice production and finding appropriate adaptation options. This study provides important information on the climate trends and highlights the risks that will help policy makers to formulate future policies for increasing rice production in the country. However, the study mostly qualitatively estimated the impact of climate variability and changes on the production of rice.

Conclusion

Historical spatio-temporal variability and trends in rainfall and temperature across Bangladesh over the period from 1980 to 2014 have been investigated using the observed daily data of 34 climate stations distributed over the country. Thirteen climate metrics closely linked to rice production were derived from the daily data for the wet (May to October) and dry (November to April) cropping seasons, which capture the main growing seasons of the country's two wet season rainfed Aus and Aman rice and dry season irrigated Boro rice. Rainfall is significantly decreasing both in the wet and dry seasons in the central and northern areas, the main areas for production of rice, whilst dry spells are increasing throughout Bangladesh, significantly in central and southeast areas. The drying conditions can adversely affect the production of rainfed Aman rice, and raise irrigation requirement of dry season Boro rice with eventual adverse effects on groundwater resources through reduced recharge and declining groundwater tables.

The maximum temperatures both in the wet and dry seasons are increasing throughout the country, significantly at most of the climate stations at 0.5˚C every ten years. The current maximum temperature estimates in the wet and dry seasons are substantially higher than the optimum temperature range for Aus, Aman and Boro rice which is likely to adversely affect their yields. Since rice is the principal staple crop of Bangladesh, any deterioration in rice production systems due to climate change would seriously impair food security in the country. The generated rainfall and temperature metrics provide important information that are useful for long-term planning of rainfed as well as irrigated agriculture in Bangladesh.

Supporting information

S1 Text. Rainfall double-mass curves.
(DOCX)

S2 Text. Autocorrelation analysis.
(DOCX)

S3 Text. Variability and trends in rainfall-based agriculturally relevant climate metrics.
(DOCX)

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