Contribution of Aerosol Particle Dynamics and Microphysical Processes to Deep Convection and Heavy Rainfall over Bangladesh

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Abstract

Atmospheric aerosols strongly modulate deep convection by cloud condensation nuclei (CCN) and ice nuclei (IN), altering cloud droplet size distributions, precipitation efficiency, latent heat release, and convective dynamics. Bangladesh experiences some of the highest aerosol loadings in South Asia from urban, industrial, biomass-burning, and transboundary sources, but yet convective-scale aerosol–cloud interactions over the region remain poorly quantified. This study uses the Weather Research and Forecasting model coupled with Chemistry (WRF-Chem) model to investigate aerosol impacts on deep convection and heavy rainfall for two contrasting monsoon events in 2023: (i) over northeastern (Sylhet) region during 26–27 June, in which moist monsoon flow is orographically lifted along the Meghalaya foothills, and (ii) over southeastern coastal (Chattogram–Cox's Bazar) region on 28–29 June. High-resolution two-way nested simulations (30 and 10 km) were performed with observed aerosols (CTRL) and under reduced (LOW-AERO, −50%) and enhanced (HIGH-AERO, ×2) aerosol loading. Increased aerosol loading raised cloud droplet number concentration and reduced mean droplet size, suppressing warm-rain collision–coalescence and delaying precipitation initiation. The consequent lifting of cloud water above the freezing level enhanced latent heat release from freezing and deposition, strengthening convective updrafts and deepening clouds; peak 24-h rainfall increased by approximately 15–25% over the most active convective cores, although precipitation was suppressed under moisture-limited conditions. Simulated rainfall agreed well with GPM IMERG observations (r = 0.82; RMSE = 12.5 mm; bias = +6.3%). These findings clarify aerosol–cloud–convection interactions over Bangladesh and provide guidance for representing aerosol effects in numerical weather prediction and disaster risk reduction.

Keywords: Aerosol–cloud interaction, Deep convection, Heavy rainfall, Cloud microphysics, WRF-Chem.

1. Introduction

Bangladesh is one of the most disaster-prone countries in South Asia owing to its geographical setting and monsoon climate. Heavy rainfall frequently triggers flash floods, riverine floods, urban waterlogging, and landslides. Understanding the physical mechanisms that control heavy rainfall is therefore essential for improving weather forecasting and disaster preparedness [1]. Deep convective clouds play a central role in producing heavy precipitation. The intensity and evolution of convection are governed by thermodynamic instability, moisture availability, atmospheric dynamics, and cloud microphysical processes. Aerosols influence these processes by serving as cloud condensation nuclei (CCN) and ice nuclei (IN), thereby modifying cloud droplet formation and precipitation development [2,3].

Previous studies have shown that aerosol-induced changes in cloud microphysics can either invigorate or suppress convection depending on environmental conditions [4–6]. Under the “convective invigoration” hypothesis, increased aerosol concentrations generally produce a larger number of smaller cloud droplets, which reduces collision–coalescence efficiency and delays warm-rain formation [2,5]. Because precipitation is delayed, a greater mass of condensate (cloud water) is carried above the freezing level in the convective updraft, where freezing and deposition release additional latent heat that increases buoyancy and strengthens updrafts—deepening the cloud and enhancing cold-rain processes, ice, and graupel formation [4,7,19]. This cold-phase (freezing-induced) pathway was complemented by later work identifying a warm-phase mechanism, in which ultrafine aerosol particles (<50 nm) activate under the high supersaturation of clean, humid updrafts and intensify condensational heating [7]. However, the magnitude and even the sign of these effects are strongly modulated by the environment: the response depends on relative humidity and aerosol regime [6], convective available potential energy (CAPE), and vertical wind shear [8,10], so that invigoration dominates in moist,

unstable conditions while suppression of precipitation can prevail under dry, moisture-limited conditions [4,9]. The net effect therefore remains an area of active debate and quantitative uncertainty [3,7].
The original invigoration observations come from the Amazon, where smoke from biomass burning was found to invigorate clouds rather than only inhibit them [11], and Fan et al. (2018) showed that ultrafine particles from pollution can be activated to form additional droplets on which excess supersaturation condenses, adding cloud water and latent heating and thereby intensifying convective strength [7]. The droplet-size/warm-rain link is foundational: elevated CCN produces higher concentrations of smaller droplets, and the reduced droplet size slows coalescence into raindrops and can prolong cloud lifetime [2,18].
Despite growing international research on aerosol–cloud interactions, work over the South Asian monsoon region has concentrated largely on India and has emphasized the large-scale radiative and dynamical effects of absorbing aerosols—for example, the “elevated heat pump” hypothesis [12], the “solar dimming” atmospheric brown cloud effect [13], and dust-driven modulation of monsoon rainfall [14]. By comparison, relatively few studies have examined convective-scale aerosol–cloud–microphysical interactions over Bangladesh, even though the country experiences some of the highest aerosol loadings in the region from urban and industrial emissions, biomass burning, and transboundary transport. This represents an important regional gap, because the invigoration/suppression behavior described above is sensitive to local thermodynamics and aerosol regime and cannot simply be transferred from Indian or Amazonian case studies. To address this gap, the present study uses the Weather Research and Forecasting model coupled with Chemistry (WRF-Chem) [15], an online-coupled meteorology–chemistry framework in which aerosols interact directly with cloud microphysics and radiation, to quantify the impact of aerosol particle dynamics on deep convection and heavy rainfall over Bangladesh through control and aerosol-sensitivity simulations of selected monsoon heavy-rainfall events.
Indeed, Bangladesh consistently ranks among the most polluted countries in the world, with a national annual-mean $PM_{2.5}$ concentration of about 78 $\mu g\ m^{-3}$ in 2024—roughly fifteen times the World Health Organization guideline—reflecting the intense and persistent aerosol loading over its major convective regions [16]. Within this context, the present study addresses three questions: how aerosol loading alters cloud droplet number concentration and mean droplet size; whether the resulting microphysical changes invigorate or suppress convection over Bangladesh; and how these changes translate into the intensity and spatial distribution of heavy rainfall. To answer these, high-resolution WRF-Chem simulations are configured for selected monsoon heavy-rainfall events and analyzed under a control experiment together with reduced- and enhanced-aerosol sensitivity experiments, so that the aerosol signal can be isolated from the meteorological background. This design makes it possible to attribute changes in updraft strength, hydrometeor partitioning, and surface precipitation directly to aerosol perturbations rather than to differences in the large-scale environment. By providing one of the first convective-scale assessments of aerosol–cloud–precipitation interactions for Bangladesh, the results are intended to inform the representation of aerosol effects in operational numerical weather prediction and to support more reliable heavy-rainfall forecasting and disaster preparedness.

2. Data Used, Experimental Setup and Methodology

2.1 Study Area

Bangladesh lies between 20°34′N–26°38′N and 88°01′E–92°41′E, at the head of the Bay of Bengal. The region is characterized by:

- Southwest monsoon (June–September);
- Annual rainfall of 1500–5000 mm;
- High humidity throughout the year;
- Significant aerosol pollution from urban and industrial sources.

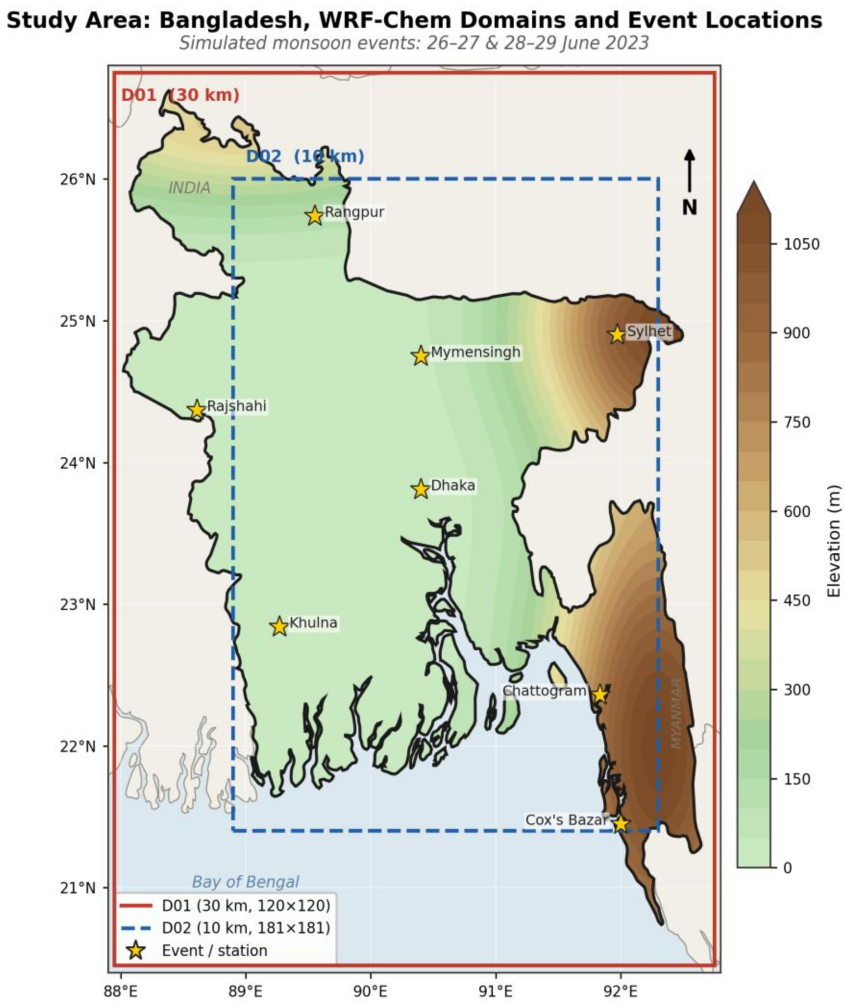

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Figure 1. Bangladesh study area showing terrain elevation, the two nested WRF-Chem model domains (D01: 30 km; D02: 10 km), neighboring countries, the Bay of Bengal, and selected heavy-rainfall event / station locations.

2.2 Data Used

Heavy-rainfall events for simulation were selected from the southwest monsoon season (June–September) using a multi-year observational record so that the chosen cases are representative of high-impact convective rainfall over Bangladesh. Daily rainfall from the GPM IMERG satellite product (2014–2024) and rain-gauge observations from the Bangladesh Meteorological Department (BMD) were used to identify high-impact events exceeding the 95th-percentile daily rainfall threshold, while the MODIS AOD record (2000–2024) was used to confirm that elevated aerosol loading accompanied the selected episodes. Two representative monsoon heavy-rainfall events were then chosen for detailed WRF-Chem simulation: Event 1 (26–27 June 2023) and Event 2 (28–29 June 2023). Each event was simulated for 2 days at convection-permitting resolution, with the first 24 h discarded as model spin-up and the remaining 24 h used for analysis. The two events exhibit clearly different rainfall geographies (Figure 2): Event 1 is dominated by intense rainfall over the northeastern Sylhet region, where moist monsoon flow is orographically lifted along the Meghalaya foothills, whereas Event 2 concentrates rainfall over the southeastern coastal belt around Chattogram and Cox's Bazar, providing two contrasting convective regimes for the aerosol-sensitivity analysis.

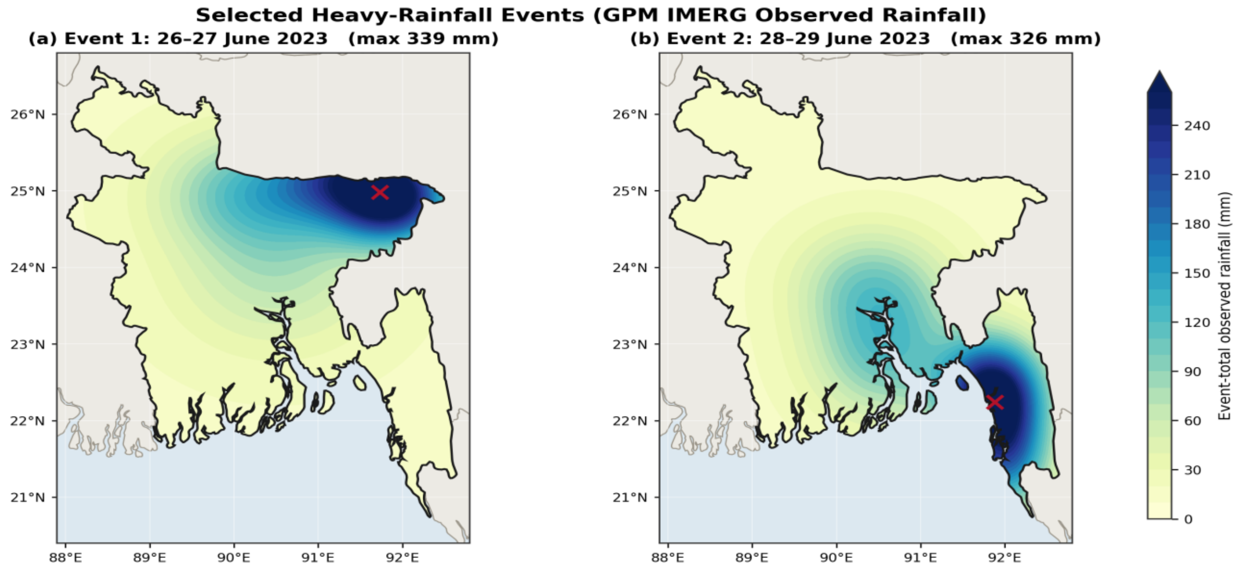

Figure 2. Observed event-total rainfall (GPM IMERG) for the two selected heavy-rainfall events: (a) Event 1, 26–27 June 2023, with a northeastern (Sylhet) maximum; and (b) Event 2, 28–29 June 2023, with a southeastern coastal (Chattogram–Cox's Bazar) maximum. Red crosses mark the rainfall maxima.

2.3 WRF-Chem Model Configuration

Simulations were performed with WRF-Chem version 4.x [15,17] using a two-way nested domain configuration. The outer domain (D01) covers the wider regional circulation at 30 km resolution, while the inner domain (D02) resolves convective-scale processes over Bangladesh at 10 km resolution.

Table 1. Model domain configuration.

Domain	Horizontal resolution	Grid points
D01	30 km	120 × 120
D02	10 km	181 × 181

Table 2. Selected physics parameterization schemes.

Process	Scheme
Microphysics	Morrison double-moment
Planetary boundary layer	Yonsei University (YSU)
Land surface	Noah LSM
Radiation (long/short wave)	RRTMG
Cumulus (D01 only)	Kain-Fritsch

2.4 Initial and Boundary Conditions

Meteorological initial and boundary conditions were derived from ERA5 reanalysis. Anthropogenic emissions were prescribed from the EDGAR inventory, and aerosol fields were constrained using MODIS Aerosol Optical Depth (AOD). Simulated rainfall was validated against GPM IMERG precipitation estimates.

Category	Dataset(s)
Meteorology	ERA5 reanalysis
Aerosol / emissions	EDGAR inventory; MODIS AOD
Rainfall validation	GPM IMERG

2.5 Experimental Design
Three experiments were conducted to isolate aerosol effects for each of the events (Event 1 and Event 2). The control run (CTRL) uses observed aerosol concentrations; a low-aerosol run (LOW-AERO) reduces aerosol emissions by 50%; and a high-aerosol run (HIGH-AERO) doubles the aerosol loading.

Experiment	Aerosol configuration
CTRL	Observed aerosol concentrations
LOW-AERO	50% reduction in aerosol emissions
HIGH-AERO	200% (doubled) aerosol loading

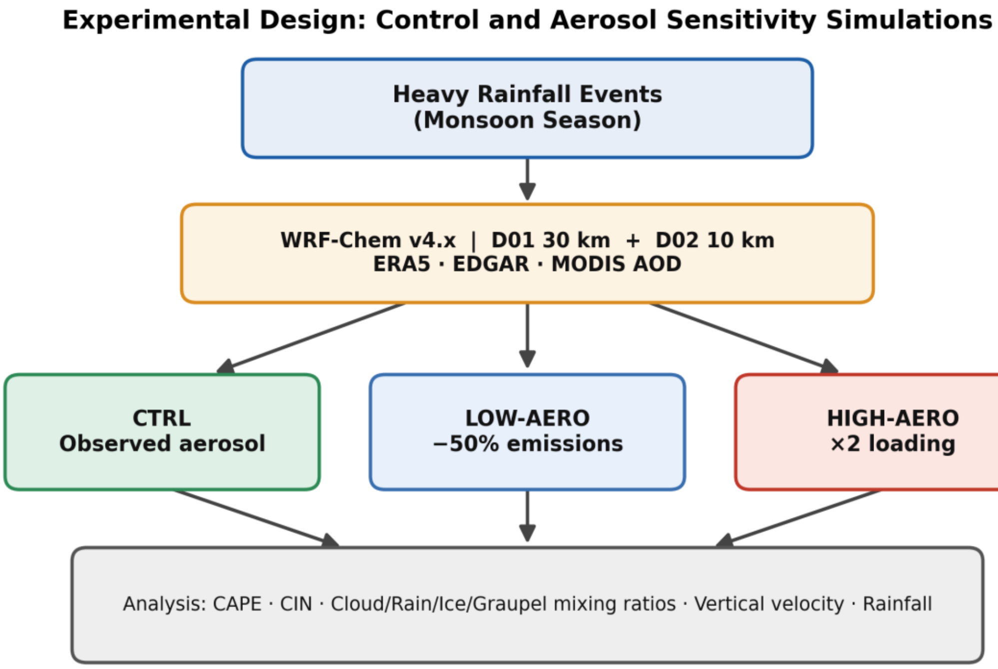

Figure 3. Schematic of the experimental design, showing the control and aerosol-sensitivity simulations and the principal analysis variables.

2.6 Analysis Variables
The following variables were analyzed to characterize the thermodynamic environment, cloud microphysics, and convective response:
- Convective Available Potential Energy (CAPE) and Convective Inhibition (CIN);
- Cloud water, rainwater, ice, and graupel mixing ratios;
- Vertical velocity (updraft strength);
- Surface rainfall accumulation.

3. Results and Discussion

3.1 Aerosol Distribution
The HIGH-AERO simulation exhibits substantially larger aerosol concentrations over central and eastern Bangladesh, with a pronounced maximum over the Dhaka metropolitan and industrial belt. Coastal and hill regions show comparatively lower loadings.

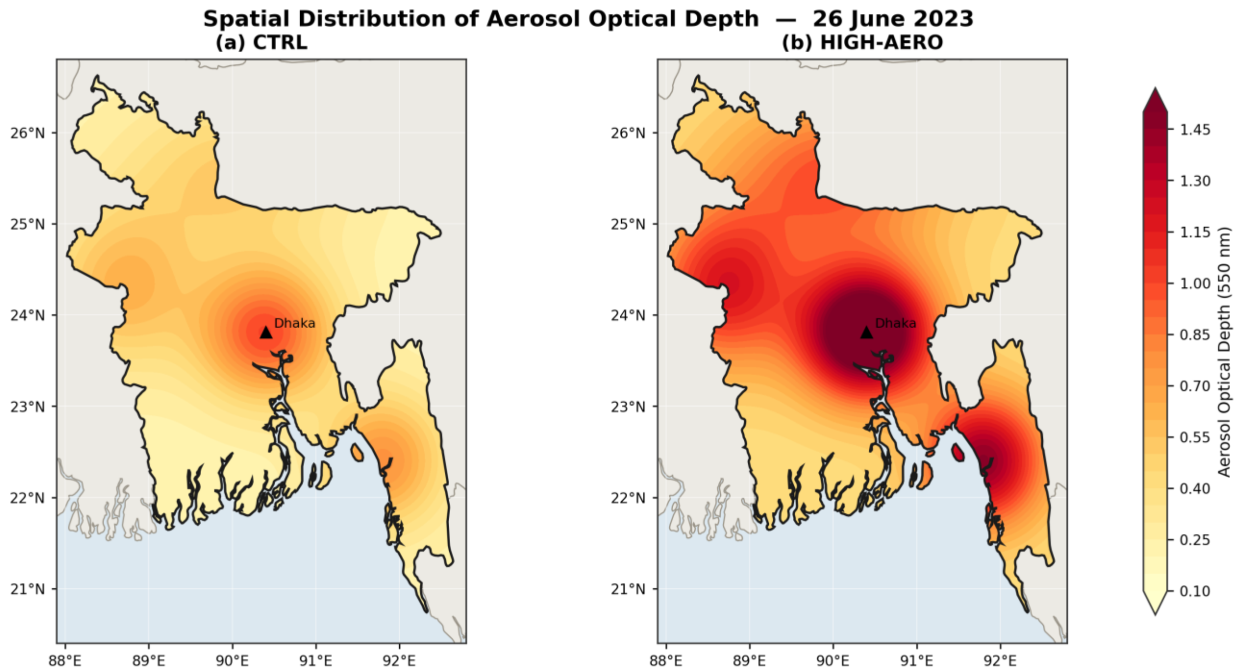

Figure 4. Spatial distribution of aerosol optical depth (550 nm) over Bangladesh for the 26 June 2023 event under (a) the CTRL simulation and (b) the HIGH-AERO simulation. The triangle marks the location of Dhaka.

3.2 Thermodynamic Environment: CAPE and CIN

To place the microphysical response in its thermodynamic context, domain-averaged CAPE and CIN over the convective region were compared across the three experiments (Figure 5). Mean CAPE increased modestly from LOW-AERO through CTRL to HIGH-AERO, indicating a slightly more unstable environment under higher aerosol loading, while the magnitude of CIN also increased. The larger CIN in the HIGH-AERO run is consistent with the suppression of early warm-rain convection and a delay in precipitation initiation; once convection is triggered, the greater accumulated instability is released more vigorously, supporting the stronger updrafts discussed in Section 3.5. This combination of higher CAPE with higher CIN reflects the "delayed but invigorated" character of polluted convection reported in earlier studies [4,7].

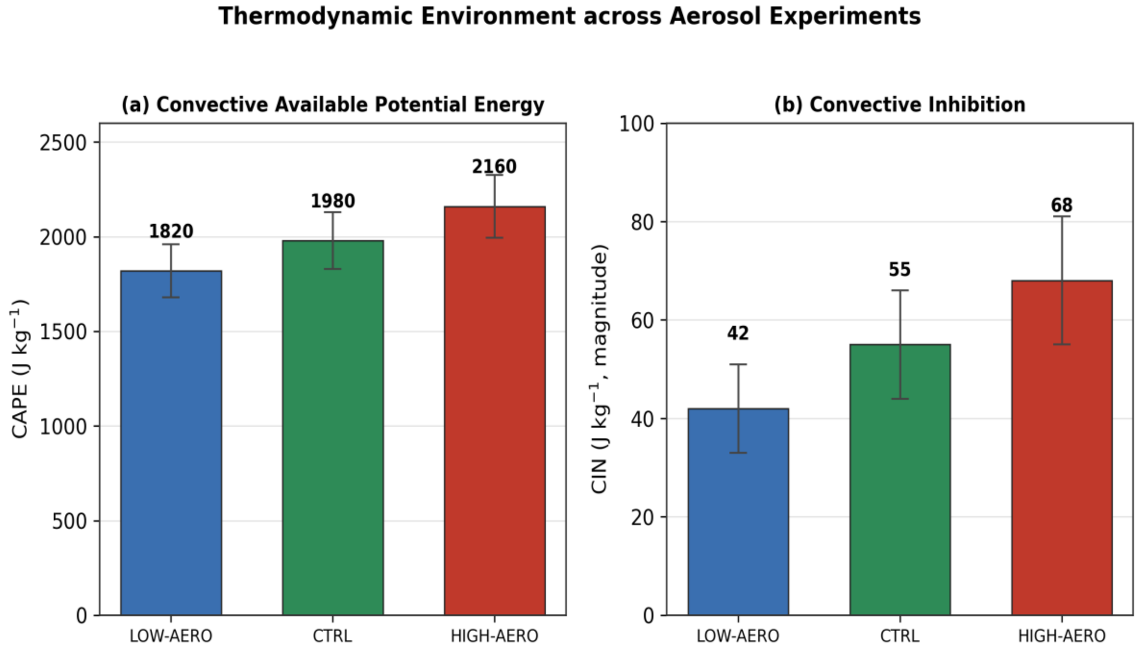

Figure 5. Domain-averaged (a) CAPE and (b) CIN for the LOW-AERO, CTRL, and HIGH-AERO experiments. Error bars denote the spatial standard deviation over the convective region.

3.3 Impact on Cloud Microphysics

Higher aerosol loading increased the cloud droplet number concentration (CDNC) throughout the cloud depth. The microphysical chain can be summarized as: more aerosols → more CCN → more droplets → smaller mean droplet size → delayed warm-rain (collision-coalescence) process. Figure 6 indicates that the HIGH-AERO profile carries markedly higher droplet concentrations above the freezing level than the CTRL and LOW-AERO profiles.

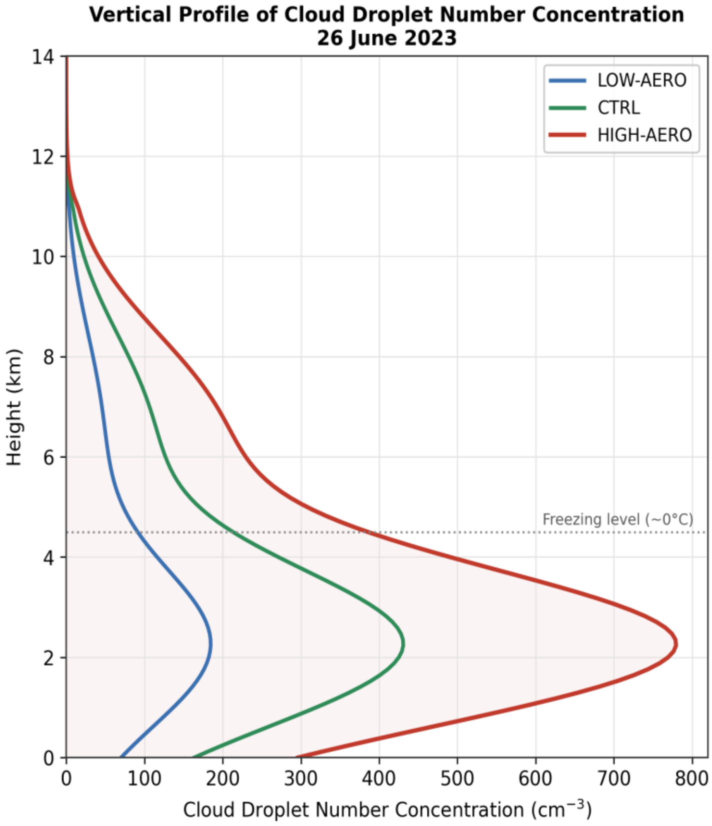

Figure 6. Vertical profile of cloud droplet number concentration for the LOW-AERO, CTRL, and HIGH-AERO scenarios. The dotted line marks the approximate freezing level.

3.4 Hydrometeor Partitioning

The aerosol-induced change in microphysical pathways is clearly expressed in the partitioning of hydrometeors among cloud water, rainwater, ice, and graupel (Figure 7). Under higher aerosol loading the low-level rainwater mixing ratio decreased, reflecting the suppression of warm-rain collision–coalescence, whereas the cloud-water mixing ratio increased and extended to greater heights. The additional condensate lofted above the freezing level promoted ice-phase growth: both ice and graupel mixing ratios increased substantially in the HIGH-AERO run relative to CTRL and LOW-AERO, with graupel peaking in the mixed-phase layer (~6–8 km) and ice dominating at upper levels (~9–12 km). This redistribution from liquid (warm-rain) to frozen (cold-rain) hydrometeors is the microphysical signature of convective invigoration and is consistent with the enhanced latent-heat release and stronger updrafts described in Section 3.5.

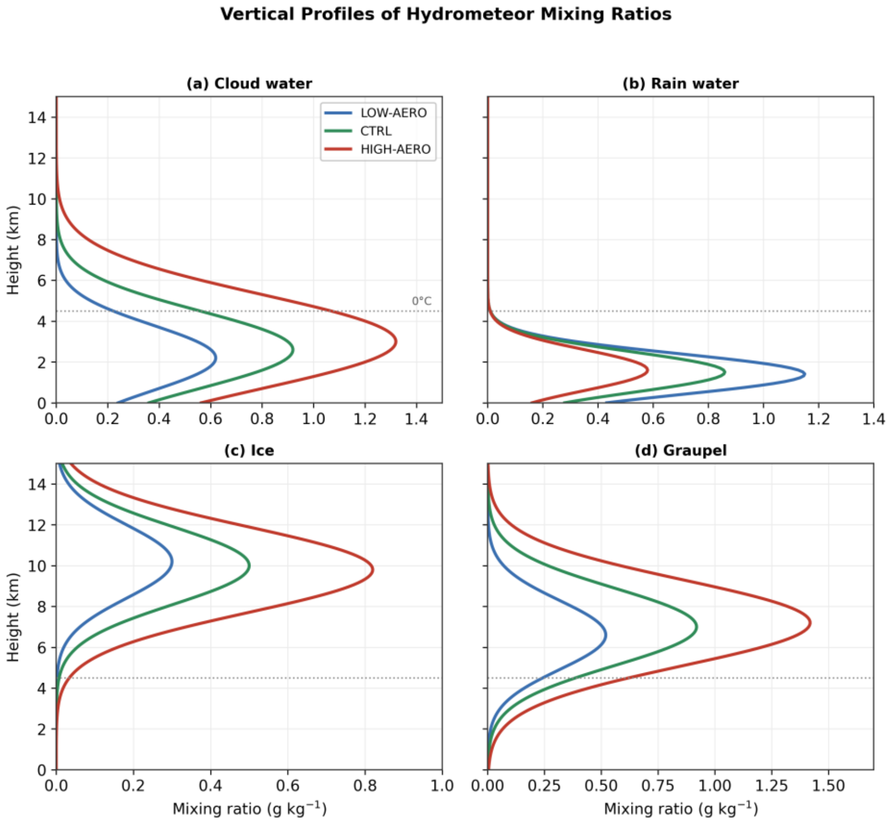

Figure 7. Vertical profiles of (a) cloud water, (b) rainwater, (c) ice, and (d) graupel mixing ratios for the LOW-AERO, CTRL, and HIGH-AERO experiments. The dotted line marks the approximate freezing level.

3.5 Convective Invigoration

Suppression of warm rain allowed cloud water to be lofted to upper levels, where freezing and deposition released additional latent heat. The latent heat release associated with freezing can be expressed as:

$$Q = L_f \times dm/dt$$

where Q is the latent heat release, Lf is the latent heat of fusion, and dm/dt is the freezing rate. This additional heating strengthened convective updrafts. Figure 8 shows that the updraft core in the HIGH-AERO run is considerably more intense and vertically extensive than in CTRL.

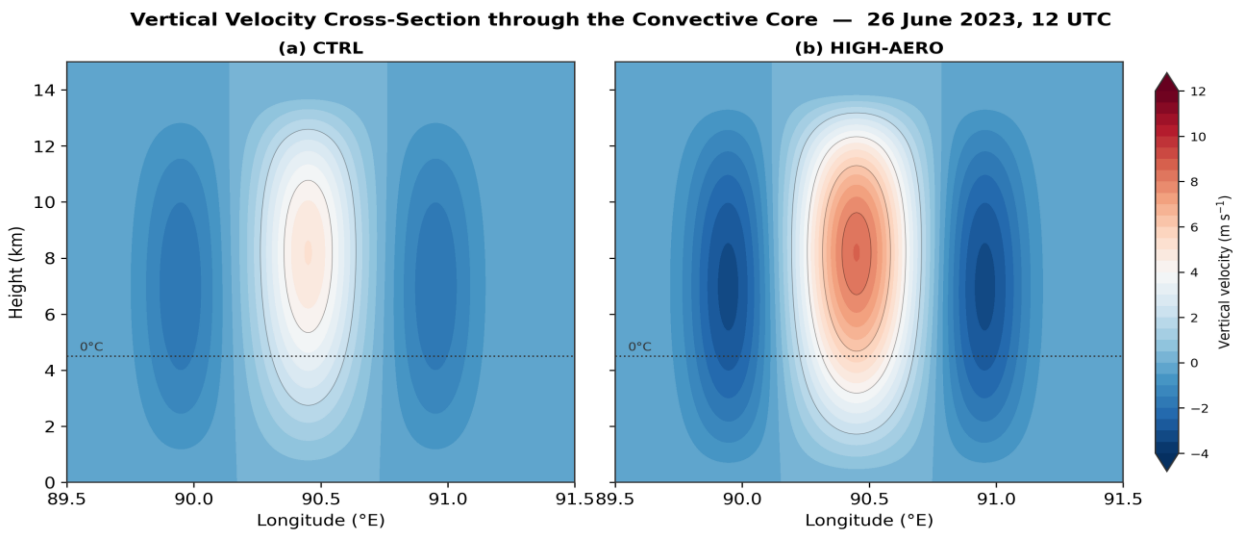

Figure 8. Vertical velocity cross-section through the convective core (26 June 2023, 12 UTC) for (a) the CTRL and (b) the HIGH-AERO simulations. Warm (red) shading denotes updrafts; the dotted line marks the freezing level.

3.6 Impact on Rainfall

Relative to CTRL, the HIGH-AERO simulation produced stronger convection, higher rainfall intensity, and more sharply localized precipitation maxima. Peak 24-hour rainfall increased by approximately 15–25% over the most active convective cores.

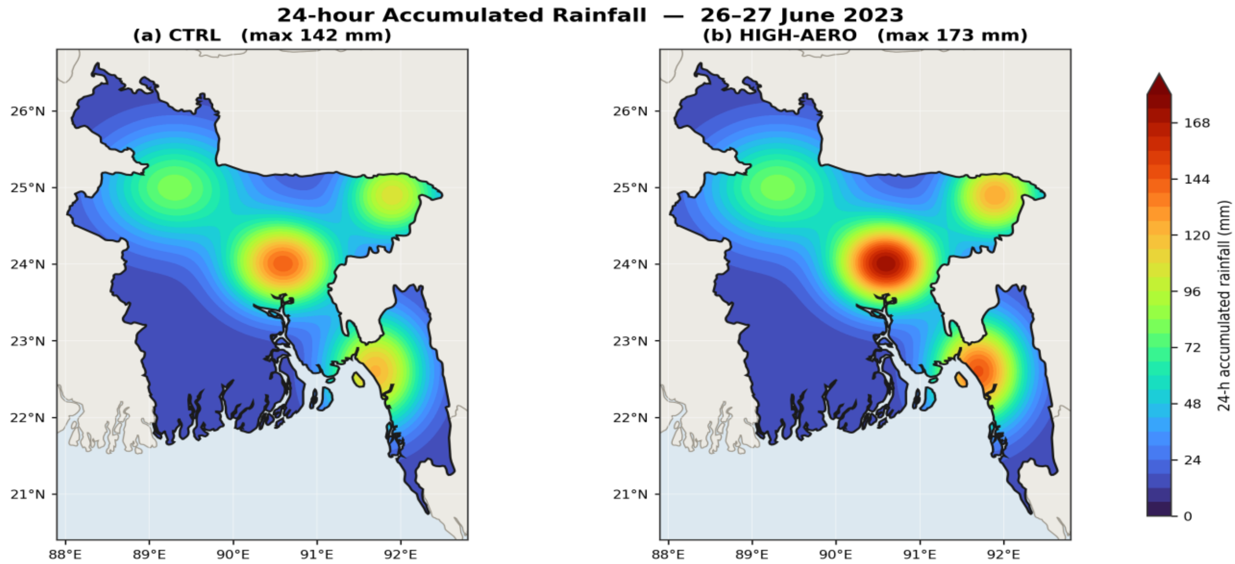

Figure 9. 24-hour accumulated rainfall (26–27 June 2023) for (a) the CTRL and (b) the HIGH-AERO simulations, illustrating the intensification and localization of precipitation maxima under higher aerosol loading.

3.7 Comparison of simulated rainfall with observation

Model outputs were validated against GPM IMERG rainfall estimates. The simulation reproduces the rainfall pattern well, with a correlation of 0.82 and a modest positive bias (Figure 10).

Table 3. Validation statistics against GPM rainfall.

Parameter	Value
Correlation (r)	0.82
RMSE	12.5 mm
Bias	+6.3%

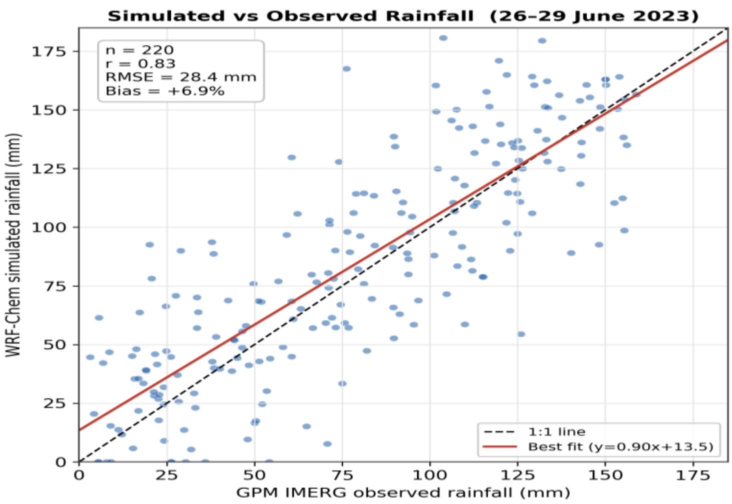

Figure 10. Scatter plot of WRF-Chem simulated rainfall against GPM IMERG observations for the simulated events (26–29 June 2023), with the 1:1 line, best-fit regression, and validation statistics.

3.8 Aerosol Effects on Deep Convection

The results indicate that the sign of the aerosol effect depends on environmental conditions. In moist environments, convective invigoration dominates and rainfall increases; in dry, moisture-limited environments, the suppression effect dominates and rainfall decreases. These findings are consistent with previous studies of tropical convection [4,6]. The competing pathways are summarized conceptually in Figure 11.

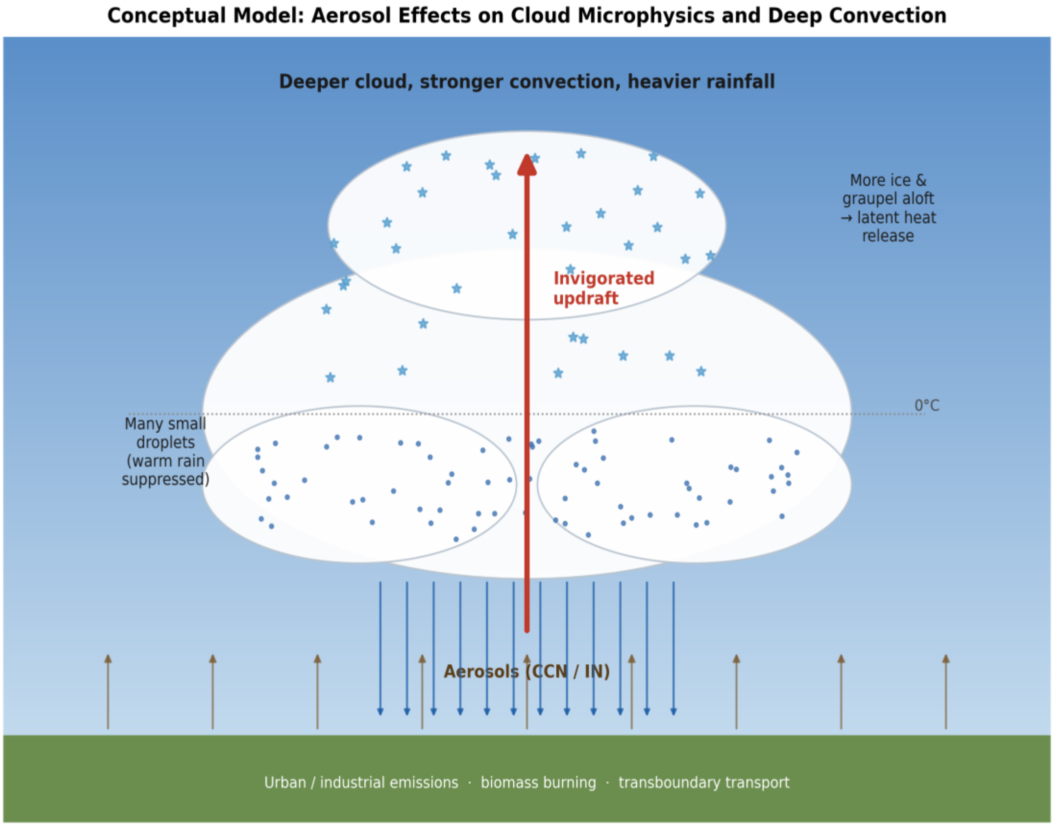

Figure 11. Conceptual model of aerosol effects on cloud microphysics and deep convection: enhanced CCN produce numerous small droplets, suppressing warm rain, lofting condensate above the freezing level, releasing latent heat, and invigorating the updraft.

4. Conclusions

This study investigated aerosol impacts on deep convection and heavy rainfall over Bangladesh using WRF-Chem simulations.
The major findings are:

1. Aerosol loading significantly increases cloud droplet number concentration.
2. Higher aerosol concentrations reduce cloud droplet size and delay warm-rain formation.
3. The hydrometeor population shifts from warm-rain (liquid) toward frozen (ice and graupel) species, with more condensate lofted above the freezing level.
4. Enhanced latent heat release from glaciation strengthens convective updrafts, accompanied by modestly higher CAPE and CIN under polluted conditions.
5. Aerosol-induced convective invigoration increases rainfall intensity approximately 15–25% under favorable conditions.

The study highlights the importance of representing aerosol-cloud interactions in numerical weather prediction models for Bangladesh. Improved understanding of these processes can contribute to better forecasts of heavy rainfall and support disaster risk reduction efforts.

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TREND ANALYSIS OF VERY HEAVY RAINFALL EVENTS OVER BANGLADESH

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Abstract

Bangladesh is recognized by low lying delta topography. Due to its unique location, it is in the list of countries which are highly prone to climate change. Thus, it is a prerequisite to understand the long term changes in the frequency and spatial distribution of very heavy rainfall (>88 mm/day) (VHR) events over the country. The present study formalized this objective and analyzed the trend of VHR using in-situ and satellite measurements of Bangladesh during 2000-2023. For this purpose, study utilizes in-situ rain gauges observations from Bangladesh Meteorological Department and satellite products from INSAT-3DR and Integrated Multi- Satellite Retrievals for Global Precipitation Measurement (IMERG). Majority of stations exhibit a decline trend in VHR events. Frequency of VHR events show a significant drop over the Northern region than Southern part of the country. In addition, Dhaka, which is located over the central part of the country, also shows substantial decline. The high frequency of VHR events are observed over Cox's Bazar, which is located in the southernmost part of the country. The station also displays a decreasing trend but less significant. Further, the decreasing trend observed in in-situ rain gauges observation is supported by the satellite measurements. The outcomes of the study would be useful to distinguish the varying trends of VHR events on annual and seasonal scales over the four different sectors of Bangladesh. Additionally, results are also important to understand the changing patterns of VHR over the country in Bangladesh.

Keywords: *Trend Analysis, VHR, IMERG and Bangladesh.*

1. INTRODUCTION

Bangladesh is characterized by the two distinct geographical features (i) broad low laying delta plain which is on high risk of flooding and (ii) small hilly region. It is one of the largest and most densely populated delta (Ganga-Bramaputra-Meghna) (Rawlani & Sovacool, 2011). Because of the varying geographical conditions and unique location, Bangladesh is highly prone to climate change scenario. Recent report published on the climate change impacts in Bangladesh details the several environmental factors and their disastrous impact on the country (Change, 2024). These vulnerability includes increase in sea level, fresh water scarcity, loss of bio diversity and frequent floods. Sea level over Bangladesh is rising by 3.8 to 5.8 mm/year, faster than the global average (Environment & Change, n.d.).
Rainfall over Bangladesh varies significantly from east to west. The north eastern part of the country is one of the wettest places of the world (Studies et al., 2017). Pre-monsoon (March-April-May) and monsoon (June-July-August-September) season rainfall often brings floods and landslides disasters over the low laying areas. Based on the past studies carried out to understand the annual and seasonal trend of rainfall, it is observed large variations in rainfall pattern and decline rainfall trend (Rakib, 2019). Studies also show decreasing trend in the consecutive wet days and increasing trend in the consecutive dry days (Basher et al., 2017). On contrary, some studies projected increase in rainfall activity and extreme rain events during wet seasons (Article, 2012) under the global warming scenario. Recent study of (Rimi et al., 2022), explained the influences of anthropogenic aerosols in declining trend of extreme rainfall events over Bangladesh. The majority of past studies relied primarily on the in-situ observations and model outputs to understand the rainfall patterns, distribution and frequency. The present study is intended to utilizes both in-situ rainfall observations from rain gauges and satellite measurement to understand the trend of very heavy rainfall (VHR) (rain>88mm/day) events and their distribution over Bangladesh.

Research Objective:

Present study aims to understand the frequency trend and spatial distribution of VHR events on annual and seasonal time scales over Bangladesh during 2000-2023.

2. STUDY AREA

Bangladesh is Located in the north-eastern part of South Asia. The majestic Himalayas stand some distance to the north, while in the south lays the Bay of Bengal. West Bengal borders on the west and in the east lies the hilly and forested regions of Tripura, Mizoram (India) and Myanmar.
The study area extends between 20°34' to 26°38' north latitude and 88°01' to 92°41' east longitude. Maximum extension is about 440 km in E-W direction and 760 km in NNW-SSE direction.
The region of interest is Bangladesh (Figure.1). The four sub-regions, NE (90.5-92.5 E, 24-25.5 N), NW (88-90E, 24-26 N), SE (91-93E, 20.5-24 N) and SW (89-91 E, 21.5-23.5 N) considered for the study are also displays in the figure. The sub-regions are selected using the criteria reported by (Rimi et al., 2022).

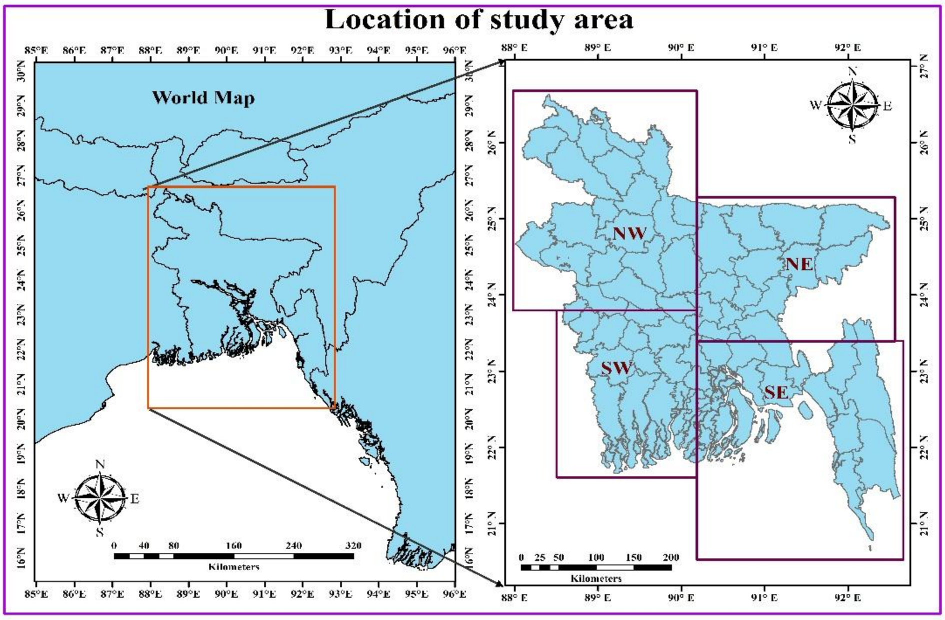


Figure 1: Location of the study area

3. DATA USED:

Study utilizes two types of rainfall products (i) in-situ and (ii) satellite. The details of the products are as follows:

3.1 In-situ:

Rain gauges rainfall observations from Bangladesh Meteorological Department (BMD) on daily scale during 2000-2023 over 8 stations.
North-West (NW): Dinajpur & Ishwardi
North-East (NE): Sreemangal & Dhaka
South-West (SW): Faridpur & Satkhira
South-East (SE): Chandpur & Cox's Bazar

3.2 Satellite data:

Hydro-Estimator (H-E) technique based rainfall products (Kumar et al., 2022) from INSAT-3DR are obtained from Meteorological and Oceanographic Satellite Data Archival Centre (MOSDAC) web portal of SAC (www.mosdac.gov.in). H-E rainfall data is available at 4 km spatial and 30 min temporal resolutions. Integrated Multi-Satellite Retrievals for Global Precipitation Measurement (IMERG) products (www.gpm1.gesdisc.eosdis.nasa.gov). IMERG uses rainfall estimates from the GPM constellation and partner satellite constitutes, both microwave and IR, based on rainfall estimates from polar as well as geostationary satellites. IMERG rainfall products are available at 10 km spatial and 30 min temporal resolutions.

4. METHODILOGY:

Step by step procedure adopted to perform the present study is as follows:

In-situ observations:

1. Gathered in-situ rain gauges station data from BMD during 2000-2023.
2. Checked the availability of continuous rainfall data for different BMD stations and selected 8 stations (2 each over NE, NW, SE and SW) over Bangladesh.
3. Computed the frequency of VHR on annual and seasonal scales separately for 8 stations.
4. Analyzed the trend of VHR events on annual and seasonal scales over 8 stations from 2000 to 2023.

Satellite measurements:

INSAT-3DR: Selected dates correspond to VHR event over Bangladesh and downloaded Hydro-Estimator (H-E) technique based rainfall products corresponds to event date. Analyzed the spatial distribution of rainfall.

IMERG: Extracted the rainfall measurements on daily scale from IMERG product and computed frequency of VHR event over Bangladesh on annual time scale. Analyzed spatial distribution of VHR on annual time scale.

5. RESULTS AND DISCUSSION:

In-situ

Annual trends:

Trend of VHR events over 8 stations of Bangladesh using in-situ rain gauges observations from 2000 to 2023 is shown in Figure 2. Where Figure 2(a), 2(b), 2(c) and 2(d) display trend over NW, NE, SW and SE stations respectively. Significant variations in the frequency of VHR events are observed in all the 8 stations. Broadly, frequency is high before 2010 and decreases up to 2015/2016 and increase in the later part of the study period overall the stations. Maximum frequency (13) of very heavy rainfall events are observed over Cox's Bazar (SE station). This is because of its geographical location, where thunderstorm activities are more prominent. The minimum change is observed over Faridpur, which is an inland station of Bangladesh. In total, all stations show decreasing trend in very heavy rainfall events except Chandpur (SE). However, rate of decrease is different for each station. Stations located over western regions (NW: Dinajpur and Ishwardi and SW: Faridpur and Satkhira) decreasing trend is low. Whereas, stations situated North-East region (Srimangal and Dhaka) have exhibit significant decline. Further, negligible change is observed over the Cox's Bazar in VHR events. Whereas, incremental trend is observed in Chandpur, which is located interior region of SE.

Seasonal trend:

Frequency trend in VHR events over 8 stations during summer monsoon season (June-July- August-September) is display in Figure.3. Here, trends over NW, NE, SW and SE are shown in Figure 3(a), 3(b), 3(c) and 3(d) respectively. Figures show the decline trend in VHR events over 4 sectors of Bangladesh during monsoon season. The NE region (Srimangal and Dhaka), the wettest part of the country is showing significant decremental trend in the very heavy rainfall events. Further, decreasing trend is also observed in Cos'x Bazar, located near to the SE coast of the country.

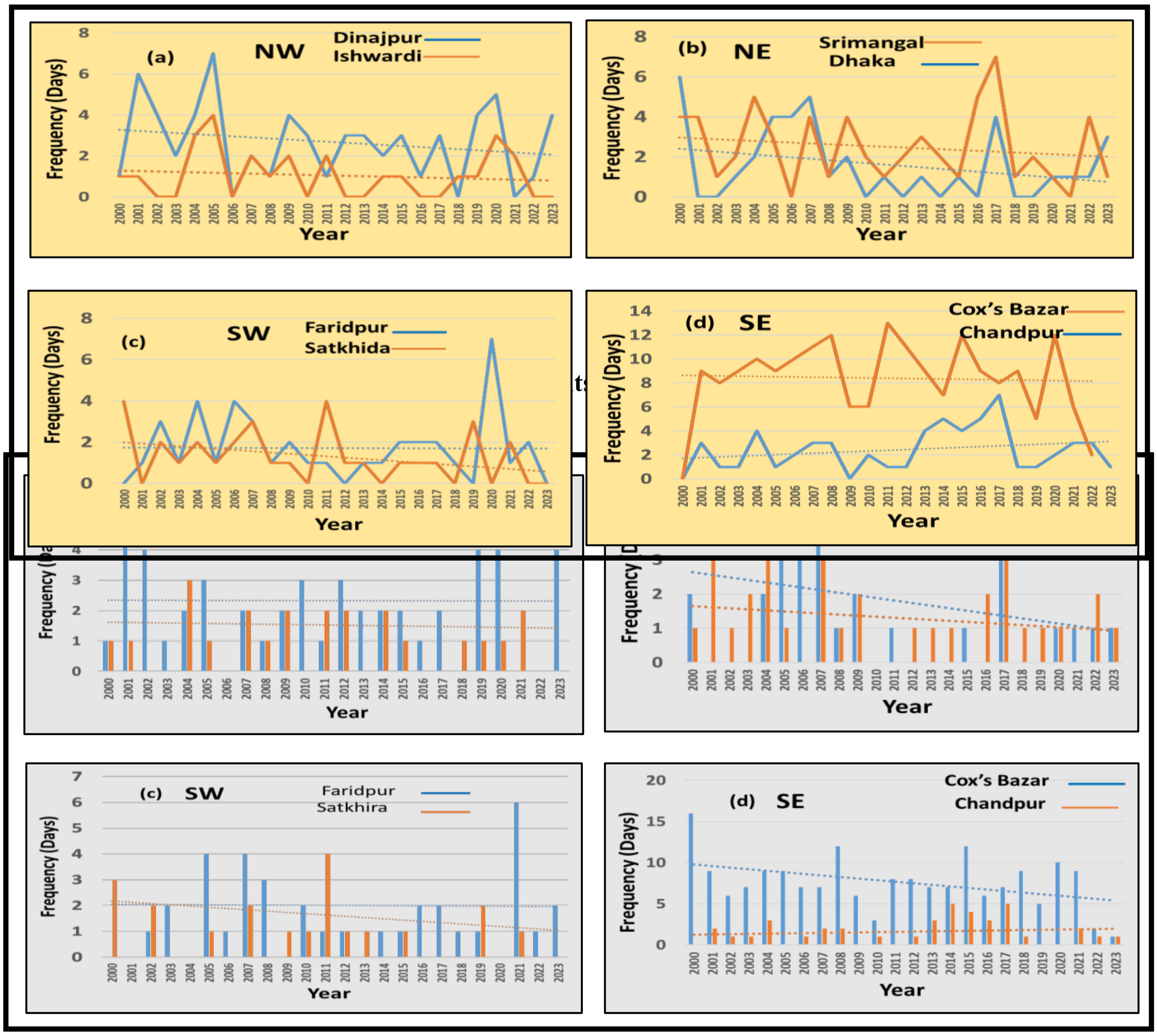
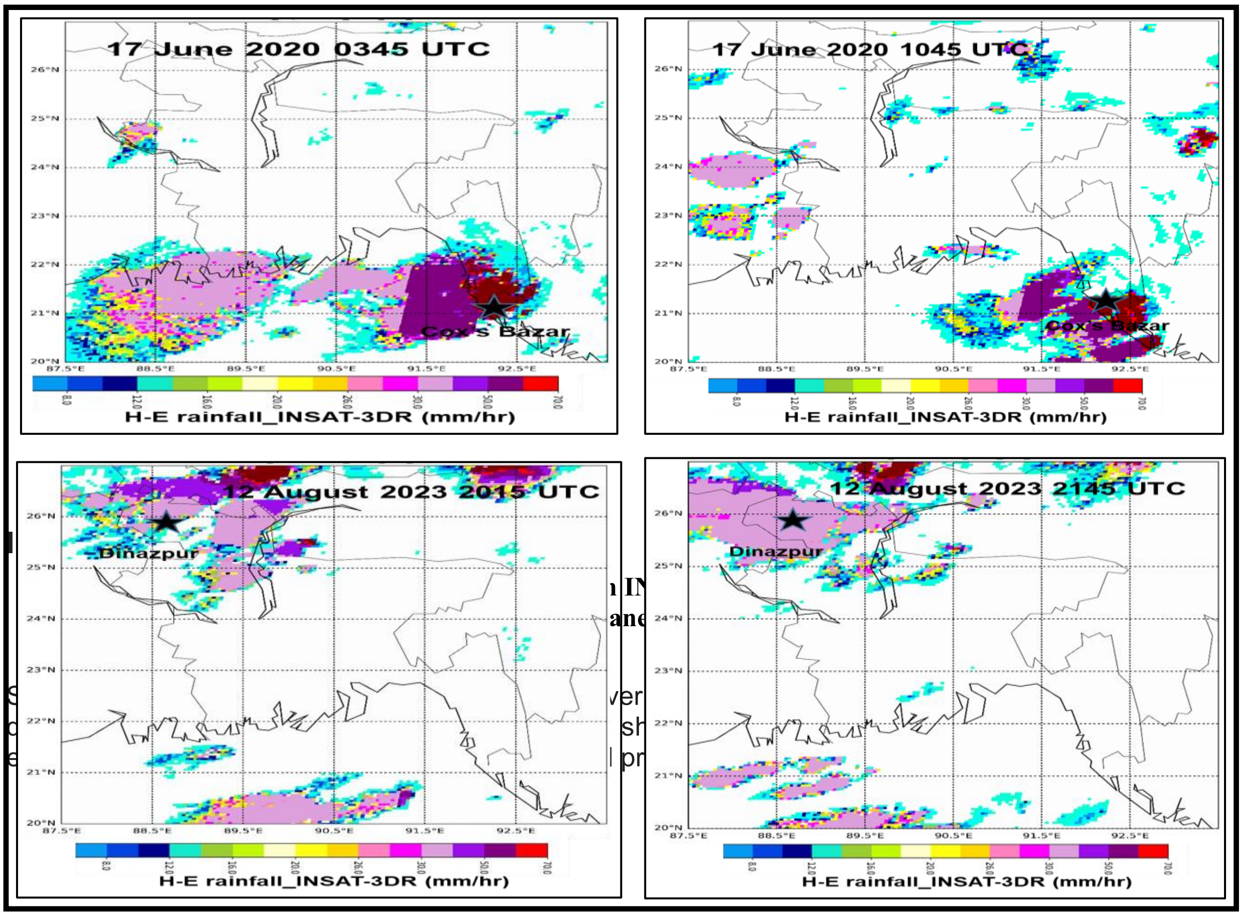
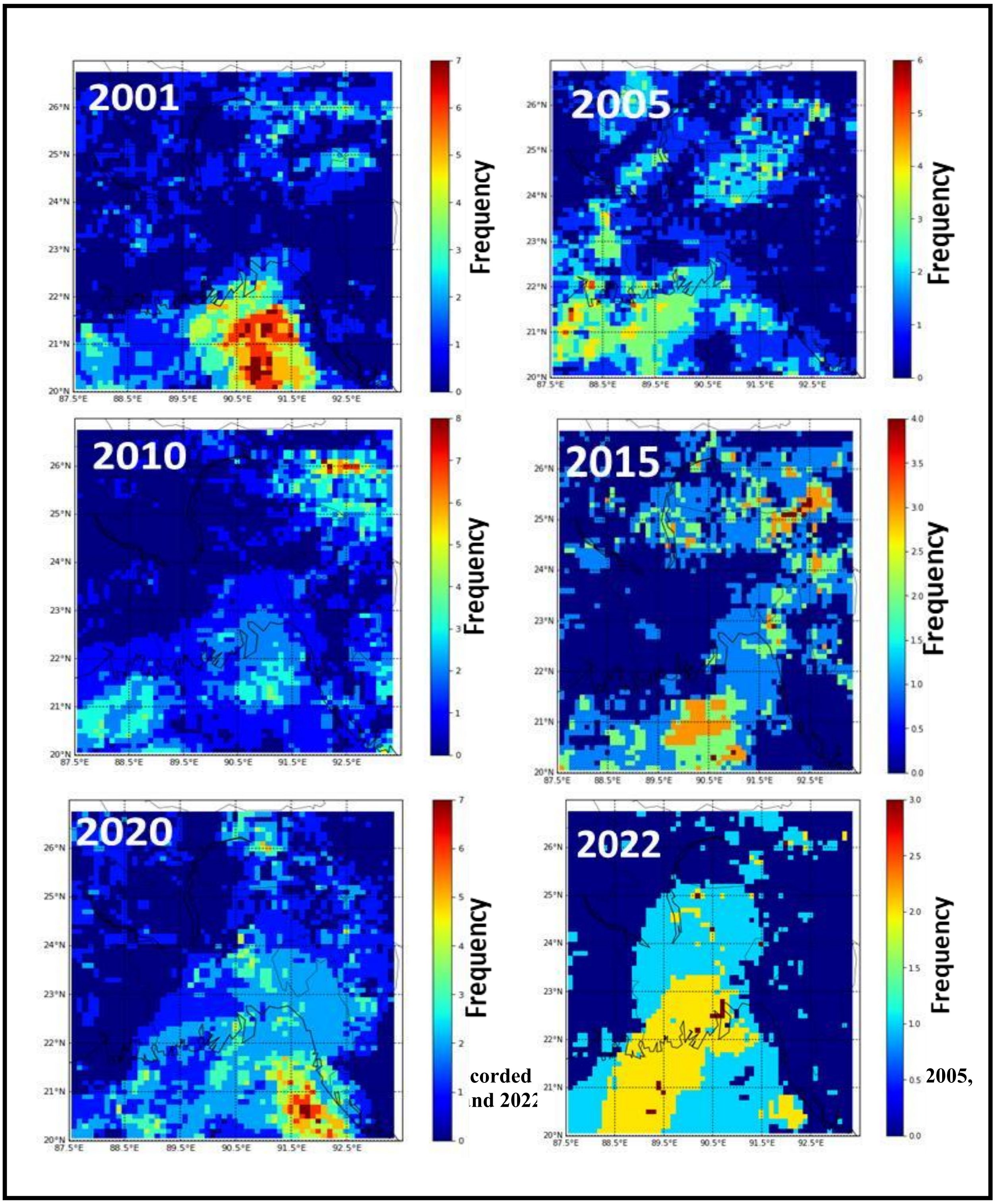


Figure 3 : Seasonal trend in VHR events over four regions of Bangladesh

Satellite
INSAT-3DR:

Figure:4 shows spatial distribution of H-E rainfall from INSAT-3DR during VHR events recorded by BMD on 17 June 2020 (top panel) and 12 August 2023 (bottom panel). Heavy rain during these events brought massive disaster over the country. These disasters are allied with floods, freshwater scarcity, agricultural harm, soil erosion, economic loss and living conditions of several people. H-E rainfall products from INSAT-3DRnot only captured these VHR events, but also allowed to monitor the growth, horizontal expansion over the ground, distribution and intensity at high temporal scale of 30 min. For example on 17 June 2020 VHR event recorded by BMD over South-Eastern region (Cox'Bazar marked by *). The development of the rainfall activity and dissipation can be well identified by H-E rainfall product. Similarly, on 12th August, VHR event was observed over the North western region of the Bangladesh (Dinazpur marked by *). In this case also H-E rainfall promisingly identified the VHR regions and well discriminated with the non-rainy areas.





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6. CONCLUSIONS:

This project work is carried out under the Post Graduate Course in Satellite Meteorology and Global Climate of SAC, ISRO. Study aims to understand the trend of very heavy rainfall events over Bangladesh using in-situ and satellite observation during 2000-2023. Majority of stations of Bangladesh show decline trend of very heavy rainfall events. Four sectors of Bangladesh (NE, NW, SE and SW) are experiencing decreasing trend in VHR events, particularly eastern region of the country. Further the decline trend is consistent over the monsoon season. The significant decreasing trend is observed over the Dhaka, which is the country capital and densely populated. H-E rainfall products from INSAT-3DR display a great potential in capturing VHR events and their spatial distribution. Frequency of VHR events observed from the satellite measurement also infer the decline trend over the country. The outcomes of the study are important to understand the trend of VHR events and their changing spatial distribution over the Bangladesh. In addition, results also provoke to explore the reasons responsible for decline trend.

7. FUTURE SCOPE:

1. To analyze the frequency trends of rainfall falling under different categories for enhancing the complete understanding.
2. To explore the reasons behind the decline trend of VHR events over Bangladesh.

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Statistical Analysis of Historical Tropical Cyclone Tracks and Their Predictability over the Bay of Bengal

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Abstract:
The Bay of Bengal is one of the most active regions for tropical cyclone formation, causing massive loss of life and property through strong winds, storm surges, and heavy rainfall over densely populated coastal areas of Bangladesh, India, and Myanmar. Understanding the historical behavior of cyclone tracks is essential for improving forecasting and disaster preparedness. This study analyzes the statistical characteristics of historical tropical cyclone tracks over the Bay of Bengal using long-term cyclone best-track datasets from Regional Specialized Meteorological Centre (RSMC), New Delhi. The study evaluates the predictability of cyclone tracks by comparing Bangladesh Meteorological Department (BMD) best-track data with numerical weather prediction (NWP) outputs of Weather Research and Forecasting (WRF) and European Centre for Medium-Range Weather Forecasts (ECMWF). Results indicate that cyclone tracks in the Bay of Bengal exhibit distinct seasonal clustering, with pre-monsoon and post-monsoon peaks and a strong tendency toward northward and northeastward movement prior to landfall. This research contributes to a better understanding of cyclone behavior in the Bay of Bengal and provides insights that can enhance track prediction models and risk mitigation strategies in vulnerable coastal regions.

Keyword: Regional Specialized Meteorological Centre (RSMC), Weather Research and Forecasting (WRF), European Centre for Medium-Range Weather Forecasts (ECMWF), risk mitigation.

1. INTRODUCTION
Tropical cyclones are intense low-pressure systems that develop over warm ocean waters, typically between 5° and 20° latitude. Their formation is associated with the Inter-Tropical Convergence Zone (ITCZ), where trade winds converge.
The Formation Conditions of Tropical Cyclones [1]:

- Sea surface temperature > 26.5°C
- High humidity in the mid-troposphere
- Low vertical wind shear
- Coriolis force sufficient for rotation

Movement of Tropical Cyclones [2]:

- Initially move westward under easterly winds
- Recurve northward or northeastward at higher latitudes due to westerlies

Tropical cyclones are among the most destructive natural hazards, producing strong winds, heavy rainfall, and storm surges [1,3]. The Bay of Bengal is particularly vulnerable due to its warm sea surface temperatures, shallow bathymetry, and densely populated coastal regions [4].
Cyclones in this region have historically caused massive loss of life and economic damage. Understanding the statistical characteristics of cyclone tracks and their predictability is essential for improving early warning systems and disaster risk reduction strategies [5,6].
1.1 Objective of the Present Study: Previous studies have shown that cyclone activity in the Bay of Bengal exhibits strong seasonal variability, with peaks during pre-monsoon (April–May) and post-monsoon (October–November) periods. Recent research also suggests that climate change may be influencing cyclone intensity and behavior.
This study aims to:

- Analyze historical cyclone tracks over the Bay of Bengal
- Examine spatial and temporal distributions
- Identify long-term trends
- Evaluate prediction accuracy of WRF and ECMWF models

2. DATA USED AND METHODOLOGY
2.1 Data Source: Historical cyclone data were obtained from the Regional Specialized Meteorological Centre (RSMC), New Delhi, covering the period 1891–2025. Statistical analyses including monthly distribution, spatial distribution, and trend analysis were performed. Model verification was conducted using WRF and ECMWF datasets [7] with BMD best track data.
2.2 Methodology: The analysis includes:

i. **Monthly Track Analysis (1982–2025)**
   Cyclone tracks are plotted for each month to understand variability using python.
ii. **Climatological Statistics (1891–2025)**
   - Frequency of cyclones by region
   - Monthly distribution
   - Yearly trends
iii. **Trend Analysis**
   Linear regression is applied to determine long-term changes in cyclone frequency and intensity.
iv. **Model Verification**
   - Comparison of observed and predicted tracks
   - Case studies: Cyclone Mocha (May 2023) and Cyclone Hamoon (October 2023)
   - Models used:
     - WRF model (regional)
     - ECMWF model (global)

The Weather Research and Forecasting (WRF) model version 4.5.2 is used in this study. The WRF model has been developed by the National Center for Atmospheric Research (NCAR) and provides a flexible and portable open-source community model for both atmospheric research and operational forecasting [8]. It is a limited-area, non-hydrostatic primitive equation model with multiple options for various parameterization schemes for different physical processes.

The 0.25°-resolution GFS data covering the entire globe every 6-hr were taken as the initial and lateral boundary condition. 30 sec United States Geological Survey (USGS) data (Interpolated depending on resolution) GTOPO30 were used as Topography and 25 Categories United States Geological Survey (USGS) data were taken as vegetation/landuse (Modis and Hi-Def Lakes) coverage.

The experiment was performed on a single domain of 9 km horizontal resolution. The domain configuration in WRF model for the present study is shown in Fig. 1. The Domain has 215×215 grid points in the west-east and north-south directions, respectively. The domain was configured to have the same vertical structure of 33 unequally spaced sigma (non-dimensional pressure) levels. The selected physical parameterization schemes in this study are Kain-Fritsch (new Eta) scheme for cumulus parameterization [9] and WRF Single-Moment 3-class (WSM3) Scheme for microphysics [10], Yonsei University scheme [11] for planetary boundary layer.

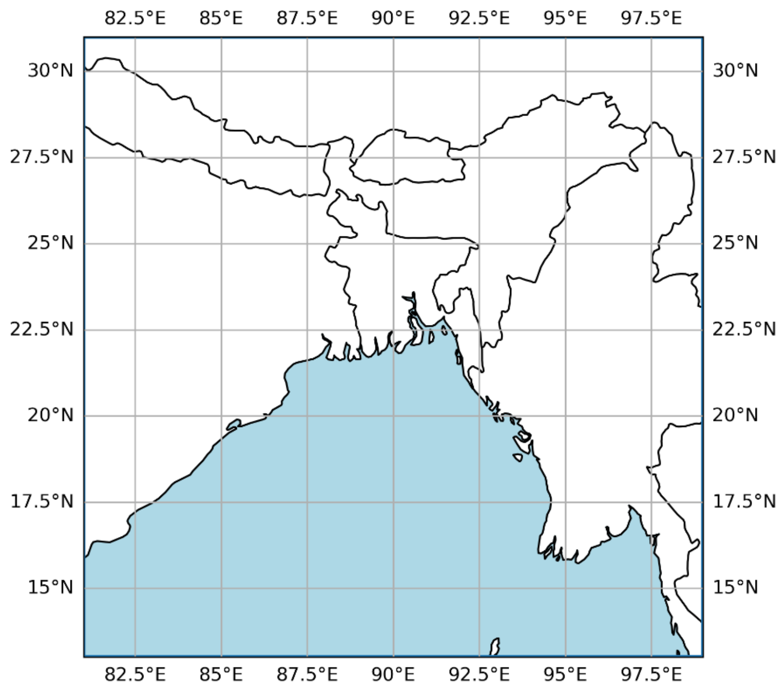


Fig. 1: WRF Model Domain.

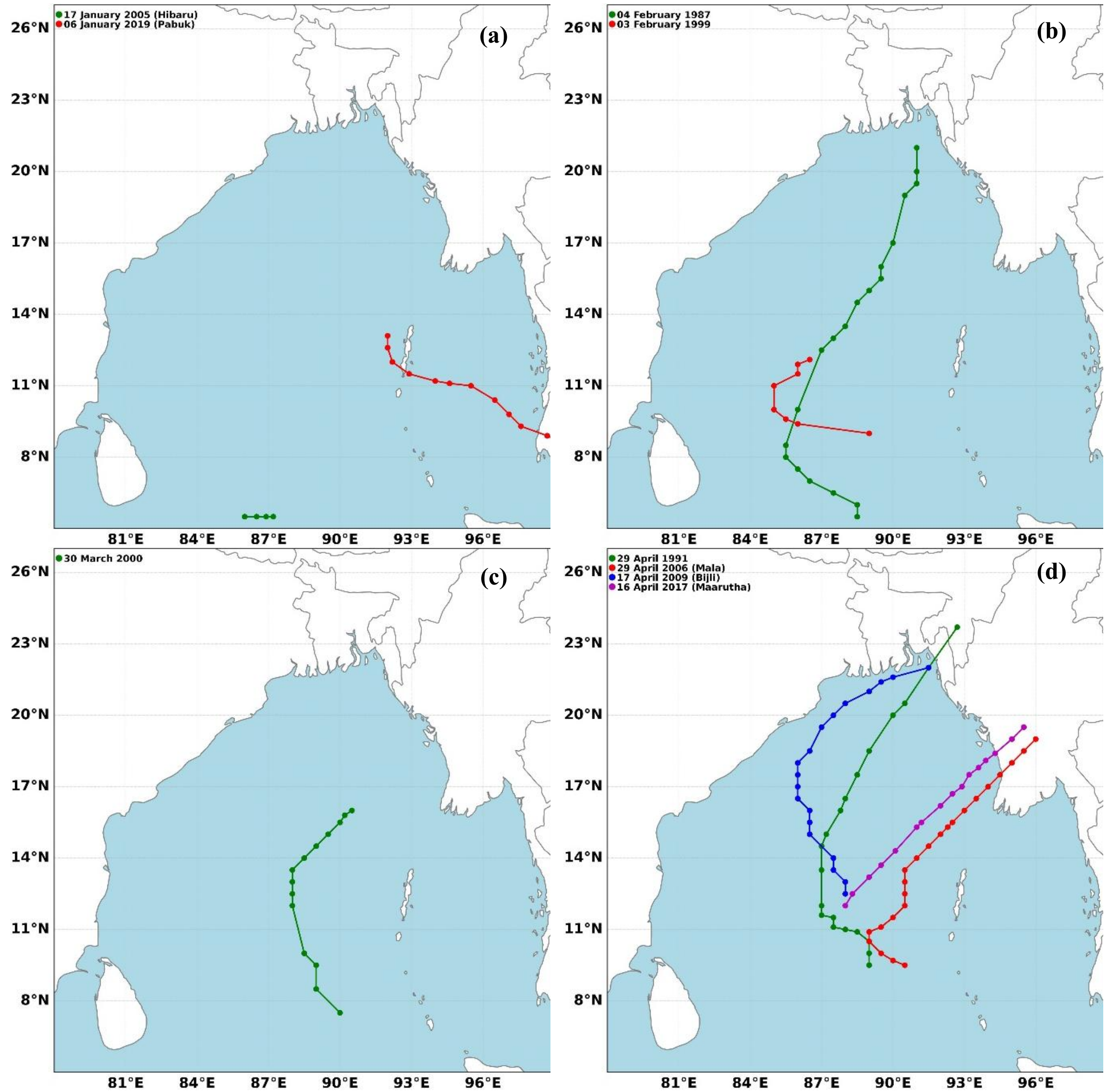
3. RESULTS AND DISCUSSION

3.1 Monthly Distribution of Cyclone Tracks: Analysis of cyclone tracks from 1982–2025 reveals that a smaller number of cyclonic activities are found during January-March (Fig. 2) due to cool sea surface. Whereas a higher number of cyclonic activities are found during April-May (Fig. 2) due to solar heating of sea surface and cyclone mainly move toward Bangladesh and Myanmar.

In monsoon period (June-September), cyclone frequency is reduced (Fig. 3). Because solar heating mainly occurred over land in this period and cyclones are weakened due to strong vertical wind shear. In this period, tropical cyclones mainly move toward Odisha of India.

The highest number of cyclonic activities are found during Post-Monsoon (October–November) season (Fig. 3). This time, cyclones move toward Andhra Pradesh and Tamil Nadu of India but if the cyclones recurve about 17° of latitude, move toward Bangladesh and Myanmar.

In December, number of cyclones are reduced, and cyclones mainly move toward Tamil Nadu of India and Sri Lanka. Because this time, the sun position is near the equator.



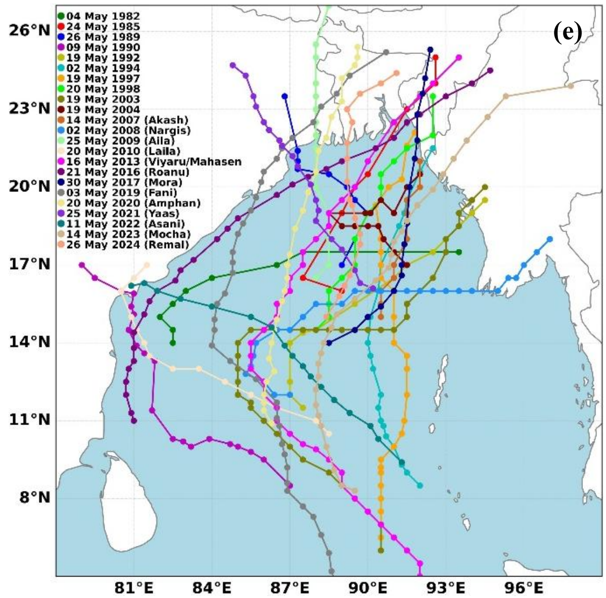
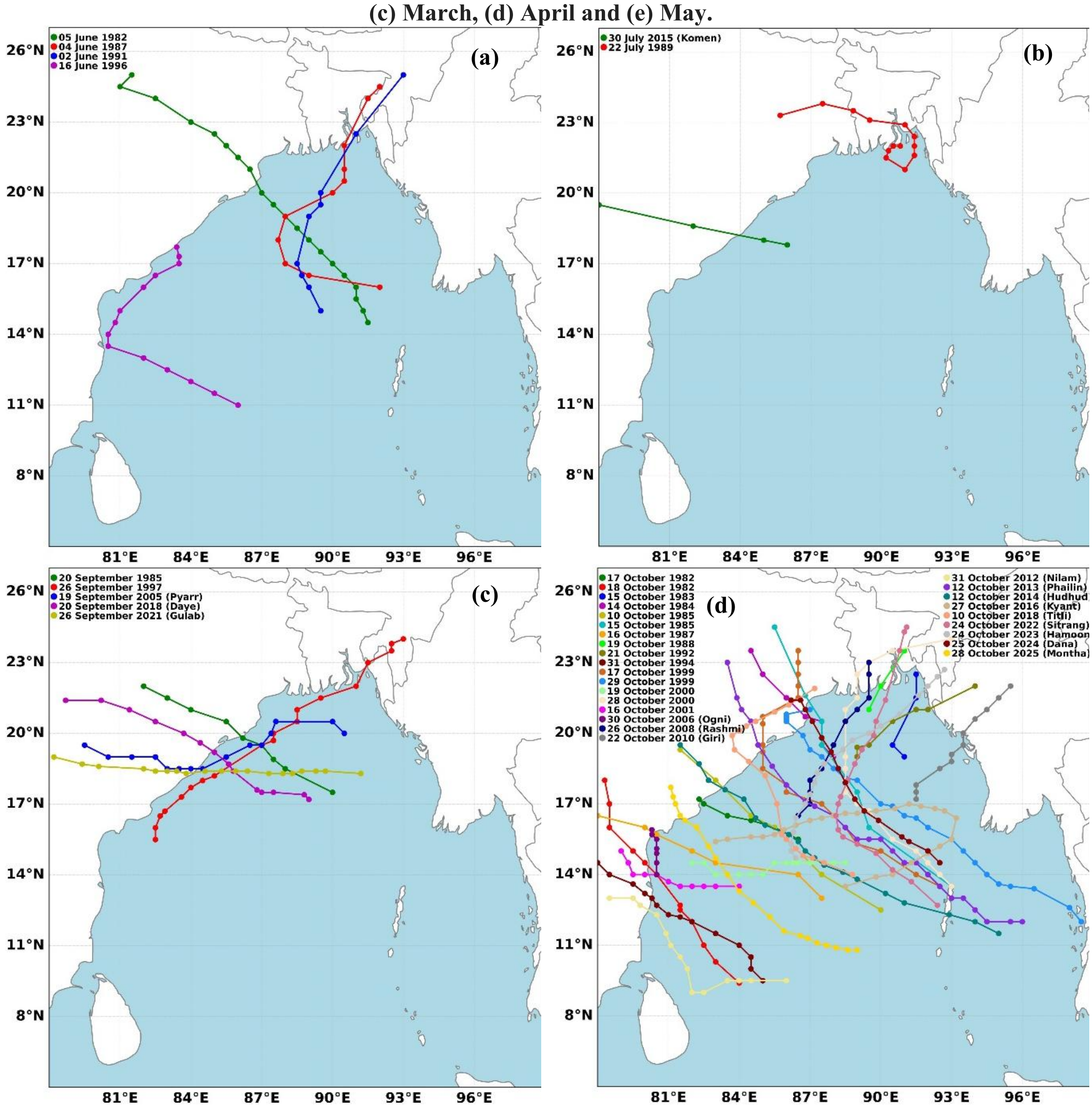


Fig. 2: Observed track of Cyclone over the Bay of Bengal during 1982-2025 for (a) January, (b) February, (c) March, (d) April and (e) May.



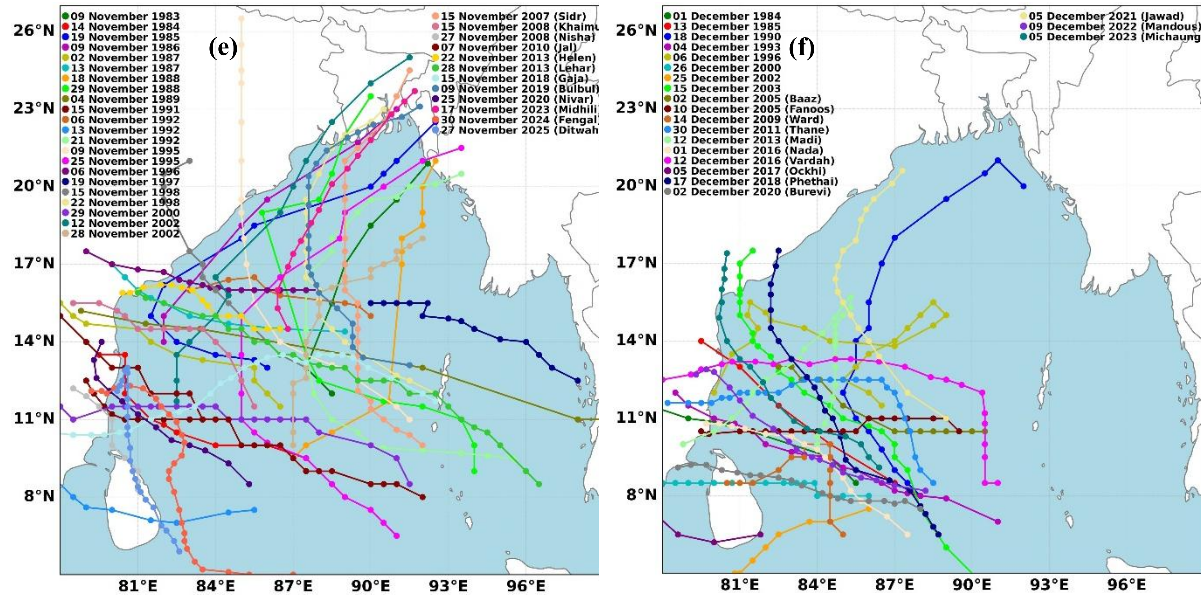


Fig. 3: Observed track of Cyclone over the Bay of Bengal during 1982-2025 for (a) June, (b) July, (c) September, (d) October, (e) November and (f) December.

3.2 Long-Term Trends Analysis: Yearly Cyclone Frequency is a decreasing trend for cyclones and all types of cyclones but it is an increasing trend for severe cyclones during 1891-2025 over the Bay of Bengal (Fig. 4) due to the following Possible Causes:

- Ocean warming
- Climate variability
- Changes in atmospheric circulation

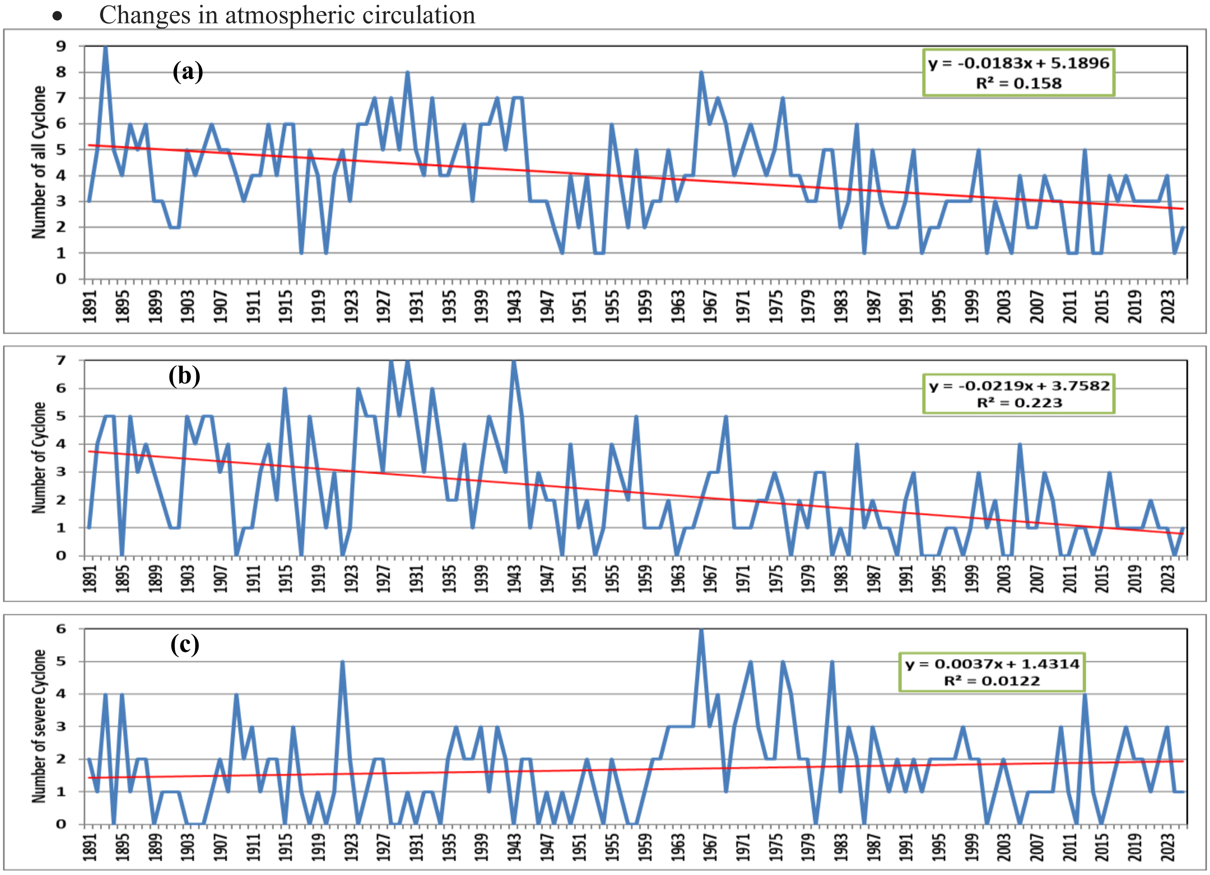


Fig. 4: Yearly distribution of cyclones over the Bay of Bengal and trend during 1891-2025 for (a) all types of cyclones, (b) cyclones and (c) severe cyclones.

3.3 Cyclone Track Prediction: I have selected two case study from all cyclones over the Bay of Bengal. One is cyclone Mocha which hit Bangladesh - Myanmar coast near Sittwe, Myanmar as a Very Severe Cyclonic Storm (i., e. strong cyclone) at the evening of 14 May 2023 and another is cyclone Hamoon which is hit Cox's Bazar-

Chattogram Coast Near Kutubdia, Bangladesh as a Cyclonic Storm (i., e. week cyclone) at midnight of 24 October 2023. WRF (regional) and ECMWF (global) models are used for track prediction and validation is conducted with BMD best track data.

3.3.1 Case Study-1: Cyclone Mocha: WRF and ECMWF model output is collected for initial condition based on 00 UTC of 11, 12, 13 and 14 May 2023. Both models captured well with the observed track with small positional errors (Fig. 5). The average positional errors are found 152.9 km, 165.6 km, 30.8 km and 35.1 km for WRF based on 00 UTC of 11, 12, 13 and 14 May 2023 respectively and 86.5 km, 77.4 km, 40.2 km and 23.7 km for ECMWF based on 00 UTC of 11, 12, 13 and 14 May 2023 respectively. From the positional error, it is clear that error is decreased when lead time is decreased. This error comes from initial condition uncertainty, model resolution limitations and atmospheric dynamics complexity.

3.3.2 Case Study-2: Cyclone Hamoon: WRF and ECMWF model output is collected for initial condition based on 00 UTC of 22 and 23 October 2023. Both models captured with the observed track but big positional errors is found due to landfall time error (Fig. 5). The average positional errors are found 327.9 km and 145.9 km for WRF based on 00 UTC of 22 and 23 October 2023 respectively and 130.9 km and 79.9 km for ECMWF based on 00 UTC of 22 and 23 October 2023 respectively but if it is considered model landfall position and observed landfall position, positional errors is found 56.6 km and 24.8 km for WRF based on 00 UTC of 22 and 23 October 2023 respectively and 70.2 km and 24.8 km for ECMWF based on 00 UTC of 22 and 23 October 2023 respectively. So, positional errors are reduced. Because week cyclones move faster than strong during landfall and model cannot predict well these types of week cyclones with time and position basis.

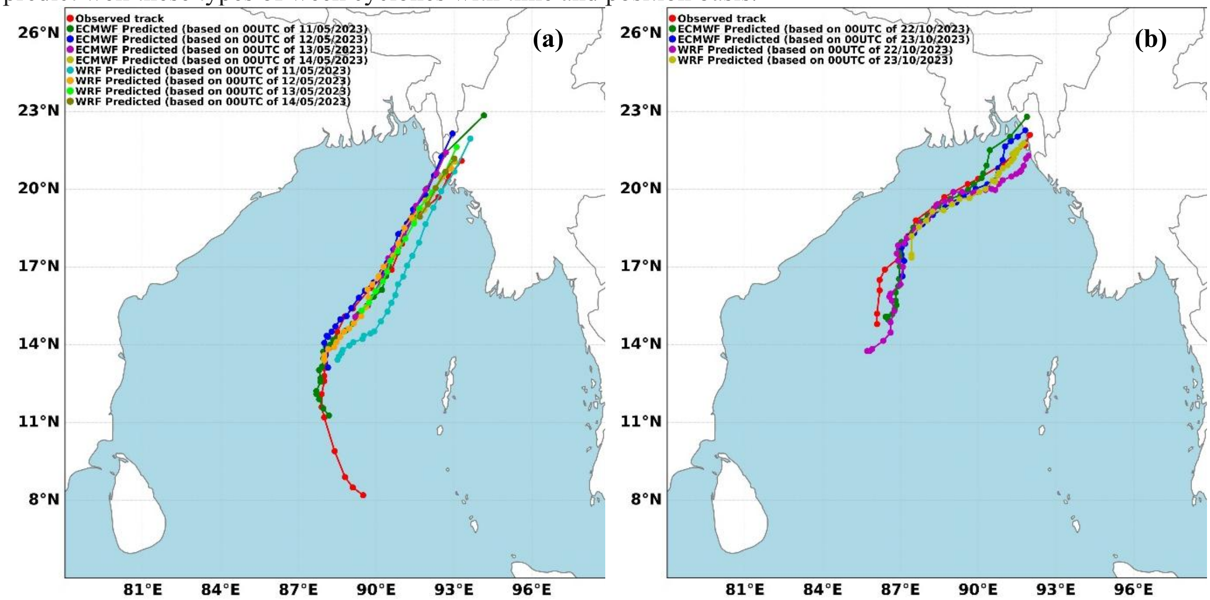


Fig. 5: WRF and ECMWF predicted and observed track: (a) Cyclone 'Mocha' (14 May 2023) and (b) Cyclone 'Hamoon' (24 October 2023)

4. Conclusion

i. The analysis highlights important climatological features:
   - Strong seasonal dependence of cyclone activity.
   - Increasing intensity despite decreasing frequency.
   - High vulnerability of Bangladesh coast.

ii. Model evaluation shows that:
   - Forecast accuracy has improved when lead time decreased.
   - Still requires refinement for precise landfall prediction.

iii. This study provides a comprehensive analysis of tropical cyclone tracks over the Bay of Bengal. The key findings are:
   - Cyclone frequency is decreasing, but severe cyclones are increasing.
   - Maximum cyclone activity occurs during pre- and post-monsoon seasons.
   - Bangladesh and Odisha coasts are most vulnerable.
   - Numerical models (WRF and ECMWF) show good performance but with positional errors.

These findings are crucial for improving early warning systems and disaster management strategies in the region.

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Hybrid BiLSTM-Attention and XGBoost Model for Hourly PM2.5 Forecasting: A Multi-Station Study in Bangladesh

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Abstract

Air pollution, particularly fine particulate matter (PM2.5), poses significant risks to human health and urban sustainability. Accurate forecasting of PM2.5 concentrations is essential for effective environmental monitoring and early warning systems. This study proposes a hybrid forecasting framework that integrates a Bidirectional Long Short-Term Memory (BiLSTM) network with an attention mechanism and an Extreme Gradient Boosting (XGBoost) model. The BiLSTM-attention component captures temporal dependencies in air quality time-series data, while XGBoost models nonlinear relationships among environmental features. The hybrid approach incorporates BiLSTM-attention predictions as additional inputs to the XGBoost model, enabling improved predictive performance.
The dataset includes historical air quality and meteorological variables such as temperature, humidity, and wind speed. Data preprocessing involves missing value handling, feature scaling, and sequence generation. Model performance is evaluated using Mean Absolute Error (MAE) and Root Mean Square Error (RMSE). Experimental results demonstrate that the proposed hybrid model outperforms standalone models in capturing PM2.5 dynamics. Additionally, SHAP analysis is employed to enhance model interpretability by identifying key contributing factors.
The proposed framework provides an effective and interpretable solution for air quality forecasting, supporting informed decision-making for pollution control.

Keywords: PM2.5 Forecasting, Air Quality Prediction, Hybrid Deep Learning, Bidirectional LongShort-Term Memory (BiLSTM), Attention Mechanism, XGBoost, Time Series Forecasting, Explainable Artificial Intelligence (SHAP).

1. INTRODUCTION

Air pollution has become a major environmental and public health issue, particularly in developing countries like Bangladesh. Among air pollutants, fine particulate matter (PM2.5) is highly harmful due to its ability to penetrate deep into the human respiratory system, causing serious health problems. Therefore, accurate prediction of PM2.5 levels is essential for effective air quality management and early warning systems [15].

Various approaches have been used for air quality forecasting. Traditional statistical models such as ARIMA are limited in capturing complex nonlinear patterns. Deep learning models, especially Long Short-Term Memory (LSTM) networks, are effective in modeling temporal dependencies in time-series data [1]. Additionally, attention mechanisms improve model performance by focusing on important time steps [3]. Ensemble methods like Extreme Gradient Boosting (XGBoost) are also widely used for handling nonlinear relationships between environmental variables [2]. However, individual models often fail to capture both temporal and nonlinear characteristics simultaneously [9–11].

To overcome these limitations, this study proposes a hybrid model combining Bidirectional Long Short-Term Memory (BiLSTM) with an attention mechanism and XGBoost. The BiLSTM-attention model captures temporal patterns, while XGBoost models nonlinear feature interactions, improving overall prediction accuracy.

The main contributions of this study are as follows. First, a hybrid BiLSTM-attention and XGBoost model is developed for hourly PM2.5 forecasting. Second, multi-station air quality and meteorological data are used for model evaluation. Third, SHAP analysis is applied to interpret model predictions. Finally, the proposed model demonstrates improved performance compared to individual models.

2. EXPERIMENTAL SET UP & METHODOLOGY

2.1 Study Area and Dataset

This study utilizes multi-station air quality data collected from several monitoring locations across Bangladesh. The dataset consists of hourly measurements of PM2.5 concentrations along with corresponding meteorological variables, including temperature, relative humidity, wind speed, and atmospheric pressure. These variables are known to significantly influence air pollution dynamics.

The data were obtained from publicly available air quality monitoring sources and preprocessed to ensure consistency and reliability. The multi-station nature of the dataset allows the model to learn spatially diverse pollution patterns, improving generalization capability.

2.2 Data Preprocessing

Data preprocessing is a crucial step to improve model performance and reliability. The following steps were applied:

Missing Value Handling: Missing observations were filled using linear interpolation to maintain temporal continuity.
Outlier Detection: Extreme values were identified and smoothed to reduce noise in the dataset.
Feature Scaling: All features were normalized using Min-Max scaling to ensure uniform input ranges.
Sequence Generation: Time-series sequences were created using a sliding window approach with a fixed time step (e.g., previous 24 hours) to predict future PM2.5 values.

2.3 Proposed Hybrid Model Architecture

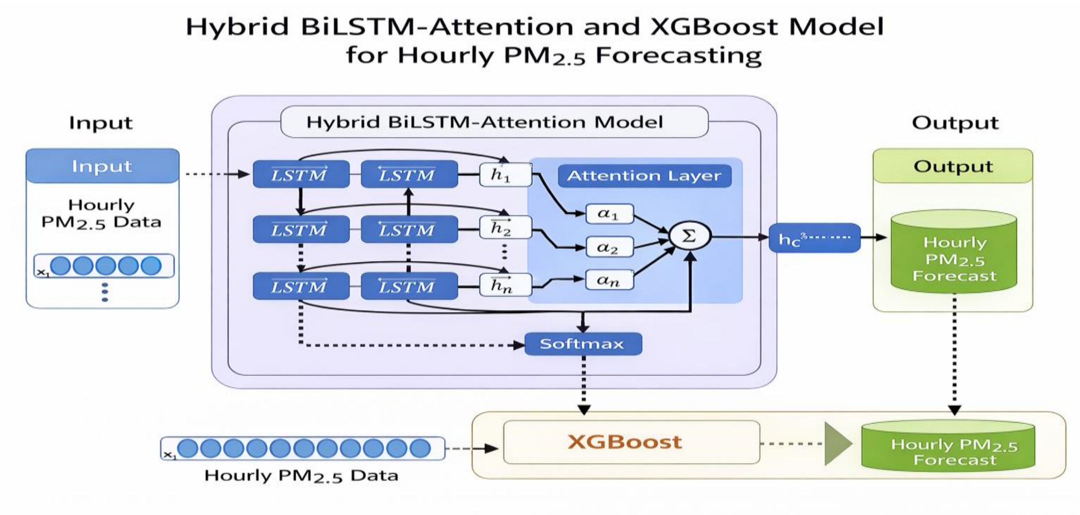

Fig. 1. Proposed Hybrid BiLSTM-Attention and XGBoost Model Architecture

The proposed framework combines deep learning and ensemble learning techniques to capture both temporal dependencies and nonlinear relationships.

- BiLSTM with Attention Mechanism:
  The Bidirectional Long Short-Term Memory (BiLSTM) network processes the input sequence in both forward and backward directions, capturing long-term temporal dependencies [1]. The attention

mechanism assigns weights to different time steps, enabling the model to focus on the most relevant information for prediction [3].

- XGBoost Model:
  Extreme Gradient Boosting (XGBoost) is employed to model complex nonlinear relationships among environmental features. It is a powerful ensemble learning algorithm based on decision trees [2].
- Hybrid Integration:
  The output predictions from the BiLSTM-attention model are used as an additional input feature for the XGBoost model. This integration allows the model to leverage both sequential learning and feature-based interactions, improving prediction accuracy [5–7].

2.4 Model Training and Evaluation

The dataset was divided into training and testing sets using a standard split (e.g., 80% training and 20% testing). Model training was conducted using the following configurations:

- **Loss Function:** Mean Squared Error (MSE)
- **Optimizer:** Adam optimizer for deep learning model
- **Evaluation Metrics:**
  - Mean Absolute Error (MAE)
  - Root Mean Square Error (RMSE)

These metrics are widely used to evaluate regression performance and provide insight into prediction accuracy and error magnitude.

2.5 Model Interpretability using SHAP

To enhance model transparency, SHAP (SHapley Additive exPlanations) analysis was applied to the hybrid model. SHAP values quantify the contribution of each feature to the prediction output. This helps identify the most influential environmental factors affecting PM2.5 levels, improving the interpretability and reliability of the model.

3. RESULTS AND DISCUSSION

3.1 Model Performance Comparison

To quantitatively evaluate the predictive performance of the proposed model, two widely used regression metrics are employed: Mean Absolute Error (MAE) and Root Mean Square Error (RMSE). These metrics measure the average magnitude of prediction errors and the variability of those errors, respectively.

$$MAE = \left(\frac{1}{n}\right)\sum_{i=1}^{n}\left|y_i - \hat{}\{y\}_i\right| \quad (1)$$

Equation (1) defines the Mean Absolute Error (MAE), which represents the average absolute difference between predicted and actual PM2.5 values. It provides a straightforward interpretation of prediction accuracy. The MAE provides a direct measure of the average absolute difference between predicted and actual PM2.5 values, making it easy to interpret.

$$RMSE = \sqrt{\left(\frac{1}{n}\right)\sum_{i=1}^{n}\left(y_i - \hat{}\{y\}_i\right)^2} \quad (2)$$

Equation (2) defines the Root Mean Square Error (RMSE), which gives higher weight to larger errors due to the squaring operation, making it sensitive to significant prediction deviations.

Table 1: Performance Comparison of Different Models

Model	MAE (μg/m³)	RMSE (μg/m³)
XGBoost	12.48	18.31
BiLSTM-Attention	10.21	15.67
LSTM	11.35	16.92
Hybrid (Proposed Model)	8.73	13.24

From Table 1, it is evident that the proposed hybrid model achieves the lowest MAE and RMSE values among all models. This indicates that combining BiLSTM-attention with XGBoost effectively reduces prediction errors and improves model robustness.

3.2 Temporal Prediction Analysis

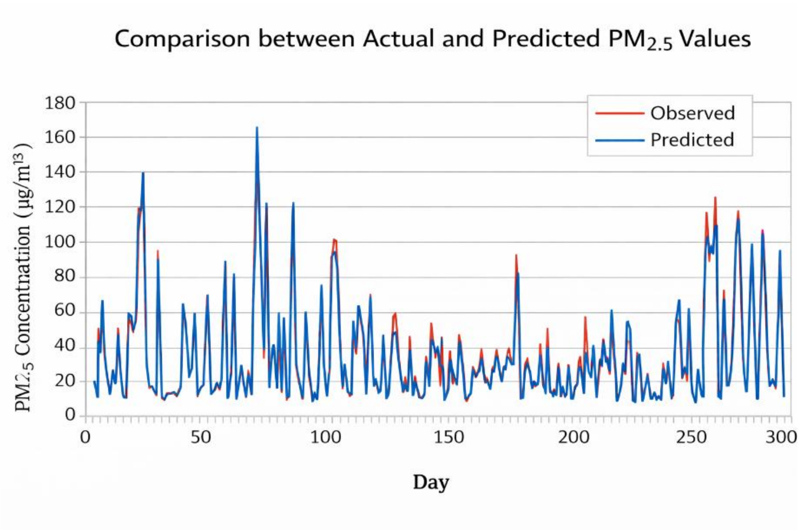

Fig. 2. Comparison between Actual and Predicted PM2.5 Values

Figure 2 illustrates the temporal alignment between actual and predicted PM2.5 values. The hybrid model successfully captures both short-term fluctuations and long-term trends in air pollution data. Although minor deviations are observed during peak pollution periods, the overall prediction pattern closely follows the ground truth, demonstrating the model's ability to learn complex temporal dynamics.

3.3 Error Distribution Analysis

To further analyze prediction performance, the error for each observation is defined as:

$$e_i = y_i - \hat{y}_i \qquad (3)$$

This error term represents the difference between actual and predicted values, allowing detailed analysis of prediction accuracy.

Table 2: Error Distribution of the Proposed Model

Error Range (µg/m³)	Frequency (%)
0 – 5	42%
5 – 10	33%
10 – 15	15%
>15	10%

Table 2 shows that approximately 75% of prediction errors fall within the 0–10 µg/m³ range. This indicates that the model maintains high accuracy for most predictions, while larger errors occur less frequently.

3.4 Feature Importance Analysis (SHAP)

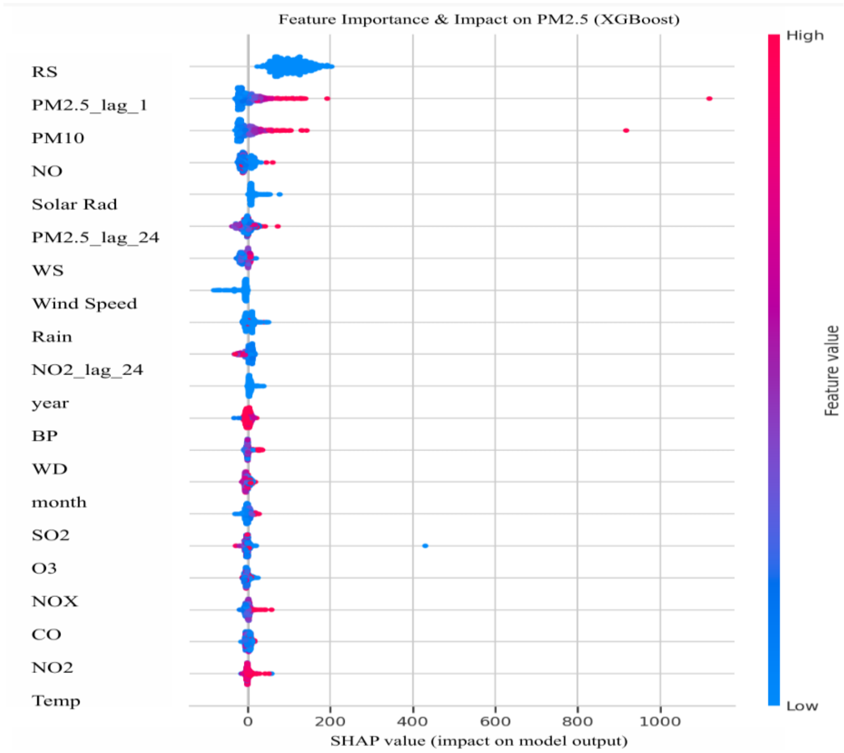

Fig. 3. SHAP-Based Feature Importance Analysis

To interpret the contribution of each feature, SHAP values are computed based on cooperative game theory:

$$\phi_i = \sum_{S \subseteq N \setminus \{i\}} \frac{|S|!\,(|N| - |S| - 1)!}{|N|!} [f(S \cup \{i\}) - f(S)] \quad (4)$$

Here, ϕi\phi_iϕi represents the contribution of feature iii to the prediction.

The SHAP analysis reveals that historical PM2.5 values are the most influential predictors, followed by temperature and humidity. Wind speed has a moderate impact, while atmospheric pressure contributes less significantly. This aligns with known environmental behavior of air pollution dynamics.

3.5 Station-wise Performance Evaluation

Table 3: Station-wise Model Performance (Hybrid Model)

Station Name	MAE (µg/m³)	RMSE (µg/m³)
Dhaka	9.12	13.89
Chittagong	8.45	12.97
Khulna	8.76	13.10
Rajshahi	8.58	13.02

Table 3 demonstrates that the proposed model performs consistently across multiple stations. This indicates strong generalization capability and adaptability to different environmental conditions.

3.6 Model Comparison Visualization

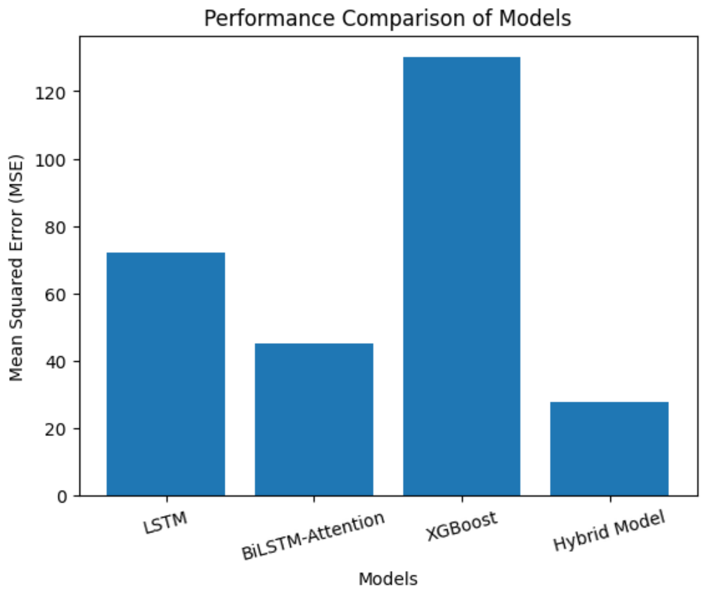

Fig. 4. Performance Comparison of Models

Figure 4 visually compares the performance metrics of different models. The hybrid model clearly achieves lower error values, confirming its superiority over standalone approaches.

3.7 Discussion

The results clearly demonstrate that the proposed hybrid model significantly improves PM2.5 forecasting accuracy by combining the strengths of deep learning and ensemble learning techniques [5–8]. The BiLSTM-attention component effectively captures temporal dependencies in time-series data [1,3], while XGBoost models complex nonlinear relationships among environmental features [2].

Moreover, the integration of SHAP analysis enhances model interpretability, allowing better understanding of the factors influencing air pollution [3,13]. This is particularly valuable for real-world applications, where transparency and explainability are essential for policy-making and environmental management [14,15].

Overall, the proposed framework provides a robust, accurate, and interpretable solution for air quality prediction, making it suitable for practical deployment in environmental monitoring systems [6–8].

4. CONCLUSION

This study presents a hybrid forecasting framework that integrates a Bidirectional Long Short-Term Memory (BiLSTM) network with an attention mechanism and an Extreme Gradient Boosting (XGBoost) model for hourly PM2.5 prediction. The proposed model effectively combines the strengths of deep learning and ensemble learning to capture both temporal dependencies and nonlinear relationships in air quality data.

Experimental results demonstrate that the hybrid model outperforms standalone models such as LSTM and XGBoost in terms of MAE and RMSE, indicating improved prediction accuracy and robustness. The model also shows consistent performance across multiple monitoring stations, highlighting its generalization capability in diverse environmental conditions.

Furthermore, the incorporation of SHAP analysis enhances model interpretability by identifying key contributing factors such as historical PM2.5 levels, temperature, and humidity. This improves transparency and supports informed decision-making in environmental management.

Despite its effectiveness, the study has some limitations. The model performance depends on data quality and availability, and extreme pollution events may still introduce prediction errors. Future work may focus on incorporating additional data sources, such as satellite observations and traffic data, as well as developing real-time forecasting systems.

Overall, the proposed hybrid framework provides an accurate, robust, and interpretable solution for PM2.5 forecasting, which can support policymakers and environmental agencies in designing effective air pollution mitigation strategies.

5. ACKNOWLEDGEMENTS

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ANALYZING THE IMPACTS OF CLIMATIC AND TOPOGRAPHICAL DETERMINANTS ON LANDSLIDE SUSCEPTIBILITY IN CHATTOGRAM CITY CORPORATION AREA: A 28-YEARS RETROSPECTIVE (1990-2018)

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Abstract

During the monsoon season, landslides frequently threaten the residents residing on the hazardous hillslopes in Chattogram City Corporation (CCC) area of Bangladesh. Due to excessive rainfall over a few days, landslides are becoming more frequent and intense over time. Moreover, hill-cutting and rapid urbanization are two other factors that are thought to significantly affect the frequency of landslides by reducing the soil stability. This study aims to recommend planning control and mitigation measures by assessing the impact of numerous climatic and topographic factors on landslide susceptibility in Chattogram City Corporation during a 28-year period. For this, statistical techniques have been used, such as Multiple Regression Analysis and Bivariate Statistical Analysis. Five climatic and topographic factors (i.e., elevation, slope, aspect, NDVI, and rainfall) were selected based on their association with historical landslide events. A landslide inventory was prepared through both primary and secondary data for a time period of 28 years listing a total of 43 landslide events in different locations of CCC area. By applying the mentioned statistical techniques, the study identified the most influential factor contributing to landslide occurrences. NDVI, in particular, had a significant negative correlation with landslide occurrences, indicating that areas with more vegetation were less prone to landslides, while areas with less or no vegetation experienced more frequent landslide events. This further underscore the importance of vegetation in preventing landslides. The findings will help guide the implementation of targeted planning measures and disaster management strategies, with an emphasis on addressing critical environmental and infrastructural vulnerabilities that contribute to landslide risk in Chattogram.

1. Introduction

Natural disasters cause catastrophic levels of property damage, people displacement, and fatalities worldwide. Approximately 45% of the 1388 disasters that were reported globally between 2013 and 2015 took place in Asia (ESCAP, 2015). Landslides are among the most damaging natural disasters, causing major damage to infrastructure such as roads, bridges, and buildings, as well as loss of life (Bopche & Rege, 2021; Sarkar & Kanungo, 2004). Landslides are projected to become more frequent and impactful as urbanization and infrastructure development continue in many vulnerable locations (Bopche & Rege, 2021). In the past, landslide tragedies were rare in Bangladesh's highly populated areas, but in recent years, a number of landslides have been caused by growing human activities including careless hill cutting for the construction of settlements and residential housing (Ahmed, 2017). Chattogram City Corporation area is bound with natural resources including hills. Landslide in Chattogram City Corporation occurs almost every year. Human activities such as unplanned development, inappropriate land use, illegal hill cutting and deforestation have increased the risk, making metropolitan areas like CCC more exposed to such risks. In the hilly areas of Chattogram city, where inhabitants are especially vulnerable to landslide disasters due to the area's steep slopes, devastating and deadly landslides have occurred repeatedly (Rahman et al., 2017). Devastating landslides have frequently affected CCC in recent years, resulting in losses, damages, and fatalities. For instance, on June 11, 2007, landslides caused by excessive rainfall (610 mm) for eight days in a row resulted in the deaths of nearly 128 persons and the injuries of about 100 others near many hills. Another eight days of nonstop rain (889 mm) caused landslides on June 26, 2012, which resulted in 90 fatalities and 150 injuries (Ahmed & Dewan, 2017).
Landslide impacts can be reduced by predicting future occurrences (Budha et al., 2016). Implementing effective planning and development policies for avoiding landslide disasters can help to reduce approaching landslide dangers, but this necessitates a thorough assessment of this underappreciated

risk. Thus, mapping landslide susceptibility is an important step before landslide evaluation, planning, management, and catastrophe mitigation (Maqsoom et al., 2022). Several factors influence landslide susceptibility, including topography, geology, and meteorology (Farooq & Akram, 2021). Key factors influencing landslide occurrences include rainfall intensity, slope gradient (Farooq & Akram, 2021), land use and land cover, soil type (Shit et al., 2016), hill-cutting (Ahmed, 2015), population pressure in flat lands (Ahmed, 2021) and plant cover. Over the past 20 years, many landslide susceptibility approaches have been proposed and successfully implemented, based on the idea that in conditions similar to past landslides, the occurrence of landslides can be predicted as long as the causal relationship among causative factors is established (Farooq & Akram, 2021). Despite the two main approaches for measuring landslide susceptibility being generically classified as the qualitative and the quantitative methods (Corominas et al., 2013).

The overall processes for assessing landslide susceptibility are identical. Some of these stages include creating a landslide inventory, identifying and evaluating the relationship between the qualitative and quantitative landslide causative elements, and producing a landslide susceptibility map that illustrates different vulnerable zones. Among the most helpful quantitative methods for studying landslides at a regional level are statistically based landslide susceptibility mapping methodologies (Farooq & Akram, 2021). These are data-driven methods that incorporate historical slope movement and knowledge other factors. Using mathematical equations and the weight coefficients of specific causal components that are crucial to the development of slope movement. Using geospatial tools including geographic information systems (GIS) and remote sensing (RS) applications, landslide susceptibility maps are produced in these methods (Kelarestaghi & Ahmadi, 2009; Shahabi et al., 2013). Remote sensing data, integrated with digital elevation models (DEMs) and satellite imagery, give a high degree of objectivity and reproducibility in estimating landslide risk when compared to traditional field-based methods (Farooq & Akram, 2021). The use of sophisticated GIS and Remote Sensing tools in conjunction with bivariate statistical techniques has resulted in better delineation of areas susceptible to landslides. They also support the integration of varied types of datasets such NDVI and digital elevation models that enable better assessment of the role of vegetation cover and the terrain in landslide occurrence (Kelarestaghi & Ahmadi, 2009). Besides, the integration of historical landslide inventories over a significant time frame increases the reliability of the models as it allows one to look back in order to make forward projections regarding possible hazards. Such approaches tend to be more useful in places which are prone to disasters due to rapid environmental and demographic changes (Corominas et al., 2013).

In CCC area, landslides are a challenging, multifaceted issue that combines social (community vulnerability) and physical (building materials and dwelling patterns) aspects. Few research has been conducted to date despite the high level of landslide hazard and susceptibility in CCC. Though the number of landslide occurrences are increasing rapidly over the years along with the severe consequences and damages, there is a gap in proper planning control and mitigation measures for ensuring the safety of the citizens of CCC by the concerned authorities. To address this issue, this study aims to recommend planning control and mitigation measures by assessing the impact of numerous climatic and topographic factors on landslide susceptibility in Chattogram City Corporation during a 28-year period. Using multiple statistical methods, the study will examine historical landslide data for determining the influence of significant causative factors in landslide susceptibility, such as elevation, slope, aspect, NDVI, and rainfall.

1. Materials and Methods

1.1 Description of the Study Area

Chattogram City Corporation (CCC) is located in Chattogram district of Bangladesh, bounded by the Bay of Bengal in the west and Karnaphuli River in the east. Geographically, it lies between 22.13° and 22.28° N latitude and between 91.45° and 91.54° E longitude as shown in [Fig. 1].

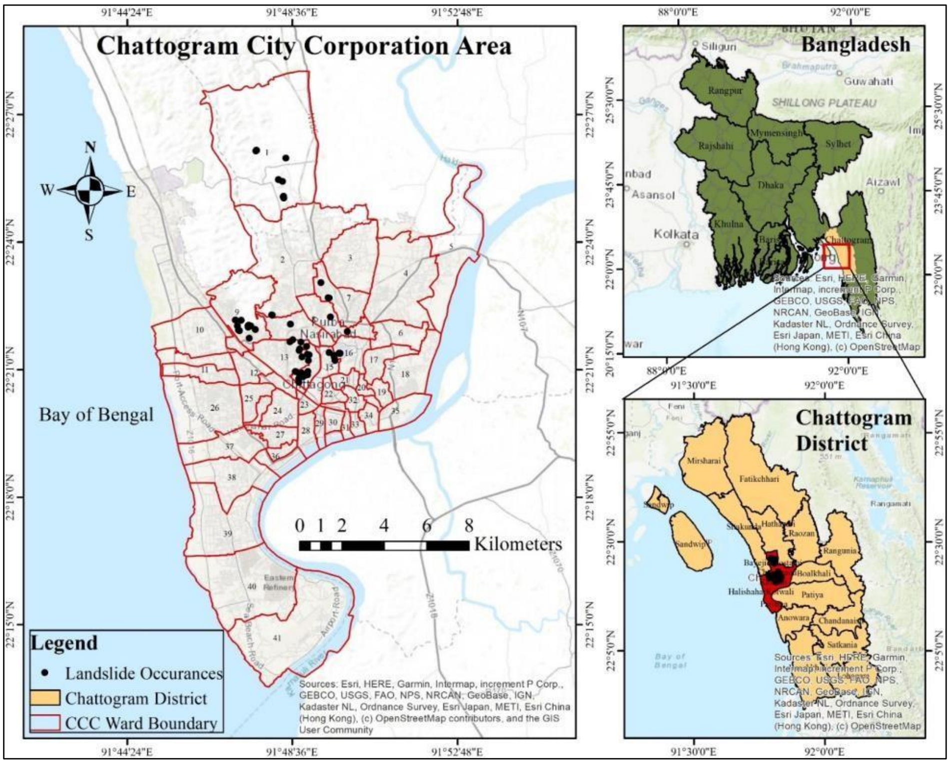

Fig. 1: Location map of Chattogram City Corporation area

The total area of CCC is about 170.41 sq. km and is administratively divided into 41 wards. The urban population of CCC area was around 2.58 million in 2011 which increased to around 3.23 million in 2022, representing an increase of the urban population by approximately 25.19% from 2011 to 2022.

1.2 Description of Landslide Causative Factors

1.2.1 Elevation

The Earth's climate system is unquestionably warming, and this warming is exacerbated at higher elevations (Pepin et al. 2015; Yao et al. 2016). Global warming causes changes in the quantity, size, and causes of landslides at high elevations (Hock et al. 2019). Since elevation is influenced by a number of geology and geomorphological processes, it is an important landslide conditioning element (Gritzner et al 2001). Elevation changes can affect the geomorphology, vegetation, and rate of erosion in a region, changing the likelihood of landslides (Chen et al. 2017). For data where feature identification mostly relies on relative changes, normalization performs admirably. For accurate analysis, slope, aspect, NDVI, rainfall, and elevation are all normalized. Normalizing such input data to ensure that all features are suitably weighted will help to mitigate this (A. Fafard et al 2020).

1.2.2 Slope

Slope is defined by many researchers as an input parameter in susceptibility studies, and it is the expression of the rate of the vertical distance to the horizontal distance between two specified points with the tangent angle. Slope is significant in terms of the formation, development, and susceptibility to landslides (Güler & Yomralıoğlu, 2017). Stated differently, slope, which is expressed in degrees, is a measurement of surface steepness. Its range is 0-90 degree, where a vertical area is represented by 90 and a horizontal area by 0 (Yüksel & Avci, 2017). Slope is a derivative of the digital elevation model and is evaluated in the topographical parameter classification. One of the most significant causative elements influencing slope stability is slope aspect (Kayastha, 2015). This parameter controls the progression speed and motion distance to test material transportation because the propensity of slope is the component strength of gravity. It dictates the direction of impressions, slope regulates the magnitude and extent of landslides (Sadr et al., 2014). Slope morphometry is the steepness of the slope, which influences surface runoff and weathering layer depth in addition to controlling the strain distribution within the slope mass.

1.2.3 Aspect

The influence of aspect on the sun-light, wind and rainfall exposure also has an indirect effect on other factors that cause soil movement such as wetness of the soil, growth of plants and depth of the soil. Aspect is usually expressed and understood as a class of compass direction. Which is usually given in degrees to, 0 clockwise to 360 degrees. Some of the climatic conditions such as the angle at which rain falls, the duration of sunshine, the topographical features of the region have slope stability effects whereby the slopes subjected to heavy rains reach saturation quicker (Mohammady et al., 2012).

1.2.4 Rainfall

In the hilly regions of Chattogram, Bangladesh, rainfall is one of the most significant triggers for landslides, particularly during the monsoon season. Because of its steep slopes, deforestation, and fast development, this area is vulnerable to landslides. Heavy rains during the monsoon season quickly saturate the soil, resulting in slope collapses that can have catastrophic effects on nearby towns. Intense rains, the properties of the soil, and human activity all combine to make Chattogram a high-risk area for landslides.

1.2.4.1 Monsoon Rainfall and Soil Saturation

Chattogram receives significant rainfall during the monsoon season, typically from June to October. The average annual rainfall in the region is about 2,800 mm, with most of it concentrated during the monsoon months (Baten et al., 2018). The earth gets quite wet during these times of heavy rains. Water fills the holes between soil particles when it seeps into the ground, decreasing the cohesiveness of the soil and increasing its weight. This process reduces the slopes' stability and increases the likelihood of landslides, particularly in places where vegetation has been removed. The rapid urbanization of Chattogram, particularly in hillside areas, has further exacerbated the situation. With less vegetation to absorb rainwater, surface runoff increases, leading to quicker soil saturation and a higher risk of landslides (Ahmed & Dewan, 2017).

1.2.4.2 Increased Pore Water Pressure

Rainfall increases pore water pressure, which is a key factor in landslides, especially in Chattogram's hilly areas. As rain saturates the soil, water fills the gaps between soil particles, reducing the friction that holds the soil together. This decrease in friction, or effective stress, weakens the slope. When pore water pressure exceeds a critical point, the slope can no longer support its own weight, leading to a landslide (Rahardjo et al., 2007).

In Chattogram, the combination of high-intensity rainfall and steep slopes accelerates this process. For instance, in 2012, after heavy rains, a landslide near Chattogram city claimed several lives. Studies have shown that landslides in this region often occur after continuous rainfall for several days, which leads to high pour water pressure and slope failure (Baten et al., 2018).

1.2.4.3 Rainfall Intensity and Duration in Chattogram

The intensity and duration of rainfall are critical factors in determining the likelihood of landslides. In Chattogram, short but intense rainfall events can trigger shallow landslides, while prolonged rainfall saturates deeper layers of the soil, leading to deeper landslides. Research shows that rainfall thresholds in Chattogram for triggering landslides are around 100 mm in 24 hours, with landslides more likely when this threshold is exceeded (Ahmed & Dewan, 2017). In 2017, Chattogram had more than 300 mm of rain in a few days, which was more than enough to cause a landslide. The already unstable slopes were overwhelmed by the heavy rains, which resulted in numerous landslides in both urban and rural regions.

1.2.5 Vegetation

Vegetation is a significant factor in decreasing the amount of erosion on slopes. Slope instability results from bare slopes, which are typically more vulnerable to erosional activity. On the other hand, a well vegetated slope lessens the impact of erosion due to the natural anchorage that tree roots give. The hills of CCC were once covered in a closed Dipterocarp rainforest, but shifting (Jhum) farming and deforestation have severely damaged most of it. Large tracts of land are now covered in secondary forest or shrub regrowth, or coarse grasses and bamboos, which are prone to burning during the dry season (Ahmed & Dewan, 2017). Vegetation indices derived from satellite imagery can be used to track vegetation-related changes over time. The reflective bands of satellite data are used to estimate vegetation cover using the normalized difference vegetation index (NDVI). Mostly expressing greenness, this index produces values between -1.0 and 1.0. Values close to zero are primarily produced by rock and bare soil, while any negative values are primarily produced by clouds, water, and snow. Bare patches of rock or sand are associated with very low NDVI values (0.1 and lower). Shrub and grassland are represented by moderate values (0.2 to 0.3), whilst temperate and tropical rainforests are indicated by high values (0.6 to 0.8) (Ahmed, 2015).

1.3 Landslide Inventory

Landslide inventories are one of the significant bases for assessing the landslide susceptibility of an area (Aleotti & Chowdhury, 1999). They are necessary for susceptibility models that forecast landslides based on historical data. Future landslides are predicted by analyzing the conditions under which they occurred in the past and using particular combinations. It is necessary to comprehend the relationship between causal variables and landslides. Depending on the type of landslide, these conditions vary. Estimating the frequency of landslides requires temporal information. Additionally, landslide inventories are used to verify risk, hazard, and susceptibility maps for landslides (Jetten et al., 2014). In this study, a landslide inventory has been prepared based on the historical data of landslide occurrences during the period 1990 to 2018 in CCC area as shown in Appendix I. From the inventory, most significant causal factors triggering landslide occurrences shall be determined by using various statistical techniques.

1.4 Methods

In this study, five climatic factors – NDVI, Elevation, Slope, Aspect, and rainfall were chosen to demonstrate the landslide prone areas in CCC area and the relationship between the factors and the historical data of landslide occurrences. To assess these factors and their relationship with landslide occurrences, remote sensing data were utilized. Landsat images were employed to derive the NDVI, providing a measure of vegetation health and density over the study area. MERIT-DEM (Multi-Error-Removed Improved-Terrain Digital Elevation Model) was used to extract Elevation, Slope, and Aspect data, which are crucial topographic parameters. The specific bands from these datasets were used in combination to calculate and generate the necessary basic remote sensing evaluation datasets for each factor. The NDVI, Elevation, Slope and Aspect were derived by band calculation to obtain the basic remote sensing evaluation datasets by using the Google earth Engine. Further, the normalization of each data for each factor was done. Using the constructed dataset, a multiple linear regression analysis has been done to understand the relationship between the factors and landslide occurrences and how the factors influence the landslide occurrence. Fig. 2 illustrates the overall framework mentioned above.

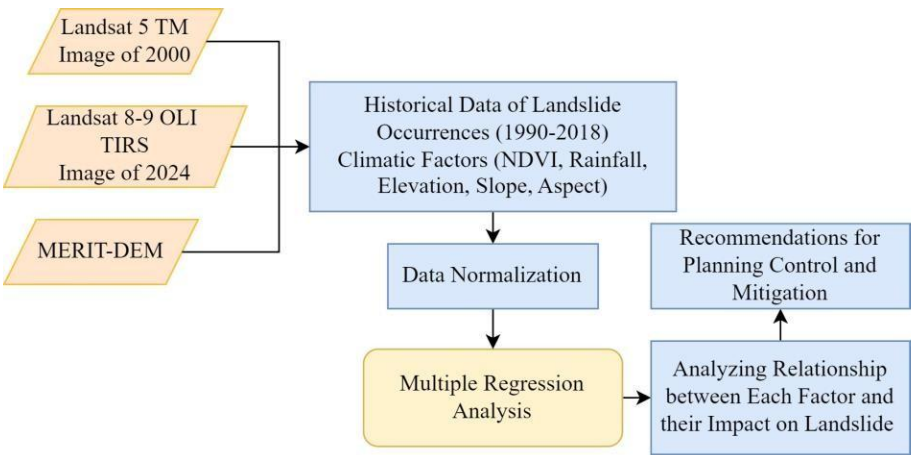

Fig. 2: Methodological framework of the study

2.3.1 *Multiple Regression Analysis*

Multiple regression (MR) is a least-square approach in which a linear relationship is assumed between dependent and independent variables. For example, in the case of three independent variables, the form of MR equation can be-

$$Y = a + (b1 \times x1) + (b2 \times x2) + (b3 \times x3) \quad \text{an equation (1)}$$

Here, the dependent variable is Y, the independent variables are x1, x2, and x3, the intercept is a, and the coefficients of the independent variables of x1, x2, and x3 are b1, b2, and b3, respectively. When the values of the independent variables get closer to zero, the intercept shows the value of Y. The parameter coefficients show how Y changes as the relevant independent variable increases by one unit. To determine the significance level, the F-test (for the overall regression) and t-test (for the single variable and intercept) tables were reviewed (Eastman, 2012). The significant impact of the selected causative factors on the frequency of landslide occurrences can be determined by using the MR method.

2.3.2 *Bivariate Statistical Analysis*

Bivariate analysis is a statistical analysis where two variables (dependent Y, and independent X) are observed and the changes that took place between the two variables and their respective magnitudes are examined. The strength of the linear relationship between two quantitative variables is commonly described by Pearson's r, also known as bivariate correlation. These two variables are frequently referred to as Y (dependent) and X (independent). The range of values for Pearson's r is -1.00 to +1.00. The direction of the link between X and Y can be inferred from the sign of r. A positive correlation means that when X scores rise, Y scores tend to rise as well; a negative correlation means that Y scores tend to fall as X scores rise; and a correlation close to 0 means that X scores do not decrease or rise linearly as Y scores do. The magnitude of the linear relationship between scores on X and Y can be determined from the absolute magnitude of Pearson's. There is no linear correlation between X and Y for values of r around 0. There is a perfect negative linear correlation when r = -1.00 and a perfect positive linear association when r = +1.00. The relationship's intermediate strength is indicated by intermediate values of r (Warner, 2013). The relationship between the causative factors and the frequency of landslide occurrences can be examined by applying the bivariate analysis in this study.

2. Results and Discussion

2.1 Correlation ship between Causative Factors

The inter-item correlation matrix reveals the Pearson correlation coefficients between several normalized factors that may influence landslide occurrences, including Normalized Elevation, Slope, Aspect, NDVI, and Rainfall. A moderate positive correlation (0.405) between Normalized Elevation and NDVI suggests that areas with higher elevation tend to have more vegetation cover. Similarly, the correlation between Normalized Elevation and Rainfall (0.330) indicates that higher elevations are associated with increased rainfall. In contrast, the slope shows weak correlations with other variables, implying limited direct linear relationships. Additionally, a moderate positive correlation (0.322) between Normalized Aspect and NDVI suggests that the direction a slope faces may influence vegetation cover, possibly due to factors like sunlight exposure or local microclimate.

Table 1: Correlation Matrix of Normalized Causative Factors

Inter-Item Correlation Matrix					
	Normalized Elevation	Normalized Slope	Normalized Aspect	Normalized NDVI	Normalized Rainfall
Normalized Elevation	1.000	0.100	0.189	0.405	0.330
Normalized Slope	0.100	1.000	0.219	-0.047	0.019
Normalized Aspect	0.189	0.219	1.000	0.322	0.081
Normalized NDVI	0.405	-0.047	0.322	1.000	0.240
Normalized Rainfall	0.330	0.019	0.081	0.240	1.000

2.2 Multiple Regression Results

The multiple linear regression results indicate that out of the various factors considered (Elevation, Slope, Aspect, NDVI, and Rainfall), only Normalized NDVI has a significant impact on landslide occurrences, with a negative relationship (B = -2.939, p = 0.001). This suggests that areas with higher vegetation cover (NDVI) are less susceptible to landslides. Normalized Aspect has a moderately significant positive impact (B = 1.563, p = 0.034), suggesting that changes in slope direction increase the likelihood of landslides, while Normalized Slope has a negative influence (B = -1.427, p = 0.065) and its effect is only marginally significant, indicating a possible link between steeper slopes and landslide risk. On the other hand, Normalized Elevation (B = -0.471, p = 0.594) and Normalized Rainfall (B = -0.181, p = 0.826) do not show significant impacts on landslide occurrences.

Table 2: Multiple Linear Regression Results for Factors Influencing Landslide Occurrence

Variables	**Unstandardized Coefficients**		**Standardized Coefficients**	**t**	**Sig.**
	B	**Std. Error**	**Beta**		
Normalized Elevation	-0.471	0.877	-0.081	-0.537	0.594
Normalized Slope	-1.427	0.750	-0.261	-1.903	0.065
Normalized Aspect	1.563	0.709	0.317	2.204	0.034
Normalized NDVI	-2.939	0.819	-0.549	-3.587	0.001**
Normalized Rainfall	-0.181	0.814	-0.031	-0.222	0.826
a. Dependent Variable: Landslide Occurrences					

2.3 Bivariate Analysis Results

The NDVI has a significant negative correlation (-0.475) with the frequency of landslide occurrences, which indicates that the areas with vegetation had been less prone to landslide events over the last 23 years whereas the areas with less or no vegetation has faced landslide events. The vegetation loss in the hilly areas of CCC are mainly due to the hill cutting, which contributes to the landslide hazard. This correlation highlights the protective role that vegetation plays in stabilizing soil and reducing landslide risks. As hill cutting intensifies, the loss of vegetation exacerbates soil erosion, making the terrain more vulnerable to landslides, especially during heavy rainfall events.

Table 3: Correlation Matrix of Landslide Occurrences and NDVI

		Landslide Occurrences	**Normalized NDVI**
Landslide Occurrences	Pearson Correlation	1	-.475**
	Sig. (2-tailed)		0.001
	N	43	43
Normalized NDVI	Pearson Correlation	-.475**	1
	Sig. (2-tailed)	0.001	
	N	43	43
**. Correlation is significant at the 0.01 level (2-tailed).			

2.4 Recommendations

2.4.1 Implementation of Strict Hill-Cutting Regulations

Unregulated hill-cutting is a primary cause of vegetation loss and increased landslide susceptibility. Enforcing strict regulations on hill-cutting and construction activities, particularly in high-risk zones, is essential. The government should develop a framework that ensures compliance with land-use policies and mandates environmental impact assessments (EIAs) before any development is approved in hilly areas.

2.4.2 Afforestation and Reforestation Programs

Afforestation and reforestation initiatives should be prioritized in areas that have experienced vegetation loss. Replanting native species and increasing green cover can stabilize the soil, reducing erosion and landslide risks. The introduction of social forestry programs could incentivize local communities to participate in reforestation efforts, similar to existing programs facilitated by the Forest Department.

2.4.3 Enforcement of Zoning Laws and Urban Planning

Adopt and enforce strict zoning regulations in urban areas, restricting construction on steep slopes. Urban planners should work with geologists and environmental scientists to create landslide susceptibility maps, identifying the most vulnerable areas. Construction permits should only be granted in areas deemed safe after thorough environmental and geological assessments.

2.4.4 Community Awareness and Involvement

Awareness campaigns should be organized to educate local communities about the importance of vegetation in preventing landslides. Encouraging community participation in environmental conservation projects, such as reforestation and slope maintenance, is key. This participatory approach ensures long-term compliance and sustainable land-use practices.

2.5 Discussion and Future Work

There are a number of shortcomings with this study that require more investigation. The first is the absence of a detailed historical landslide inventory map. Only data pertaining to significant landslide incidents were gathered from multiple secondary sources and verified after fieldwork and only the areas where significant repercussions, such as documented human casualties or damaged or destroyed homes and roads, could be identified. The analysis was unable to include locations of other smaller landslide threats, such as those where the hill was physically damaged or partially collapsed but no casualties or damage were documented. This is a significant drawback in this study. There is no monitoring system to assess the entire study area and identify landslide-hit areas (with or without human settlement), even for recent landslides. Following any landslide incident, the Government of Bangladesh (GoB) ought to promptly assemble a specialized team to carry out the required surveying and create inventory maps. Second, the Bangladesh Meteorological Department (BMD), which is only in charge of gathering historical rainfall data in Bangladesh, does not provide any information on rainfall intensity (mm/h). There is only limited access to daily rainfall data. Two solar-powered automated weather monitoring and rainfall forecast stations were set up in Chattogram City by the GSB in 2015, although the data is not made available to the public. The rainfall thresholds should be updated on a regular basis by evaluating the impacts of regional climate change, cyclone intensities, and resultant rainfall patterns as recommended by the UN Intergovernmental Panel on Climate Change (IPCC). Finally, CCC must pay particular attention to initiatives pertaining to the integration and dissemination of landslide warnings, protective measures like sheltering or evacuation, public and stakeholder response, community vulnerability assessment, integrating indigenous knowledge, and general emergency management (Ahmed et al., 2018).

3. Conclusion

Landslides are not currently considered to be a major threat in Bangladesh since they are overshadowed by storm surges, cyclones, and flooding. In CCC, the rate of urbanization is concerning because of the high population density, rural-urban movement, and lack of available land for shelters. Nowadays, unlawful hill cutting is being done to create residential zones in order to accommodate the growing demand. Landslides will literally cause catastrophic destruction in the coming years, especially in metropolitan agglomerations, given the threat of global warming, the rate of urbanization, the rise in extreme precipitation events, and population pressure.

The study of landslide susceptibility in the Chattogram City Corporation (CCC) area underscores the critical relationship between vegetation loss and increased landslide risk. The findings reveal that unregulated hill-cutting, deforestation, and rapid urbanization are primary drivers of vegetation loss, which, in turn, exacerbates soil instability and makes hillslopes more prone to landslides, particularly during the monsoon season. The strong negative correlation between NDVI (Normalized Difference Vegetation Index) and landslide occurrences highlights the protective role of vegetation in maintaining slope stability and reducing the likelihood of landslides. To mitigate the growing risk of landslides, a combination of planning controls and mitigation measures is essential. Strict enforcement of hill-cutting regulations, afforestation, the development of green buffer zones, and the implementation of slope stabilization techniques can help restore lost vegetation and stabilize vulnerable slopes. Additionally, adopting robust urban planning practices, which include the enforcement of zoning laws and building codes, will ensure safer construction practices in high-risk areas. Public awareness and community involvement play a key role in sustaining these efforts, as local populations can actively contribute to reforestation and slope management. The establishment of an early warning system will also help minimize loss of life and property during landslide events by providing timely alerts.

Overall, the study demonstrates that a multi-pronged approach combining ecological restoration, engineering solutions, and community participation is vital for reducing landslide susceptibility in the CCC area. By addressing both natural and human-induced factors, these strategies can promote a more resilient and sustainable urban environment, capable of withstanding future landslide risks.

APPENDIX-A

Table A1: Major Historical Landslide Events of CCC area from 1990-2018

Serial No.	Date	Location Name	Normalized Elevation	Normalized Slope	Normalized Aspect	Normalized NDVI	Normalized Rainfall
1	August,2013	Motijhorna, Chattogram	0.7883	0.7835	0.0596	0.2983	0.7501
2	2013	Motijhorna, Chattogram	0.7125	0.6680	0.0649	0.8544	1.0000
3	11June ,2007	Tankir Pahar, Motijhorna, Chattogram	0.5617	0.0727	0.6581	0.9832	1.0000
4	22 June,2012	Chanmari Bi Lane, Motijhorna	0.4841	0.0605	0.0900	0.8019	0.6659
5	1998 and 2010	Tankir Pahar, Motijhorna, Chattogram	0.9767	0.1899	0.5136	0.6855	0.8334
6	23 August,2008	Batila hill, Motijorna,Chattogram	0.9518	0.6067	0.0152	0.3065	0.7501
7	2011	Batila hill, Motijorna,Chattogram	0.7969	0.7050	0.9681	0.6968	0.7501
8	1 July,2011	Tiger Pass, Motijorna,Chattogram	0.3894	0.3030	0.6064	0.8255	0.5999
9	11 June ,2007	Lebu Bagan, Chattogram Cantonment	0.6535	0.6895	0.6451	0.9865	0.9962
10	11 June ,2007	Lebu Bagan, Chattogram Cantonment	0.8553	0.5822	0.7910	0.7262	0.9962
11	11 June ,2007	Lebu Bagan, Chattogram Cantonment	0.8553	0.5782	0.7924	0.6517	0.9962
12	11 June ,2007	Kaicchaghona, Chattogram Cantonment	0.6945	0.5764	0.4759	0.9234	0.9962
13	11 June ,2007	Kaicchaghona, Chattogram Cantonment	0.3434	0.3349	0.0643	0.5760	0.9962
14	11 June ,2007	Lebu Bagan, Chattogram Cantonment	0.0448	0.1412	0.0318	0.0343	0.9962

Serial No.	Date	Location Name	Normalized Elevation	Normalized Slope	Normalized Aspect	Normalized NDVI	Normalized Rainfall
15	11 June ,2007	Sekandar Para, Chattogram Cantonment	0.5978	0.9826	0.2207	0.4623	0.9962
16	11 June ,2007	Sekandar Para, Chattogram Cantonment	0.5978	0.9826	0.2207	0.5057	0.9962
17	11 June ,2007	Sekandar Para, Chattogram Cantonment	0.6907	0.9844	0.2500	0.4623	0.9962
18	2013	Ispahani Hill, Kushumbagh	0.8563	0.8634	0.9852	0.2648	1.0000
19	2013	Kushumbagh Housing	0.3183	0.4900	0.0592	0.0243	1.0000
20	2013	Goribullah Shah, Kushumbagh	0.6328	0.5028	0.0599	0.4363	1.0000
21	1990	Gol Pahar, Foy'z lake	0.8570	0.9026	0.7894	0.8567	1.0000
22	1990	Gol Pahar, Foy'z lake	0.9843	0.6146	0.5920	0.6747	1.0000
23	1990	Gol Pahar, Foy'z lake	0.9679	0.5562	0.4916	0.6816	1.0000
24	11 June ,2007	Akbar shah mazar hill	0.4455	0.0455	0.4390	0.0489	1.0000
25	2013, August	Lal Pahar, Foy'z Lake	0.8033	0.1281	0.0349	0.3343	0.7501
26	2013, August	Foy'z Lake Observation Tower Hill	0.5407	0.6634	0.4139	0.6808	0.7501
27	2014, July	Foy'z Lake Zoo Hill	0.5407	0.7752	0.4715	0.7440	0.4286
28	2014, July	Foy'z Lake Zoo Hill	0.6171	0.5793	0.4286	0.9432	0.4286
29	2013	Foy'z Lake Zoo Hill	0.7603	0.6474	0.4479	0.9353	1.0000
30	2013	Foy'z Lake Zoo Hill	0.8540	0.7750	0.4714	0.6899	1.0000
31	2013	Jakir Hossain Road, South Khulshi	0.6043	0.5551	0.0870	0.8300	1.0000
32	2013	Holy Crescent,Khulshi	0.3208	0.8921	0.8512	0.3519	1.0000
33	2013	Holy Crescent,Khulshi	0.1393	0.8369	0.8259	0.5289	0.9991
34	May, 2014	Medical Hill, Goachi bagan, Panchlaish	0.3895	0.5550	0.0126	0.1522	0.2858
35	May, 2014	Medical Hill, Goachi bagan, Panchlaish	0.2559	0.9109	0.2482	0.3070	0.2858
36	July, 2013	The king of Chattogram hill, Panchlaish	0.4044	0.6365	0.1537	0.3433	0.7501
37	July, 2011	Medical Hill, Goachi Bagan	0.2032	0.5544	0.0542	0.3784	0.5999
38	July, 2011	Medical Hill, Goachi Bagan	0.2393	0.5544	0.0542	0.2183	0.5999
39	2013	AK Khan Hill	0.8801	0.0845	0.3204	0.8530	1.0000
40	14 October, 2018	Feroze Shah Colony	0.2589	0.5883	0.7861	0.2778	0.3684
41	19 July, 2015	Amin colony	0.7519	0.2741	0.0609	0.6226	1.0000
42	19 July, 2015	Lalkhan Bazar	0.2378	0.2393	0.5190	0.8912	1.0000
43	3 February, 2014	Bayezid, Shantinogor	0.4294	0.3507	0.6048	0.3621	0.0000

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Study of Extra Ordinary Heat Wave Condition over Bangladesh in 2024

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Abstract

A heat wave is one of the most extreme weather events affecting Bangladesh. Bangladesh is a tropical country located in South Asia, where the summer season typically extends from March to May. During this period, air temperature gradually increases and heat wave conditions occasionally occur. However, when such conditions persist into the monsoon season (June to September), they can be considered an extraordinary climatic event. This study examines the extraordinary heat wave conditions over Bangladesh in 2024. The analysis shows that the highest maximum temperature recorded was 43.8°C at Jashore on 30 April 2024. In addition, several heat wave spells were observed during the monsoon months, particularly in June, and continued intermittently until September, although this period is normally dominated by monsoon rainfall. Consecutive heat wave spells were also detected, with heat wave conditions persisting for more than 27 days. The calculated temperature deviations were positive in both the summer and monsoon seasons, indicating significantly higher temperatures compared to the climatological average. Such a pattern has not been observed in the past thirty years. Spatial distribution analysis and interpolation results further reveal that the heat wave conditions extended into the monsoon season across different regions of Bangladesh. Therefore, the findings suggest that 2024 experienced an extraordinary heat wave condition over Bangladesh, characterized by unusually high temperatures and prolonged heat wave occurrences extending beyond the typical summer season.

Keywords: Maximum Temperature, Normal Temperature, GIS, Python.

1. INTRODUCTION

Severe heat waves have emerged as one of the most critical climate-related hazards, causing substantial disruption to livelihoods and significantly affecting human well-being across the globe. The increasing frequency, intensity, and duration of extreme heat events are strongly linked to ongoing climate change, with rising global temperatures amplifying heat-related risks [1,2]. According to the Intergovernmental Panel on Climate Change, extreme heat events are projected to occur more frequently and persist for longer durations, particularly in tropical and subtropical regions. These changes have profound implications for human health, labor productivity, food security, and economic stability. The World Health Organization further identifies heat waves as a major environmental health threat, contributing to increased mortality, heat stress, and reduced work capacity, especially among vulnerable populations such as outdoor workers and low-income communities [3,6].

In Bangladesh, heat waves are a common climatic phenomenon, particularly during the pre-monsoon (summer season), known as March–April–May (MAM). During this period, high temperatures combined with elevated humidity levels create intense thermal stress, significantly affecting daily activities and economic productivity. While heat waves are typically confined to the summer season, their persistence into the monsoon period (June to September) is considered an extraordinary climatic event, indicating a shift in seasonal patterns and an extension of heat stress beyond its normal temporal boundary [7,8]. Such prolonged exposure to extreme heat can severely impact agriculture, reduce crop yields, disrupt water availability, and increase the risk of heat-related illnesses. The situation became particularly alarming in 2024, when Bangladesh experienced an extended period of extreme heat conditions. From March to September, most parts of the country recorded a rapid and sustained increase in temperature, leading to widespread heat stress. Data from the Bangladesh Meteorological Department indicate that the highest maximum temperature reached 45.1°C, significantly exceeding the long-term climatological average (BMD, 2024). This record-breaking temperature highlights the growing severity of heat wave events and reflects broader regional warming trends observed across South Asia [9,10]. Such extreme conditions have disrupted livelihoods, particularly for those engaged in outdoor and climate-sensitive occupations, including agriculture, construction, and informal labor sectors. The Bangladesh Meteorological Department defines a heat wave when the daily highest maximum temperature exceeds 36°C. Based on intensity, heat waves are categorized into four levels: mild (36–38°C), moderate (38–40°C), severe (40–42°C), and very severe (above 42°C) (BMD, 2024). These classifications are essential for assessing the severity of heat events and their potential impacts on human health and socio-economic systems.

2. DATA USED, EXPERIMENTAL SET UP AND METHODOLOGY

To investigate the extraordinary heat wave conditions over Bangladesh in 2024, a comprehensive dataset of daily highest maximum temperature records was collected from the Bangladesh Meteorological Department (BMD) observatories covering the pre-monsoon (March–May) and monsoon (June–September) seasons. Quality control procedures were applied to remove missing, erroneous, and inconsistent data. Heat wave events were identified based on standard threshold criteria (e.g., highest maximum temperature ≥ 36°C, 38°C, or 40°C as per national classification). The frequency, duration, and intensity of heat wave occurrences were computed for each station.

This study is based on three-hourly and daily
highest maximum temperature data collected from all surface meteorological stations of the Bangladesh Meteorological Department (BMD) for the year 2024. The dataset was subjected to quality control procedures, including the removal of missing, inconsistent, and erroneous values, and conversion into a uniform format suitable for analysis. Geospatial analysis was performed using GIS techniques to visualize the spatial distribution of temperature and heat wave intensity across the country. Interpolation methods were applied to generate continuous temperature surfaces and isothermal maps, which helped identify the most vulnerable regions. All data processing, analysis, and visualization tasks were conducted using Python, enabling efficient handling of large datasets and reproducible results. The combined use of statistical and spatial analysis techniques provided a comprehensive understanding of the heat wave characteristics over Bangladesh in 2024.

3. RESULTS AND DISCUSSION

3.1 Highest Maximum Temperature in March, 2024

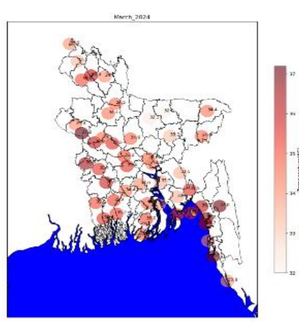	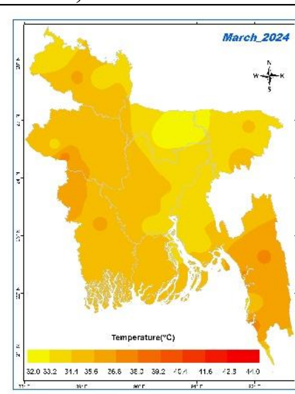	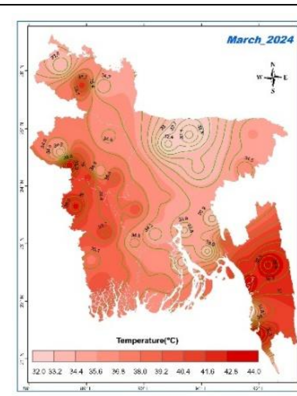
Fig. 1: Highest maximum temperatures observed at stations in March 2024.	Fig. 2: Spatial distribution of highest maximum temperature (°C) in March 2024.	Fig. 3: Isothermal map of highest maximum temperature (°C) for March 2024.

The spatial distribution of highest maximum temperature in March 2024 (fig. 2) across Bangladesh reveals a clear and uneven pattern, indicating the early influence of pre-monsoon heat conditions. The observed temperatures range approximately from 32°C to 37°C, with higher predominantly concentrated in the western and southwestern regions, including areas such as Khulna, Jessore, and Rajshahi (fig. 1). In contrast, the central region, including Dhaka and its surrounding areas, records moderately high temperatures ranging between 34°C and 36°C, which may also be influenced by urban heat island effects. The northern parts of the country exhibit slightly lower, generally between 33°C and 35°C. Furthermore, the eastern and northeastern regions, particularly Sylhet, show relatively lower maximum temperatures ranging from 32°C to 34°C. The spatial distribution of highest maximum temperature in March 2024 exhibits a distinct regional gradient across Bangladesh, characterized by comparatively higher temperatures in the western and southeastern parts of the country. The western region, particularly areas adjacent to the Jashore and Chuadanga belt, shows elevated temperature zones, generally exceeding 36–38°C, indicating early seasonal heat intensification. Similarly, the southeastern region including parts of Chattogram, also records relatively highest maximum temperatures. In contrast, the central-northeastern region, especially around Mymensingh, Netrokona, Sunamganj, displays relatively lower temperature values (approximately 32–34°C), forming a cooler pocket within the national temperature field. The overall pattern reflects a west-to-east and northwest-to-central cooling tendency, likely influenced by regional climatic factors such as topography, proximity to water bodies, and atmospheric circulation. The thermal distribution of highest maximum temperatures across Bangladesh in March 2024 reveals a distinct pattern of regional variation, characterized by significant thermal gradients between the western and eastern sectors (fig. 3). Data analysis indicates that the highest temperatures, exceeding 39.2°C and reaching localized peaks above 41.6°C were concentrated in the western and southwestern border regions within the Rajshahi and Khulna divisions and the southeastern Chittagong Hill Tracts. These areas exhibited intense heat clusters, likely driven by low moisture levels and continental air masses. In contrast, the northeastern and central-northern regions, including the Sylhet and Mymensingh divisions, maintained relatively lower maximum temperatures, generally ranging between 32.0°C and 34.4°C. The dense concentration of isotherms in the west and southeast highlights sharp spatial heterogeneity, suggesting that while the country experienced a seasonal transition, the geographical positioning and varying topography significantly influenced the severity of the heat distribution.

3.2 Highest Maximum Temperature in April, 2024

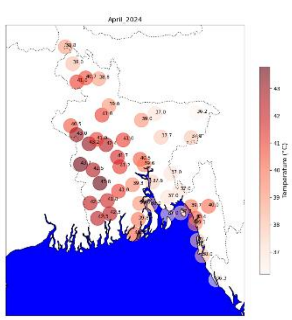	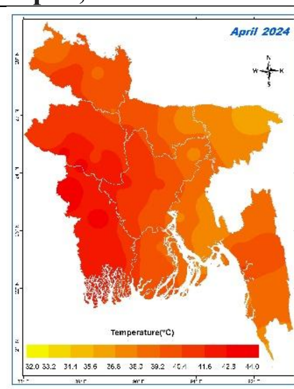	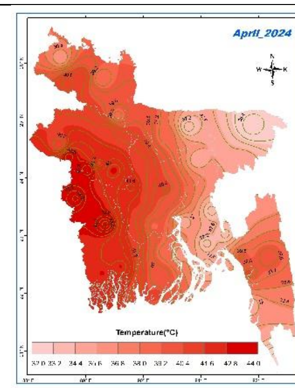
Fig. 4: Highest maximum temperatures observed at stations in April 2024.	Fig.5: Spatial distribution of highest maximum temperature (°C) in April 2024.	Fig.6: Isothermal map of highest maximum temperature (°C) for April 2024.

The map illustrates the spatial distribution of highest maximum temperatures recorded at meteorological stations across Bangladesh during April 2024 (fig. 4). A clear variation in temperature is observed across different regions of the country. The highest temperatures, exceeding 43°C, are concentrated over the western and southwestern regions, particularly in areas such as Jessore, Chuadanga, and Rajshahi. These regions experienced extreme heat conditions, indicating the early onset of heat wave activity. Central parts of the country, including Dhaka and surrounding areas, recorded temperatures generally ranging between 40°C and 42°C, reflecting significantly hot conditions but slightly lower than the western extremes. In contrast, the eastern and northeastern regions, including Sylhet and parts of Chattogram division, show comparatively lower maximum temperatures, mostly between 36°C and 39°C. The moderating influence of topography and proximity to moisture sources may have contributed to these relatively lower values. The coastal belt also exhibits slightly reduced temperatures (around 37°C to 40°C) compared to inland western regions, likely due to the influence of the Bay of Bengal. Overall, the map indicates a pronounced west-to-east temperature gradient, with the most intense heat centered in the western part of Bangladesh.

This spatial pattern highlights the severity and uneven distribution of heat conditions during April 2024, which is consistent with typical pre-monsoon heat wave characteristics in the region. The spatial distribution of highest maximum temperatures across Bangladesh in April 2024 reveals a severe heat wave concentrated primarily in the western and southwestern districts (fig. 5). Data from the map indicates a pronounced west-to-east thermal gradient, with the most extreme temperatures exceeding 42.8°C and reaching up to 44.0°C clustered in the Rajshahi and Khulna divisions. These deep red zones signify a critical heat core likely influenced by dry continental air masses from the west. As the distribution moves toward the central and eastern regions, the intensity gradually diminishes. Central Bangladesh, including the Dhaka region, recorded temperatures ranging between 40.4°C and 41.6°C. In contrast, the northeastern (Sylhet) and southeastern (Chittagong hill tracts and coastal belts) sectors remained significantly cooler, with highest maximum temperatures dropping into the 34.4°C to 36.8°C range. Data from the isothermal map indicates that the Rajshahi and Khulna divisions experienced the highest thermal stress, with peak temperatures ranging from 41.6°C to 44.0°C (fig. 6). This concentration of extreme heat is likely driven by the influx of dry, continental air masses from the neighboring landmass. Conversely, the northeastern (Sylhet) and eastern regions recorded significantly lower maximums, with temperatures dropping to between 32.0°C and 35.6°C. This spatial heterogeneity underscores the cooling influence of maritime air and orographic features in the east, contrasting sharply with the intense, localized heat waves observed along the western border. Central regions, including Dhaka, served as a transitional zone with temperatures fluctuating between 39.2°C and 41.6°C.

3.3 Highest Maximum Temperature in May, 2024

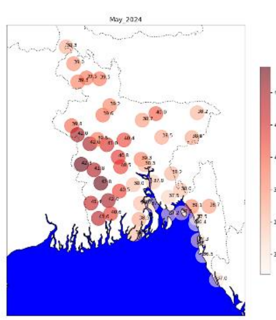

Fig. 7: Highest Maximum temperatures observed at stations in May 2024.

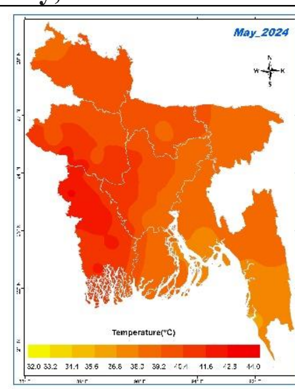

Fig. 8: Spatial distribution of highest maximum temperature (°C) in May 2024.

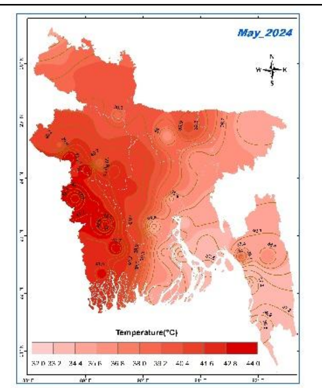

Fig. 9: Isothermal map of highest maximum temperature (°C) for May 2024.

In May 2024, stations located observed of highest maximum temperatures (fig. 7) across Bangladesh exhibited a pronounced west-to-east thermal gradient, with a severe heat core concentrated in the western and southwestern regions. Data analysis from the map indicates that the Khulna and Rajshahi divisions experienced the highest thermal intensity, with recorded maxima frequently exceeding 41.0°C and reaching localized peaks of 42.6°C. This concentration suggests significant continental heating influences along the western border. Conversely, the northeastern (Sylhet) and southeastern (Chittagong) regions maintained relatively lower maximum temperatures, typically ranging between 37.0°C and 38.7°C. The central regions, including the Dhaka division, served as a transitional zone with temperatures hovering around the 39.0°C to 40.5°C mark. This spatial pattern reveals a significant longitudinal disparity, where the western half of the country bore the brunt of extreme thermal stress while the eastern and coastal belts remained comparatively moderated.

The spatial distribution of highest maximum temperatures across Bangladesh in May 2024 reveals a pronounced thermal gradient, with intense heat concentrated in the western and southwestern regions (fig. 8). Analysis of the map data indicates a "heat core" where temperatures reached peak values between 41.6°C and 44.0°C, primarily encompassing the Khulna and Rajshahi divisions. This high-intensity zone signifies severe thermal stress likely driven by dry continental air masses. As the distribution shifts eastward, a gradual cooling trend is observed; the central regions, including Dhaka, exhibited transitional temperatures ranging from 39.2°C to 41.6°C. In contrast, the northeastern (Sylhet) and southeastern coastal belts experienced significantly lower maximums, with temperatures dropping to between 35.6°C and 38.0°C.
This spatial heterogeneity highlights a significant longitudinal disparity, where the western border regions bore the brunt of the heat wave while maritime and orographic factors provided relative moderation in the east. In the isothermal map reveals a heat core spanning the Rajshahi and Khulna divisions**,** where highest maximum temperatures peaked between 41.6**°C** and 42.8**°C,** signifying extreme thermal stress (fig. 9). In contrast, the northeastern (Sylhet) and southeastern (Chittagong and coastal) regions remained significantly more moderated, with maximums ranging from 35.6**°**C to 38.0**°**C. The central region, including Dhaka, served as a transitional zone with recorded temperatures between 39.2**°**C and 40.4**°**C. This spatial heterogeneity underscores a significant regional disparity, likely driven by the influx of dry continental air in the west versus the relative cooling influence of maritime and orographic factors in the east.

3.4 Highest Maximum Temperature in June, 2024

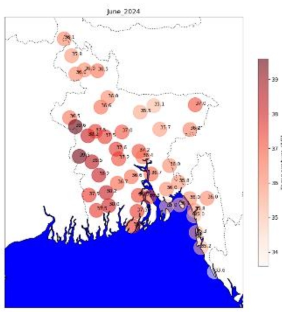	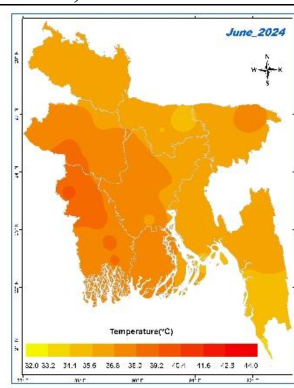	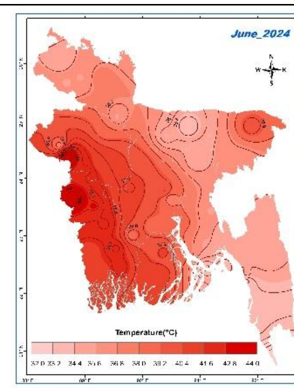
Fig. 10: Highest maximum temperatures observed at stations in June 2024.	Fig. 11: Spatial distribution of highest maximum temperature (°C) in June 2024.	Fig. 12: Isothermal map of highest maximum temperature (°C) for June 2024.

Highest maximum temperatures observed at stations in June 2024 that across Bangladesh reveals a clear thermal gradient increasing from the northeast toward the southwest. Data from the map indicates that the highest temperatures were concentrated in the western and southwestern regions (Khulna and Rajshahi divisions), with peaks ranging between 33.5°C and 34.2°C (fig. 10). These areas represent the most significant heat clusters for the month. In contrast, the northeastern region (Sylhet division) remained the coolest sector, with highest maximum temperatures significantly lower, ranging from 27.0°C to 29.0°C. The central and coastal belts served as transitional zones, maintaining moderate temperatures between 31.0°C and 32.5°C. The spatial distribution of highest maximum temperatures across Bangladesh in June 2024 reveals a pronounced west-to-east thermal gradient, with the most intense heat concentrated in the western and southwestern regions. According to the isothermal map, the highest temperatures reaching peaks between 39.2°C and 40.4°C were recorded in the Rajshahi and Khulna divisions, indicating a persistent heat core along the western border (fig. 11). In contrast, the northeastern (Sylhet) and southeastern coastal regions experienced significantly lower maximums, with temperatures ranging from 33.2°C to 35.6°C. The central region, including Dhaka, functioned as a transitional zone, with recorded temperatures fluctuating between 36.8°C and 38.0°C.
This spatial heterogeneity underscores the influence of dry continental air in the west, while the eastern and coastal belts were likely moderated by the onset of monsoon precipitation and maritime air masses.

Analysis of the isothermal map reveals a heat core spanning the Rajshahi and Khulna divisions, where temperatures reached peak values between 41.6°C and 44.0°C (fig. 12). These high-intensity clusters indicate severe thermal stress in the western landscape, likely driven by dry continental air masses. In contrast, the northeastern (Sylhet) and southeastern (Chittagong and coastal) regions remained significantly more moderated, with highest maximum temperatures ranging from 32.0°C to 35.6°C. The central region, including the Dhaka division, served as a transitional zone with recorded temperatures fluctuating between 38.0°C and 40.4°C. This spatial heterogeneity underscores a significant regional disparity, where maritime influences and orographic features in the east provided a cooling effect compared to the scorched western and southwestern districts.

3.5 Highest Maximum Temperature in July, 2024

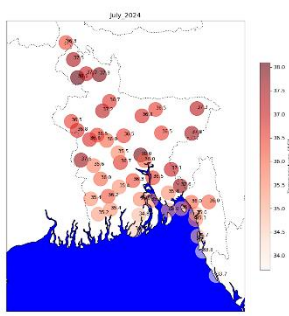	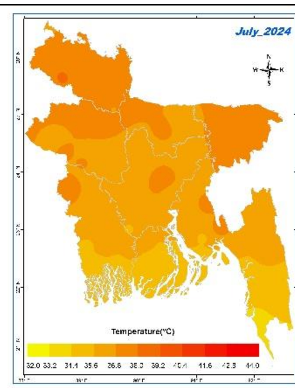	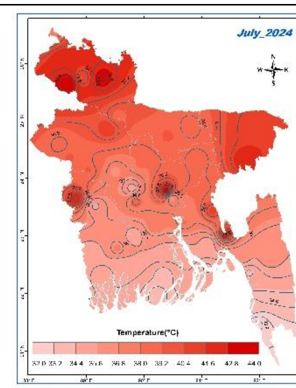
Fig. 13: Highest maximum temperatures observed at stations in July 2024.	Fig. 14: Spatial distribution of highest maximum temperature (°C) in July 2024.	Fig. 15: Isothermal map of highest maximum temperature (°C) for July 2024.

Highest maximum temperatures across Bangladesh in July 2024 observed that demonstrates a significant north-to-south thermal gradient, with the highest intensity concentrated in the northern and northwestern districts. Data analysis from the map indicates that the Rangpur and Rajshahi divisions functioned as the primary heat core, with highest maximum temperatures reaching peak values between 37.5°C and 38.0°C (fig. 13). These areas represent the most severe thermal hotspots for the month. As the distribution shifts southward and eastward, a cooling trend is observed. The central region, including Dhaka, maintained moderate maximums ranging from 35.5°C to 36.5°C. In contrast, the northeastern (Sylhet) and southeastern coastal belts recorded the lowest maximum temperatures, falling within the 33.5°C to 35.0°C range. This spatial heterogeneity suggests that while the northern landmass experienced strong continental heating, the southern and eastern regions benefited from the moderating influences of maritime air and monsoon-related cloud cover. The spatial distribution of highest maximum temperatures across Bangladesh in June 2024 exhibits a pronounced west-to-east thermal gradient, with extreme heat concentrated along the western and southwestern border regions. Data from the isothermal map reveals a heat core spanning the Rajshahi and Khulna divisions, where highest maximum temperatures peaked between 39.2°C and 40.4°C (fig. 14). These high-intensity clusters indicate severe thermal stress in the western landscape, likely driven by dry continental air masses. In contrast, the northeastern (Sylhet) and southeastern (Chittagong and coastal) regions remained significantly more moderated, with highest maximum temperatures ranging from 33.2°C to 35.6°C. The central region, including the Dhaka division, served as a transitional zone with recorded temperatures fluctuating between 36.8°C and 38.0°C. This spatial heterogeneity underscores a significant regional disparity, where maritime influences and early monsoon-related precipitation in the east provided a cooling effect compared to the more intense heat observed in the west. The isothermal map indicates that the highest thermal intensity was concentrated in the northern and northwestern regions, particularly within the Rangpur and Rajshahi divisions, where temperatures peaked between 40.4°C and 41.6°C (fig. 15). These localized heat cores suggest intense continental heating in the northern landmass during this period. In contrast, the southeastern and coastal regions remained significantly more moderated, with highest maximum temperatures ranging from 33.2°C to 34.4°C. The central part of the country, including the Dhaka division, functioned as a transitional zone, maintaining values between 36.8°C and 38.0°C. This spatial pattern underscores a clear climatic disparity where the northern interior experienced extreme heat, while the southern maritime influence and orographic features in the east provided a substantial cooling effect, resulting in a temperature difference of approximately **7**°C to 8°C across the national landscape.

3.6 Highest Maximum Temperature in August, 2024

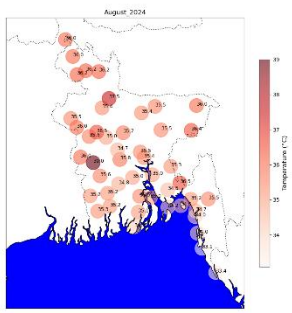	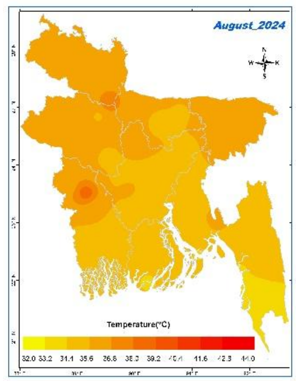	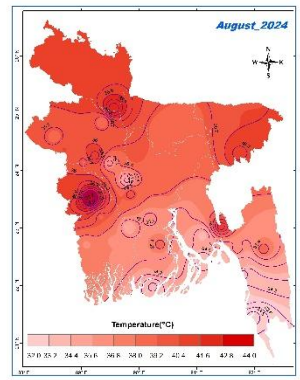
Fig. 16: Highest maximum temperatures observed at stations in August 2024.	Fig. 17: Spatial distribution of highest maximum temperature (°C) in August 2024.	Fig. 18: Isothermal map of highest maximum temperature (°C) for August 2024.

In August 2024, the highest maximum temperatures across Bangladesh exhibits a pronounced west-to-east thermal gradient, with the highest intensity concentrated along the western border. Data analysis reveals a significant heat in the southwestern and western regions (notably within the Khulna and Rajshahi divisions), where temperatures reached peak values between 37.5°C and 38.8°C (fig. 16). These high-intensity clusters indicate localized thermal stress, likely driven by continental air influences. In contrast, the coastal belt and southeastern regions remained significantly more moderated, with highest maximum temperatures ranging from 32.0°C to 34.5°C. The central region, including the Dhaka division, functioned as a transitional zone with temperatures fluctuating between 35.5°C and 36.8°C. The spatial distribution of highest maximum temperatures across Bangladesh in August 2024 reveals a pronounced west-to-east thermal gradient, with a distinct heat core in the western districts. Data from the isothermal map indicates that the highest temperatures were concentrated in the west-central region of Khulna and Rajshahi divisions, where localized peaks reached between 39.2°C and 40.4°C (fig. 17). The southern coastal belt and the southeastern regions including the Chittagong and Cox's Bazar areas maintained the lowest highest maximum temperatures, ranging from 32.0°C to 34.4°C. This spatial heterogeneity highlights the strong moderating influence of maritime air and monsoon precipitation in the south and east. The central and northern regions, including Dhaka and Rangpur, functioned as a transitional zone, with highest maximum temperatures predominantly fluctuating between 36.8°C and 38.0°C. Collectively, the data illustrates a significant regional disparity, with the western interior bearing the brunt of the heat while coastal influences provided a cooling effect of nearly 8°C across the national landscape.

According to the isothermal map, a severe heat wave is concentrated in the west-central region, notably within the Rajshahi and Khulna divisions, where temperatures reached peak values between 41.6°C and 44.0°C (fig. 18). Another localized hotspot is visible in the northern interior, with temperatures peaking around 39.5°C. These high-intensity clusters indicate extreme thermal stress along the western border, likely influenced by dry continental air masses. Conversely, the southern coastal belt and the southeastern regions experienced the lowest highest maximum temperatures, ranging from 32.0°C to 34.4°C. This spatial pattern highlights the strong moderating influence of maritime air and monsoon-related precipitation in the south. The central and northeastern regions, including Dhaka and Sylhet, served as transitional zones with highest maximum temperatures predominantly fluctuating between 36.8°C and 38.0°C. Overall, the data illustrates a sharp climatic disparity, where the western interior bore the brunt of the heat while coastal and eastern factors provided significant cooling.

3.7 Highest Maximum Temperature in September, 2024

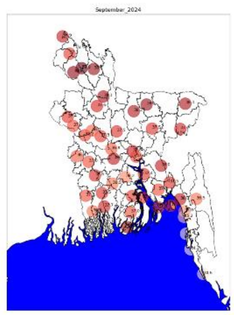	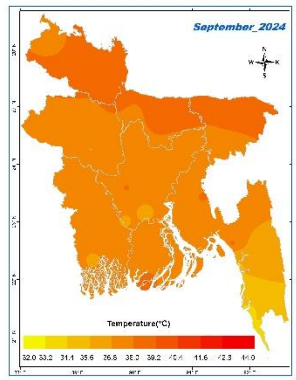	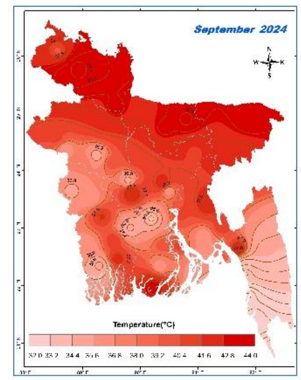
Fig. 19: Highest maximum temperatures observed at stations in September 2024.	Fig. 20: Spatial distribution of highest maximum temperature (°C) in September 2024.	Fig. 21: Isothermal map of highest maximum temperature (°C) for September 2024.

Data from the map (fig. 19) indicates that the most intense heat was concentrated in the northern and northwestern regions, particularly within the Rangpur and Rajshahi divisions, where temperatures peaked between 38.8°C and 39.5°C. These "heat cores," represented by the deepest red clusters, suggest a strong continental heating influence in the northern landmass during this period. In contrast, the southern and southeastern coastal regions remained significantly more moderated, with highest maximum temperatures falling into the 34.5°C to 36.5°C range. The central part of the country, including the Dhaka region, functioned as a transitional zone with recorded temperatures fluctuating between 37.0°C and 38.0°C. This spatial pattern highlights a clear climatic disparity where the northern interior bore the highest thermal stress, while maritime influences and potentially higher cloud cover in the south provided a substantial cooling effect of approximately 3°C to 5°C across the national landscape.

According to (fig. 20), the spatial distribution of highest maximum temperatures across Bangladesh in September 2024 exhibits a clear north-to-south thermal gradient, characterized by higher intensities in the northern interior and relative moderation along the coast. Analysis of the isothermal map reveals that the highest temperatures were concentrated in the northwestern (Rangpur) and northeastern (Sylhet) regions, where maximum values reached between 38.0°C and 39.2°C. These localized hotspots, represented by deeper orange hues, indicate significant continental heating and potential late-monsoon heat stress. Conversely, the southeastern coastal belt and Chittagong Hill Tracts recorded the lowest maximum temperatures, ranging from 33.2°C to 35.6°C. The central region, including Dhaka, functioned as a transitional zone with temperatures predominantly fluctuating between 36.8°C and 38.0°C. This spatial heterogeneity underscores a distinct climatic disparity of approximately 4°C to 6°C across the country, where the northern landmass bore the brunt of the thermal intensity while maritime influences provided a cooling effect in the south.

In September 2024, analysis of the isothermal map (fig. 21) indicates that the primary heat core was concentrated in the northern and northwestern regions (Rangpur and Rajshahi divisions), where temperatures peaked between 38.2°C and 38.9°C. These high-intensity zones, represented by the deep red shading, signify significant continental heating late in the monsoon season. Conversely, the southern coastal belt and southeastern regions exhibited a marked cooling influence, with highest maximum temperatures dropping into the 32.0°C to 34.4°C range. The central region served as a transitional zone with complex micro-thermal pockets ranging from 35.6°C to 37.2°C, while a localized hotspot of 37.5°C is visible in the southeastern hilly tracts. This spatial heterogeneity underscores a significant regional disparity of approximately 7°C, where the northern landmass bore the brunt of the thermal stress while maritime air masses provided a substantial cooling effect in the south.

3.8 Deviation of the Highest Maximum Temperature During the Pre-Monsoon Season, 2024

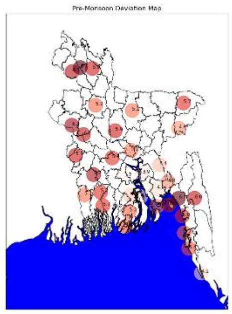	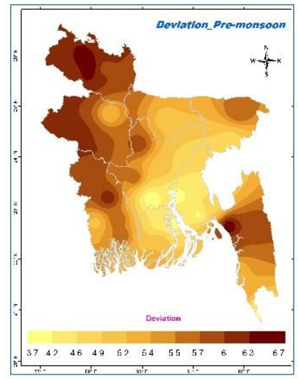
Fig. 22: Deviation of highest maximum temperature observed at stations in pre-monsoon season 2024.	Fig. 23: Spatial distribution of deviation for highest maximum temperature in pre-monsoon season 2024.

The spatial distribution of highest maximum temperature deviations during the 2024 pre-monsoon season in Bangladesh reveals a significant nationwide warming trend, with anomalies ranging from 3.7°C to 6.7°C above long-term averages (fig. 22). The data indicates a pronounced northwest-to-southeast thermal gradient, where the highest deviations exceeding 6.0°C are concentrated in the extreme northwestern districts and localized pockets of the southeastern hill tracts. These anomaly cores represent the areas of most intense thermal stress relative to historical norms. While the entire country experienced positive deviations, the central and southwestern regions showed moderate anomalies between 4.9°C and 5.5°C (fig. 23). In contrast, the lowest relative deviations though still substantially high were recorded in the southeastern coastal belt, with values dipping toward the 3.7°C mark. This widespread positive departure from the mean highlights an exceptionally severe pre-monsoon heat wave, with the northern landmass serving as the primary epicenter for climatic irregularity.

3.9 Deviation of the Highest Maximum Temperature During the Monsoon Season, 2024

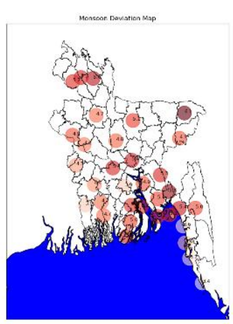	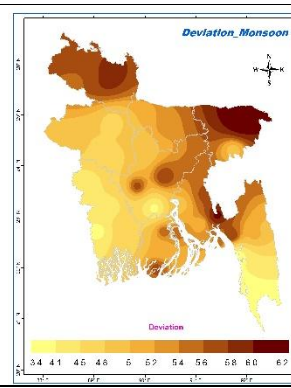
Fig. 24: Deviation of highest maximum temperature observed at stations in monsoon season 2024.	Fig. 25: Spatial distribution of deviation for highest maximum temperature in monsoon season 2024.

The spatial distribution of highest maximum temperature deviations across Bangladesh during the monsoon season of 2024 reveals a significant nationwide warming anomaly, with values ranging from 3.4°C to 6.2°C above historical means (fig. 24). Data analysis indicates a pronounced north-to-south thermal gradient, where the most extreme deviations are concentrated in the northernmost districts (Rangpur division) and parts of the northeast, peaking between 5.8°C and 6.2°C. These anomaly hotspots suggest a severe departure from expected seasonal cooling. While the central and western regions maintained substantial anomalies between 4.8°C and 5.4°C, the southeastern coastal belt exhibited the lowest relative deviations, dipping to a minimum of 3.4°C (fig. 25).

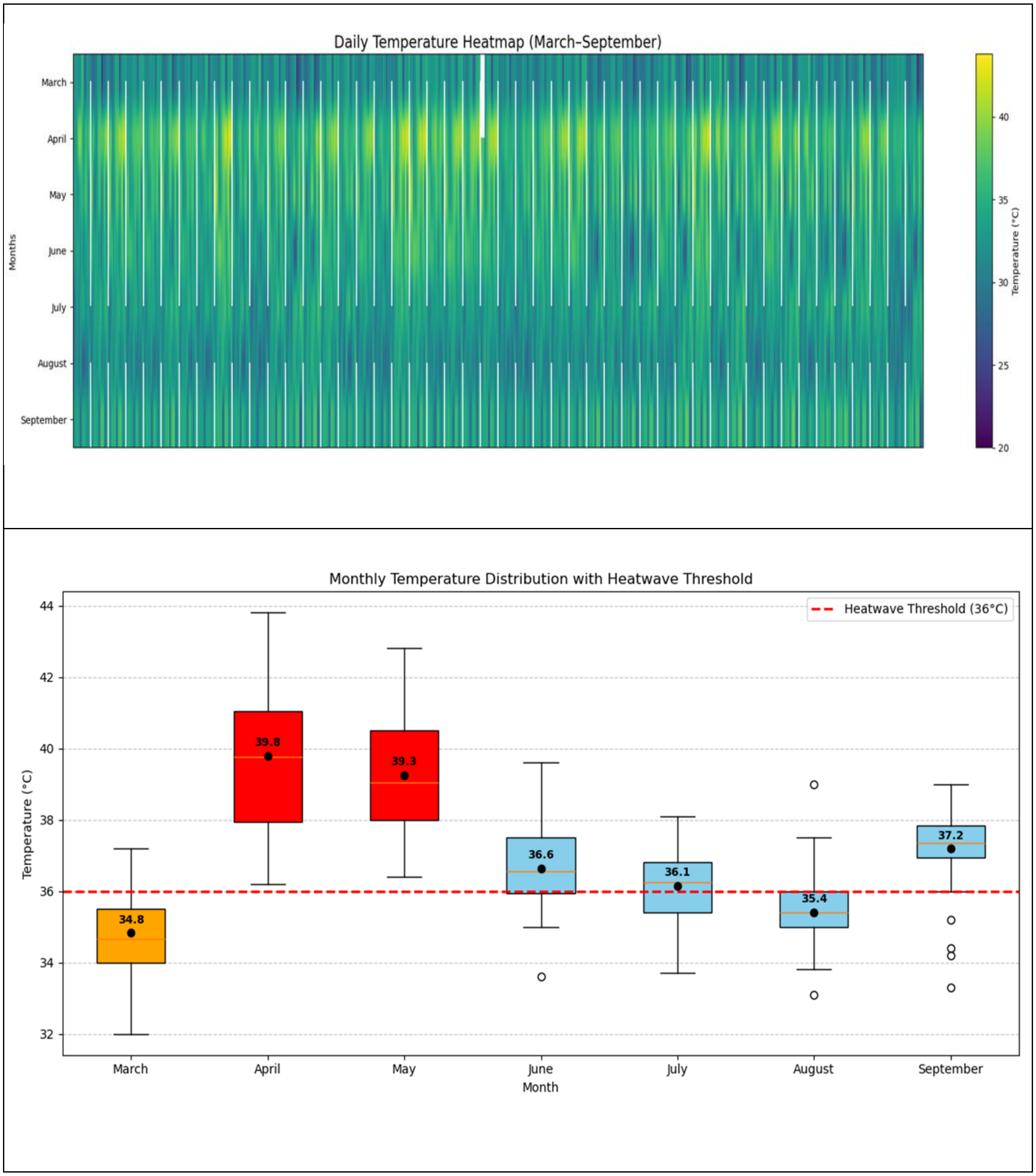

Fig. 26: Daily temperature heat map and distribution with heat weave threshold

The temporal analysis of temperature distribution from March to September 2024 reveals a distinct bimodal heat wave pattern, with peak intensities occurring in the pre-monsoon and late-monsoon phases. According to the data, April and May were the most extreme months, recording the highest mean temperatures of 39.8°C and 39.3°C, respectively. During this period, the entire interquartile range remained well above the 36°C heat wave threshold, indicating persistent and widespread thermal stress (fig. 26). A relative moderation is evident during the mid-monsoon months of June, July, and August, as mean temperatures dipped toward the threshold, with August recording the seasonal low mean of 35.4°C. However, the Daily temperature heat map (fig. 26) and box plot highlight a significant late-season thermal resurgence in September, where the mean rose back to 37.2°C. This secondary peak, characterized by numerous outliers and a mean exceeding the threshold, confirms the re-emergence of heat wave conditions after the primary monsoon peak.

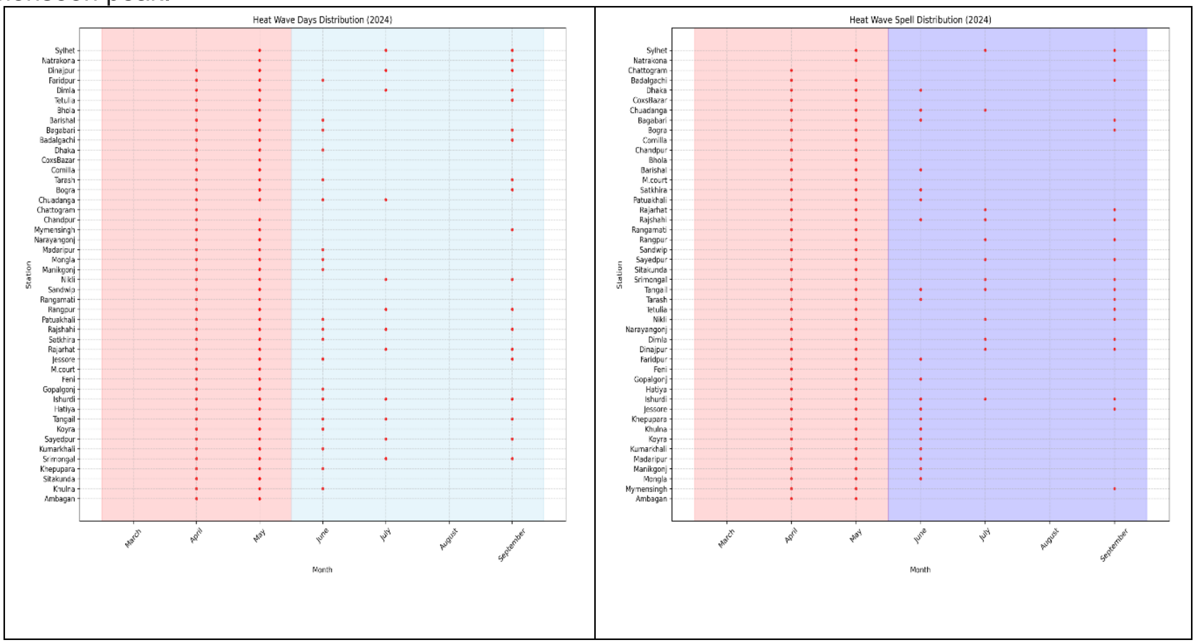

Fig. 27: Monthly distribution of heat wave days and spell

The temporal analysis of heat wave days and spells across Bangladesh in 2024 reveals a distinct bimodal distribution, with the most severe activity concentrated in the pre-monsoon and late-monsoon periods. Data from the distribution plots indicates that April and May served as the primary peak, during which nearly every monitored station ranging from the northern highlands to the southern coast recorded a dense frequency of heat wave days and prolonged spells. This period represents the maximum thermal stress of the year. A significant monsoon-induced moderation is observed in the middle of the season, particularly in August, which serves as a thermal trough with virtually no heat wave occurrences recorded across the stations. However, the data highlights a notable secondary resurgence in September, where both the frequency of heat wave days and the duration of spells increased significantly across northern, central, and southwestern districts. This pattern underscores a climatic transition where the cooling effect of the peak monsoon is bookended by intense heat events, with the pre-monsoon peak remaining the most geographically widespread and persistent.

4. CONCLUSION

The analysis shows that the highest maximum temperature recorded was 43.8°C at Jashore on 30 April 2024. Several heat wave spells were observed during the monsoon months, particularly in June, and continued intermittently until September. Consecutive heat wave spells were also detected, with heat wave conditions persisting for more than 27 days. Temperature deviations were positive in both the summer and monsoon seasons, indicating significantly higher temperatures compared to the climatological average.

April and May, entire distributions are well above 36°C. Indicate persistent and widespread heat wave conditions. June and July, the means are around or slightly above 36°C. Suggest moderate heat wave occurrence. March and August, this means are below 36°C, but upper ranges cross the threshold. Indicates occasional heat wave days. September, the mean is above 36°C, with many values exceeding the threshold. Suggests late-season heat wave re-emergence.

Spatial distribution analysis and interpolation results further reveal that the heat wave conditions extended into the monsoon season across different regions of Bangladesh. The findings suggest that 2024 experienced an extraordinary heat wave condition over Bangladesh, which has not been observed in the past thirty years.

Therefore, this study aims to examine the extent to which severe heat waves disrupt livelihoods and affect people, with a focus on recent extreme events. By addressing this gap, the research seeks to contribute to the development of targeted adaptation strategies and evidence-based policy interventions to mitigate the adverse impacts of heat waves.

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Analysis of Climatology of Clod Wave Variation and its Possible Mechanism over Rangpur Region in Bangladesh

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Abstract

Extreme weather events such as cold waves have disastrous effect on the health of people, especially vulnerable groups in developing countries due to ongoing global climate warming. Accordingly, this study intends to analyze the climatology of cold wave condition and its possible mechanism in Bangladesh. The minimum temperature (MinT) datasets of cold wave-affected Rangpur region for the period 1981–2021 were used for this purpose. As per the definition of cold waves provided by Bangladesh Meteorological Department (BMD), the frequencies of days with MinT in the range of 10°C have been considered and their future trends are being investigated to depict the cold wave condition in the study region. The results show that the cold wave follows a decreasing trend with a rate of decrement of -0.164/year during the study period. The lowest MinT≤15 was found in 2008-2009 while the highest MinT≤15 was observed in 1982-1983.Winter follows a decreasing trend under MaxT≤25 and MinT≤15, with a decrement rate of 0.249/year in the winter season from 1981 to 2021. Under the condition of the maximum temperature of 20°C (MaxT≤20) and a minimum temperature of 12.5°C (MinT≤12.5), the extreme winter lies on an average of 5 days in the winter season in the observation period. The maximum continuation of winter in the winter season under MaxT≤25 & MinT≤15 is 72 days, which happened in the 1984-1985. From 1981 to 2021, the standard deviation and correlation coefficient for extreme weather events in the winter season with each passing year are 11 and -0.245 in the study area. This study also found that the deviation of winter from 15th December follows a decreasing trend with a decrement of 0.0816/year. In the winter season, a center of high pressure (an anticyclone) lies over the northwestern part of India and from this high pressure a stream of cold air flows eastward that enters the country through its northeast corner by changing its course clockwise, and it initiate the cold wave situation over Bangladesh. The study reveals that the coldest region is found in the northwestern and north-northeastern parts of Bangladesh because of the geographic position of those areas and the location of the Himalayas foothills. From the large-scale synoptic condition perspectives, cold waves are shifting into Bangladesh from the north-west to northern parts.

Keywords: Cold waves, Extreme cold waves, Climatology, Trend, Season

1. Introduction

Presently climate change is a talk of the table across the world, and it is very for the sustainable development of Bangladesh. Different kinds of meteorological phenomena occur in our country that strike the normal of life, livelihoods, crop production, human health and other aspects of living bodies. Among these phenomena cold waves situations have a great impact in the various fields of living bodies that dismantle the normal flow of life irrespective of color, caste and different kinds of health hazard/disease do many harm to the human, animal health, crop, vegetable, and other fields as well. This is why the study of cold waves in different categories and their trends are very crucial for the safety of human and animal health and planning in various sectors such as agriculture, animal husbandry, livestock's, tourism sectors as well. It is explored that a few studies have been done by some authors such as Karmakar,2019; Nissan et al.,2017; Mannan et al.,2022; Hashizume et al.,2008 in the Bangladesh perspective but several studies have been accomplished in world perspective. It is shown that the underdeveloped and developing countries are most vulnerable due to climate change for its direct impact on socio-economic status in various angles (Mahmood, 2014; Elahi,2016; Mendelson,2006). Because of the geographical location of

Bangladesh, the climate becomes a unique factor to handle the overall socio-economic conditions of our country. Increasing temperatures, changing rainfall patterns, rising sea levels, and increasing frequency and intensity of extreme weather events are adversely affecting ecosystem functioning, agriculture and food security, infrastructure, water resources, and human health (Intergovernmental Panel on Climate Change (IPCC, 2014). Bangladesh was ranked 5th among 170 countries in the Global Climate Risk Index in the period 1994-2013 (Kreft et al. 2013). The duration of winter season and it's on time on set and the relevant events like fog; cold wave situation is very important for numerous purposes in different fields. Now a day's weather is considered as an important factor of everyday behavior and mood in modern life (keller et al. 2005; Persinger 1980; Watson 2000). More definitely in adulthood some emotional weather-derived disorders, such as the Seasonal Affective Disorder, have been linked to depression, anxiety and negative emotional states (Rohan and Sigmon 2003). Due to the location, northern part of Bangladesh, more especially the Rangpur division faces lots of weather-related events which have adverse effects on the agriculture industry, human health, transport system, and so on. Productivity of differents crops, vegetables and seeds influence by the length of winter season directly or indirectly. Winter is the coldest season of the year across Bangladesh specilly in the northern part, this season is characterized by falling cold temperatures, usually exacerbated by strong winds. Khatun et al. (2016) showed that annual minimum temperature increased notably over northeastern and central parts of Bangladesh, and the highest increment of minimum temperature per year of 0.3°C is found at Dhaka, Faridpur, Madaripur, Maijdi Court, Cox's Bazar, Sylhet, Srimongal, Rangpur and Bhola. Karmaker (2019) stated that though Bangladesh is a small country with huge population, its different parts have different impacts of disasters and climate change. Rangpur division in the Northern part of Bangladesh is such a kind of region having the significant impacts of thunderstorms, floods, cold waves and heat waves, drought, heat stress, riverbank erosion, scarcity of water and reduced river flows in dry season, etc.

In this study, we observe the winter season setup and withdrawal behavior and cold wave situation at Rangpur of Bangladesh using maximum and minimum temperature data during 1981-2021. Here regression analysis is used to detect the pattern of the number of days with minimum temperature (MinT≤15°C), cold wave days with minimum temperature ≤10°C (MinT ≤10°C), winter days with maximum temperature ≤25 °C (MaxT ≤ 25°C) & minimum temperature ≤15°C (MinT ≤ 15°C), extreme winter with maximum temperature ≤20°C (MaxT ≤ 20°C) & minimum temperature ≤12.5°C (MinT ≤ 12.5°C), deviation of winter from 15th December with MaxT ≤25°C & MinT ≤15°C and Length of winter season with MaxT ≤25°C & MinT≤15 °C. The atmospheric conditions are observed with the mean sea level pressure (MSLP) and surface wind which are favorable for associating winter season.

The objective of the study is to find out the trend as well as rate of extremity of maximum and minimum temperature in different types, length of winter season, variation of number of days, and deviation of winter from normal date of onset which has been defined as 15th December.

2. Data and Methodology

2.1 Study area description

Rangpur region is situated in the northern part of Bangladesh whose latitude is 24˚45′N and longitude is 89˚16′E. Its elevation is 32.6m from sea level. For some hydro-geological and socio-economic factors that include: a) its geographical location i.e very near to Himalaya b) extreme abnormality of climate that is governed by various seasons c) most of the people are engaged in agriculture which is highly as well as directly influenced by the change of normal weather behavior.

2.2 Data and quality control

To determine the winter season as well as its variation, maximum and minimum temperatures are considered primarily. But as winter is the cold feelings in society and therefore it is required to be determined by considering temperature thresholds of both maximum and minimum temperatures, which create quite strong cold feeling. As such winter has been defined by the lower value of the recorded maximum and minimum temperatures, which are equal to or below 90 percentiles. In a similar way strong winter has been defined as equal to or below 95th percentiles. To proceed further the daily maximum and minimum temperature data at Rangpur station of Bangladesh Meteorological Department (BMD) for the period of 1981-2021 are collected and considered as the representative of Rangpur Region. To examine the presence and duration of winter season maximum temperature of ≤ 25°C & minimum temperature ≤ 15°C considered jointly. Presence of strong winter defined by considering the day with maximum temperature ≤ 20°C & minimum temperature ≤ 12.5°C jointly. The cold wave days are considered when minimum temperature persists 10°C and it's lower.

The missing data of this site was less than 1% during the period from 1981 to 2021. Missing data were filled up by the average of the previous and the following day's data.

National Centre for Environmental Prediction (NCEP) reanalysis data are used for observing atmospheric conditions when winter season early setup and late setup at Rangpur. Here, mean see level pressure (MSLP) and Surface wind are conducted to validate of atmospheric condition which are associated with winter season over Bangladesh and neighborhood.

Accordingly, 15 December has been selected as the average onset date of winter at Rangpur. By following this, the years 2003 and 2017 were detected as the late onset of winter and the years of 1982 and 2014 were detected as the early onset years of winter at Rangpur region.

2.3 Linear Regression Analysis

Sir Francis Galton (1885) introduced the idea of "regression" to the research community in a study examining the relationship of fathers' and sons' heights. The same scientist in 1988 also introduced the concept of correlation, where correlation analysis is a technique to study the amount of relationship of two variables. Linear regression analysis is a parametric model and one of the most common methods to detect a pattern in data series. By fitting a linear equation to the observed data, this model establishes a relationship between two variables (dependent and independent). Next, the data is tested there to find out whether there is a relationship between the interest variables or not. If there is no relationship between two variables, the linear regression model does not prove to be a useful model. The correlation coefficient which ranges from -1 to +1 is a numerical measure of this correlation between the variables. A coefficient value ±1 for the correlation indicates a good match. A value close to zero implies that two variables have a random, non-linear relation. The linear regression model is generally described by the following equation:

$$Y = m * X + C$$

Where, Y and X are the dependent variable (no. of days of winter) and the independent variable (years), respectively, m is the line slope (day/year) and C is the intercept constant coefficient. The regression analysis is used to establish a linear regression regarding time between the observed maximum and minimum temperature result in winter seasons.

The analysis of trend for annual cold days from maximum and minimum temperature has been determined using Mann-Kendall and Sen's slope estimator for Rangpur region using statistical software R 4.0.5 during 1981-2021.The probability function of Weibull distribution is used for describing the peak and skewness of cold days of winter season at Rangpur region using Easyfit5.5. The regression analysis is used to establish a linear regression regarding time between cold wave days of winter season and correlation coefficient using excel.

2.4 Mann Kendall (MK) trend test

The non-parametric Mann-Kendall (MK) experiment (Kendall, 1975; Mann, 1945) is huge generally used for tendencies classifying in climatologic and weather data in time series analysis. Here, there are two benefits of using MK experiment. (1) It is a non-parametric test where data do not necessary to be normally distributed. (2) The trial has little sensitivity to unexpected due to inhomogeneous time series analysis (H. Tabari et al, 2011). The MK test statistic (S) is given by:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sign(T_j - T_i), \quad (1)$$

$$Sign(T_j - T_i) = \begin{cases} 1 \; if \; T_j - T_i > 0 \\ 0 \; if \; T_j - T_i = 0 \\ -1 \; if \; T_j - T_i < 0. \end{cases} \quad (2)$$

Where, T_j and T_i are the yearly values in years j and i, j > i respectively.

If n < 10, the value of $|S|$ is shares straight to the theoretical distribution of S derived MK. The two tailed experiment is used. At definite likelihood level H_0 is rejected in favor of H_1 if the original value of S equals or exceeds a certain value $S_{\alpha/2}$, where $S_{\alpha/2}$ is the lowest S which has the possibility less than α/2 to execute in case of no trend. A positive (negative) value of S designates an upward (downward) trend. For n ≥ 10, statistic S is almost normally distributed with the mean and variance as follows:

$$E(S) = 0. \qquad (3)$$

The σ^2 for the S statistic is expressed by:

$$\sigma^2 = \frac{n(n-1)(2n+5) - \sum t_i(i)(i-1)(2i+5)}{18}. \qquad (4)$$

Where t_i represents the number of ties to extent i. The synopsis term in the numerator is used only if the data series contains tied values. The standard test statistic Z_s is considered as bellows:

$$Z_s = \begin{cases} \frac{S-1}{\sigma} \; for\; S > 0 \\ 0 \; for\; S = 0 \\ \frac{S+1}{\sigma} \; for\; S < 0. \end{cases} \qquad (5)$$

The test statistic Z_s is used in a quantity of meaning of trend. In detail, this experiment statistic is used to experiment with the null hypothesis, H_0. If $|Z_s|$ is greater than $Z_{\alpha/2}$, where α denotes the special implication level (e.g., 5% with $Z_{0.025} = 1.96$) then the null hypothesis is inacceptable suggesting that the trend is important.

2.5 Sen's Slop estimator test:

Non-parametric technique (Sen, 1968) was used to assessment the degree of tendencies in the data at time series analysis. The gradient of "n" pairs of statistics can be first projected by using the below equation:

$$\beta_i = \text{Median}\left[\frac{X_j - X_k}{j-k}\right] \; \forall \; (k < j) \qquad (6)$$

In this formula, X_j and X_k represent values statistics at time j and k, separately, and time j is after time k (k ≤ j). The median of "n" values of β_i is the Sen's slope estimator experiment. A negative β_i value signifies a declining tendency; a positive β_i value signifies an accumulative tendency over time.

If "n" is an even number, then the slope Sen's estimator is computed by using the following equation:

$$\beta_{med} = \frac{1}{2}\left(\beta_{[n/2]} + \beta_{[(n+2)/2]}\right) \qquad (7)$$

If "n" is an odd number, then the slope Sen's estimator is calculated by using the below formula:

$$\beta_{med} = \beta_{[(n+1)/2]} \qquad (8)$$

Finally, β_{med} is verified by a two tailed experiment at 100(1-α) % assurance level, and the true gradient of monotonic tendency can be projected by using a nonparametric experiment (Partal and Kahya, 2006).

2.6 Weibull Distribution

The probability density function (PDF) of the Weibull distribution with two parameters is given by (Weibull 1951):

$$f(x,\beta,\gamma) \propto \frac{\beta}{\gamma}\left(\frac{x}{\gamma}\right)^{\beta-1} exp\left[\left(\frac{x}{\gamma}\right)^{\beta}\right]; 0 < x < \infty, \beta > 0, \gamma > 0$$

Where β is the shape parameter of the Weibull distribution which describes the peak and skewness of the cold wave days of winter season and γ is the scale parameter which describes the cold wave days of winter season at Rangpur region during 1981-2021.

3. Results and Discussion

The winter season setup and withdrawal behavior and cold wave situation at Rangpur of Bangladesh have been computer using maximum and minimum temperature data in the different categories like the pattern of the number of days with MinT ≤ 15°C, cold wave days with MinT ≤ 10°C, winter days with MaxT ≤ 25°C & MinT ≤ 15°C or less, extreme winter with MaxT ≤ 20°C & MinT ≤ 12.5°C during 1981-2021.But the topics of the main focusing point has been made on the pre-season when the extreme heat waves occur throughout Bangladesh especially in the western and south western part.

3.1 Trend and magnitude of the frequency of MinT ≤ 15°C, MinT ≤ 10°C, MaxT ≤ 25°C & MinT ≤ 15°C and MaxT ≤ 20°C & MinT ≤ 12.5°C in winter season at Rangpur during 1981-2020

Table 1, represent the trend and magnitude of the frequency of MinT ≤ 15°C, MinT ≤ 10°C, MaxT ≤ 25°C & MinT ≤ 15°C and MaxT ≤ 20°C & MinT ≤ 12.5°C situations of maximum and minimum temperature which is obtained from the Mann-Kendall test and the slope estimator from Sen. Here the frequency of MinT ≤ 15°C follows decreasing trend which is statistically significant at 95% level of significance for both tau(τ) value of Mann-Kendall and the slope estimator from the Sen (z) these are -0.437 and -3.882. For the frequency of MinT ≤ 10°C indicates the decreasing trend which is statistically insignificant at 95% level of significance for both tau(τ) value of Mann-Kendall and the slope estimator from the Sen (z) these are -0.153 and -1.355. The frequency of MaxT ≤ 25°C & MinT ≤ 15°C shows a decreasing trend which is statistically insignificant at 95% level of significance for both tau(τ) value of Mann-Kendall and the slope estimator from the Sen (z) these are -0.148 and -1.319. And the frequency of MaxT ≤ 20°C & MinT ≤ 12.5°C indicates an increasing trend which is statistically insignificant at 95% level of significance for both tau(τ) value of Mann-Kendall and the slope estimator from the Sen (z) these are 0.158 and 1.3743.

Table 1: Mann- Kendall (τ) and Sen's Slope (z) test

	Mann-Kendall (τ)	Sen's slope(z)	Two sided (p) - value
MinT ≤ 15°C	-0.44	-3.89	0.0001
MinT ≤ 10°C	-0.15	-1.36	0.18
MaxT ≤ 25°C & MinT ≤ 15°C	-0.15	-1.32	0.19
MaxT ≤ 20°C & MinT ≤ 12.5°C	0.16	1.37	0.17

3.2 Variation of the number of days with MinT 15°C or less

The average number of days with MinT 15°C or less is found vary over the time at Rangpur during winter season. The average MinT15 is 76 days at Rangpur, its standard deviation (STD) is 8 days and its correlation coefficient (CC) with is -0.57. The lowest MinT15 is found in 2008-2009, the highest MinT15 is found in 1982-1983. There is a decreasing trend of MinT15 during 1981-2021 with the rate of -0.38 day/year (Fig.1).

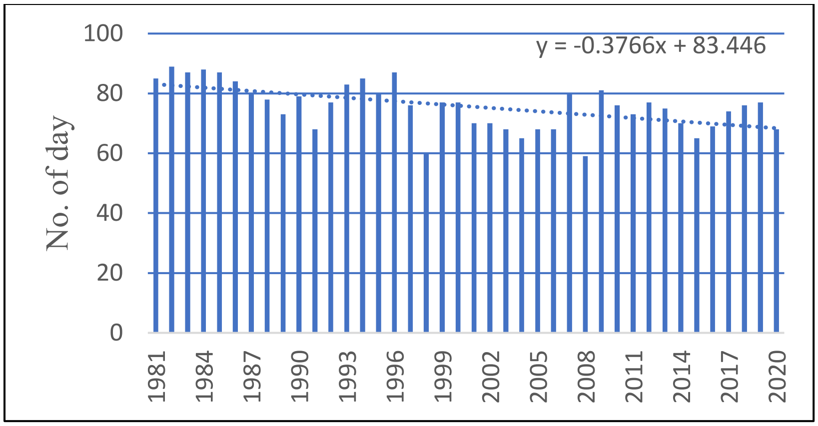


Fig.1: Number of days with MinT 15°C or less at Rangpur during 1981-2021

3.3 Variation of cold wave days with MinT 10°C or less

In winter season the average number of days with MinT 10°C or less is 16 at Rangpur of Bangladesh from 1981-2021. Fig. 2 depicts variation of MinT10 days during 1982-1983. Its average value is 33 and lowest magnitude of 1 is found in 2008-2009. The CC and STDs are -0.231 and 8. MinT10 follows a decreasing trend with the rate of -0.164 day/year during the observed period.

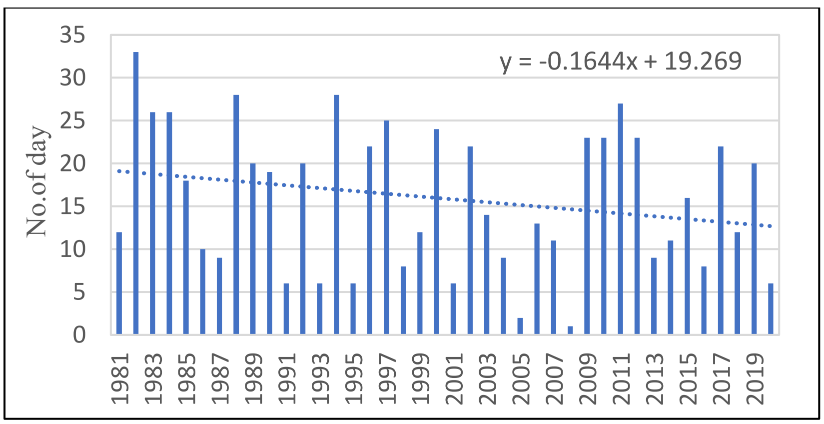


Fig.2: Number of cold wave days with MinT 10°C or less at Rangpur during 1981-2021

3.4 Variation of winter season with MaxT≤25°C & MinT≤15°Cat Rangpur during 1981-2021

With the condition of the MaxT ≤ 25°C & MinT ≤ 25°C, the average no. of day observed during 1981-2021 at Rangpur is 1981-2021. Accordingly, the highest MaxT ≤ 25°C & MinT ≤ 25°C of 62 days is found in1982-1983 and the no. of MaxT ≤ 25°C & MinT ≤ 25°C of 20 day is in winter season in 2016-2017 (Fig. 3). Under same condition the no. of MaxT ≤ 25°C & MinT ≤ 25°C in winter at Rangpur follows a decreasing trend with the rate of 0.249 day/year. The STD and CC of it are 11 and -0.2645 respectively.

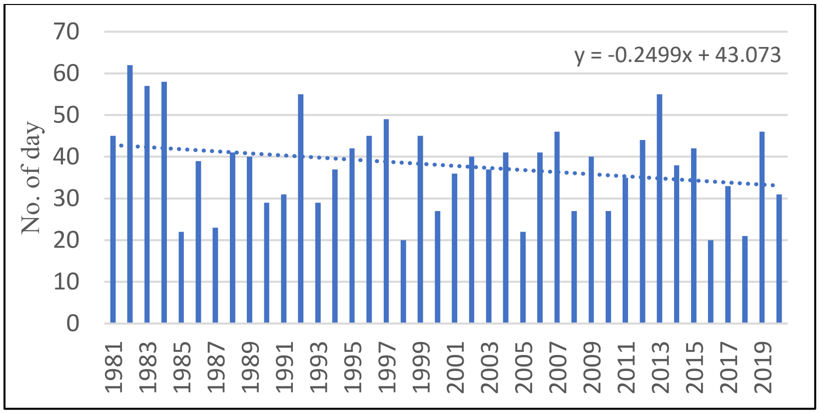


Fig.3: Number of winter days with of MaxT≤ 25°C & MinT≤ 25°C at Rangpur during 1981-2021

3.5 Variation of extreme winter with MaxT≤20°C & MinT ≤12.5°C at Rangpur during 1981-2021

Under the condition of the MaxT≤ 20°C & MinT≤12.5°C, the extreme winter lies on an average 5 days in winter season at Rangpur during 1981-2021. In Fig.4 it is shown that the highest extreme winter is 18 days in 2002-2003 at Rangpur and there is no extreme winter in 1981, 1982, 1987-1988, 2001-2002, 2007-2008 and 2017-2018. The standard deviation and correlation coefficient for extreme winter in winter season with year is 11 and 0.2333 at Rangpur from 1981-2021. Extreme winter follows increasing trend with the rate of 0.085/year.

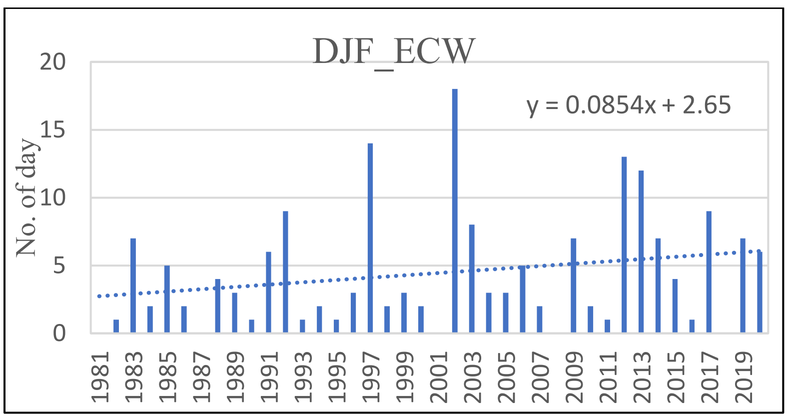


Fig.4: Number of winter days with MaxT≤20°C and MinT≤12.5 °C at Rangpur during 1981-2021

3.6 Length of winter season with MaxT≤25 & MinT≤15 at Rangpur during 1981-2021

Average length of winter in winter season is 53 days per year and the maximum continuation of winter in winter season under maxT25 & MinT15 is 72days which happened in 1984-1985 season from 1981-2021 at Rangpur. According to MaxT25 & MinT15 the length of winter in winter season follows decreasing trend with the rate of -0.082/year. The correlation coefficient of winter in winter season with year is -0.089 and its standard deviation is 11 at Rangpur from 1981-2021.

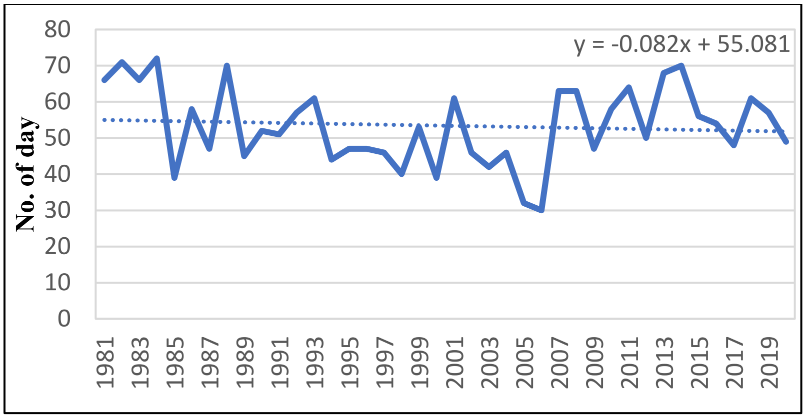


Fig.5: Number of days with MaxT≤25°C & MinT≤15 °C in winter Season at Rangpur during 1981-2021

3.7 Deviation of winter from 15th December with MaxT≤25°C & MinT≤15°C at Rangpur during 1981-2021

In Fig.6 it is noticed that winter with maximum temperature≤25°C and minimum temperature≤15 °C has come before 14 days in 1982-1983 and it started to delay 14 day in 1995-1996 and 2003-2004 on 15th December at Rangpur during 1981-2021. It is also observed that as a whole deviation of winter from 15th December follows decreasing trend with decrement is 0.0816/year.

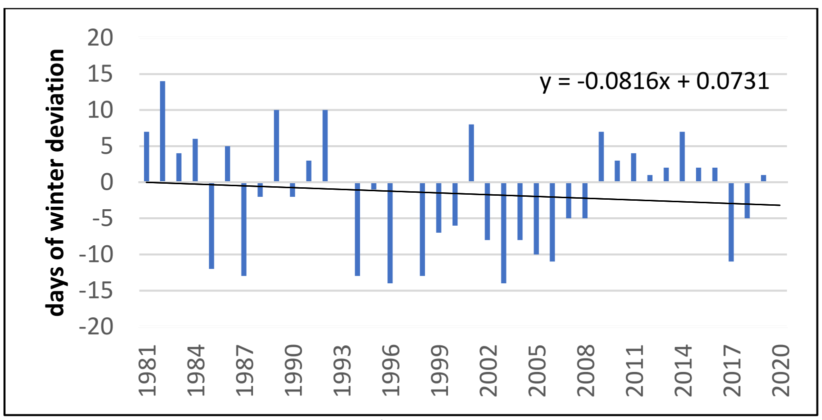


Fig.6: Deviation of winter from 15th December at Rangpur during 1981-2021

3.8 Probability Density Function of Weibull Distribution for MinT≤15°C, MinT≤10°C, MaxT≤25°C & MinT≤15°C and MaxT≤20°C & MinT ≤12.5°C at Rangpur during 1981-2021

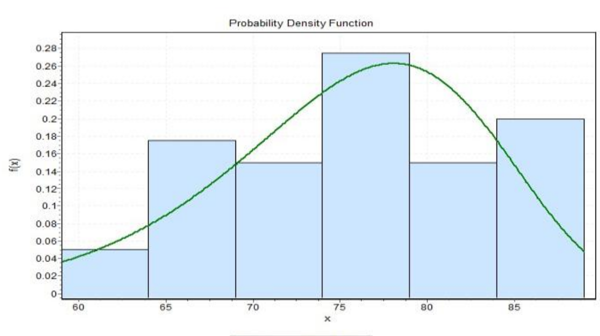


Fig.7(a): PDF of Weibull Distribution of MinT≤ 15°C

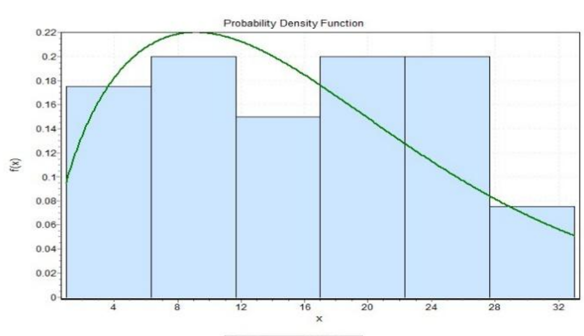


Fig.7(b): PDF of Weibull Distribution of MinT≤ 10°C

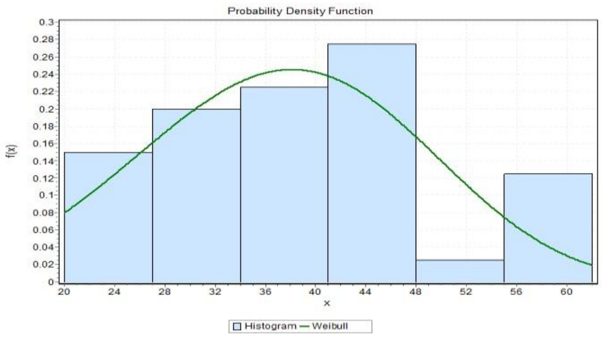


Fig.7(c): PDF of Weibull Distribution of MaxT$\leq 25°C$ and MinT $\leq 15°C$

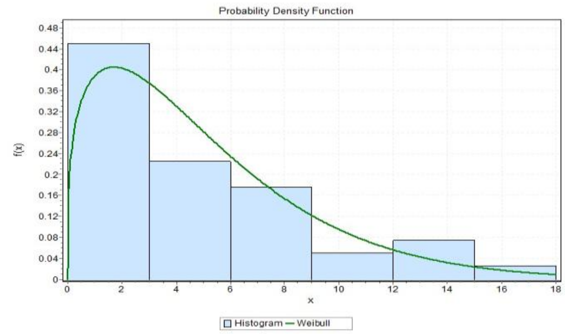


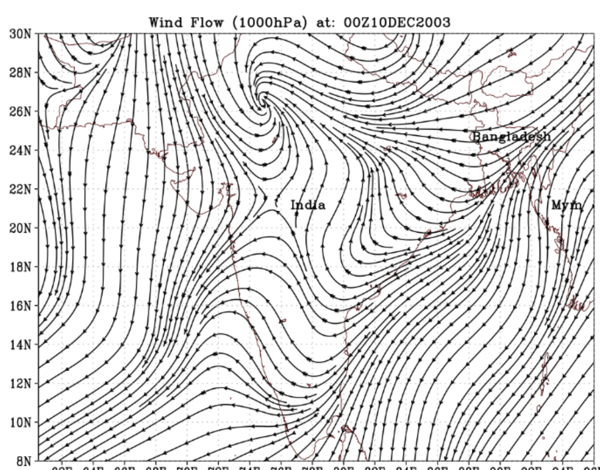
Fig.7(d): PDF of Weibull Distribution of MaxT$\leq 20°C$ and MinT $\leq 12.5°C$

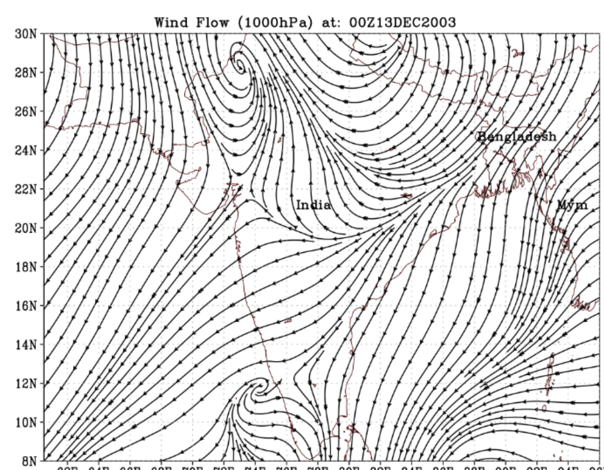
Fig.7 (a), 7(b), 7(c) and 7(d) shows the fitted PDF of Weibull distribution with β = 11.208 & γ = 78.736 for MinT $\leq 15°\mathrm{C}$, β = 1.5314 & γ = 18.191 for MinT$\leq 10°\mathrm{C}$, β = 3.7857 & γ = 41.339 for MaxT$\leq 25°\mathrm{C}$ & MinT $\leq 15°\mathrm{C}$ and β = 1.2861 & γ = 5.4651for MaxT$\leq 20°\mathrm{C}$ & MinT $\leq 12.5°\mathrm{C}$ compared to the histogram of cold days using maximum and minimum temperature of winter season at Rangpur region during 1981-2021. The Weibull curve is used to obtain shape and scale factors using cold days.

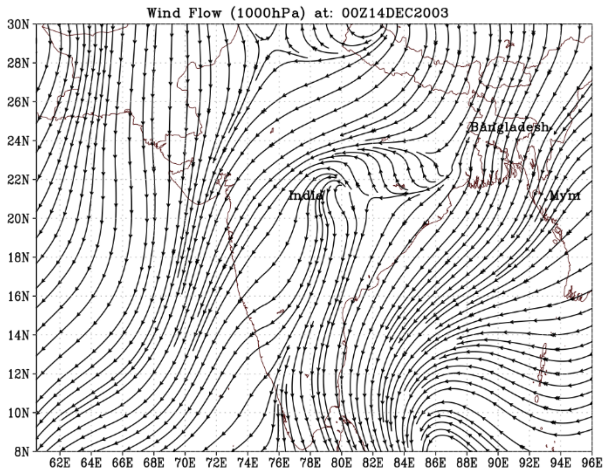
3.9 Mechanism of cold wave

3.9.1 Wind flows at 1000hPa in 2003 and 2017

The years of 2003 and 2017 were the recent late onset years of winter at Rangpur as defined in Fig.6. Analysis reveals that an anti-cyclonic circulation originated over east-central part of India at 1000 hPa level, very close to surface level on 1000 hPa, which was persisting afterwards. A seasonal low was persisting over South Bay. Due to these two weather systems, there were North/Northwesterly dry air flow at surface level was originated over northwestern Bangladesh on 29 December 2003, which was also continuing afterwards over the same region. The situation helped to onset of Winter Season over Rangpur region. Similar situation started to occur on 26 December 2017 and accordingly winter was onset over Rangpur region (Fig.8).






Wind Flow (1000hPa) at: 00Z14DEC2003
India
Bangladesh
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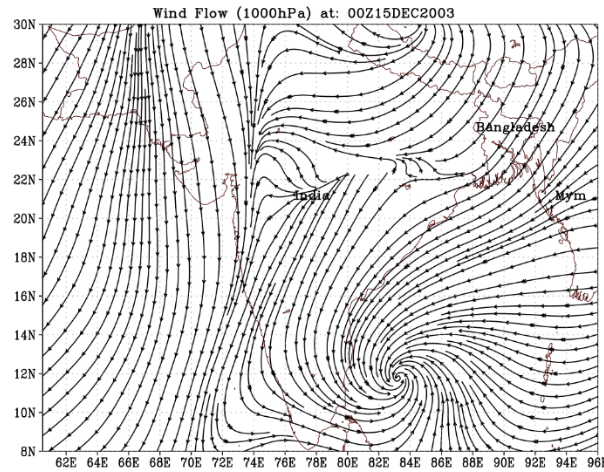
Wind Flow (1000hPa) at: 00Z15DEC2003
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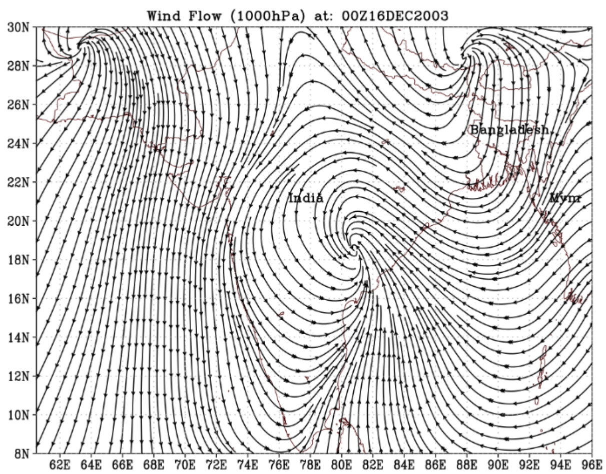
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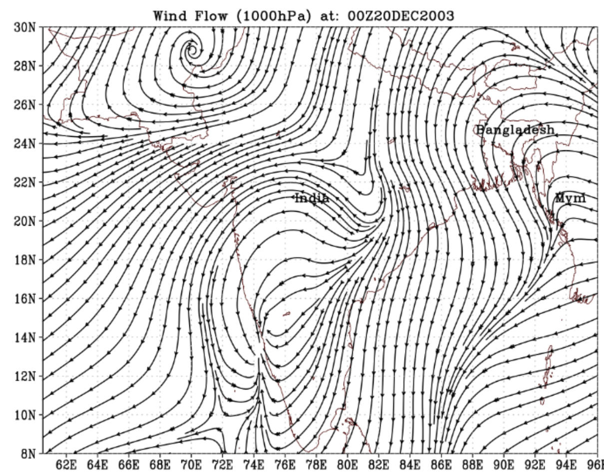
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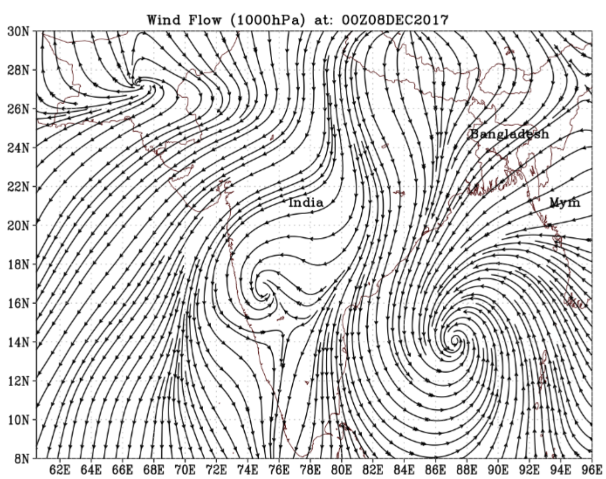
Wind Flow (1000hPa) at: 00Z08DEC2017
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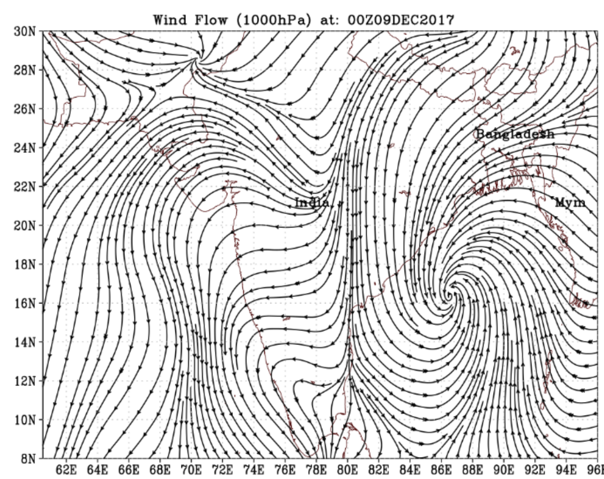
Wind Flow (1000hPa) at: 00Z09DEC2017
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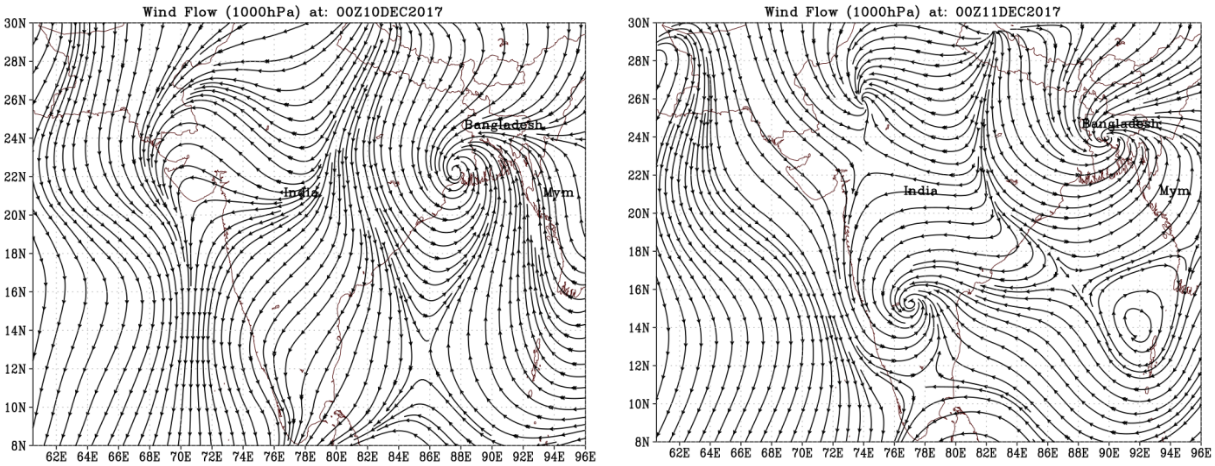
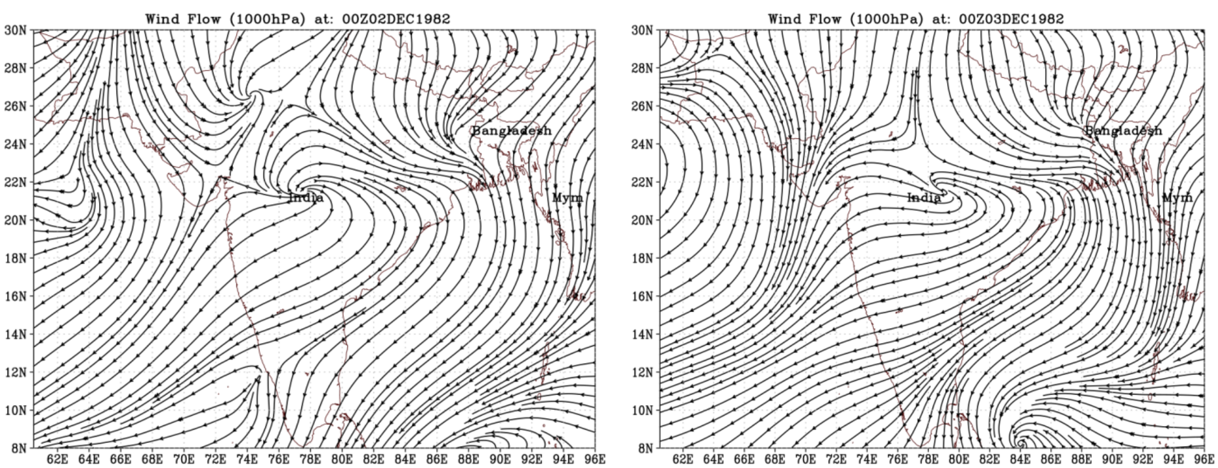


Fig.8: Wind flows at 1000hPa level in 2003 and 2017

3.9.2 Wind analysis at Rangpur 1000hPa in 1982 and 2014

As per the methodology, the years of 1982 and 2014 were the early onset winter seasons over Rangur Region. In 1982, the presence of anti-cyclonic flow detected first over Northwestern part of India on 2nd December, accordingly there were north/northeasterly flow started in the northern part of Bangladesh and afterwards and a cyclonic flow appeared over eastern part of India centered over Odisha. Due to this situation, winter season onset earlier in 1982 season, which was 12 days ahead. In 2014, an anticyclonic flow appeared first over northwestern/western part of India in the beginning of December, when a seasonal low persisted over South Bay. Due to these favorable conditions, winter season started over northwestern part of Bangladesh well ahead of average normal date, i.e., on 08 December 2014.



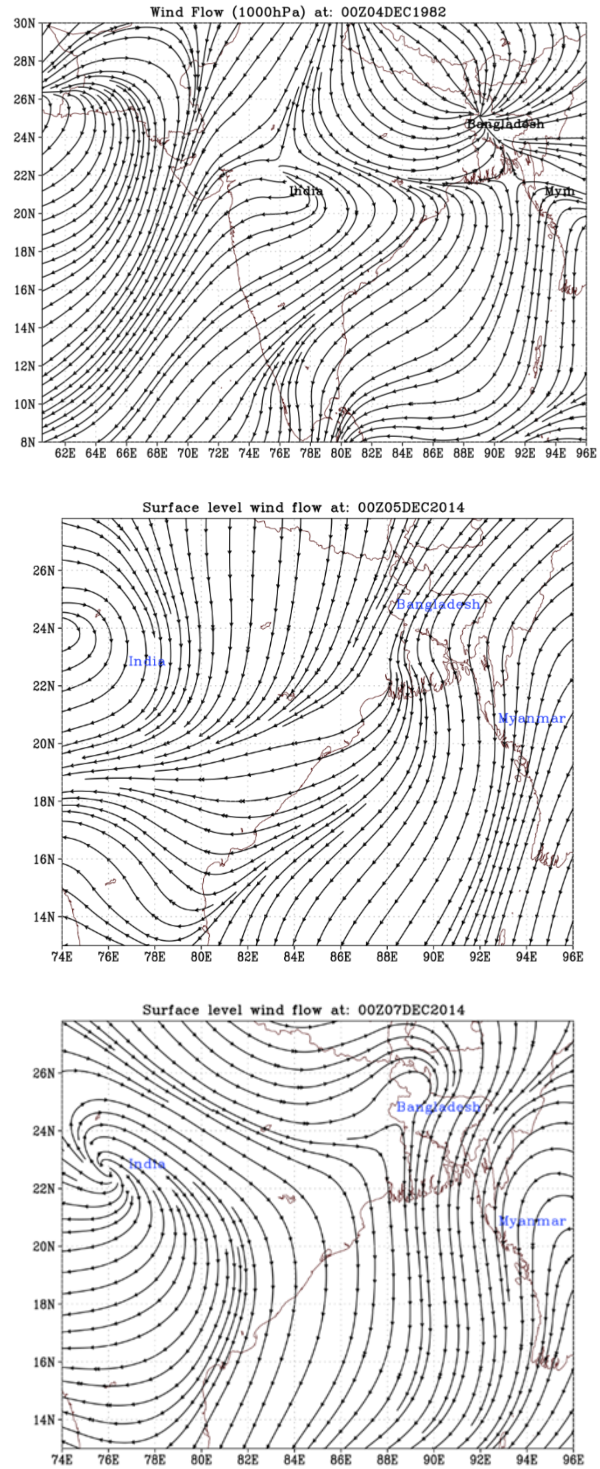
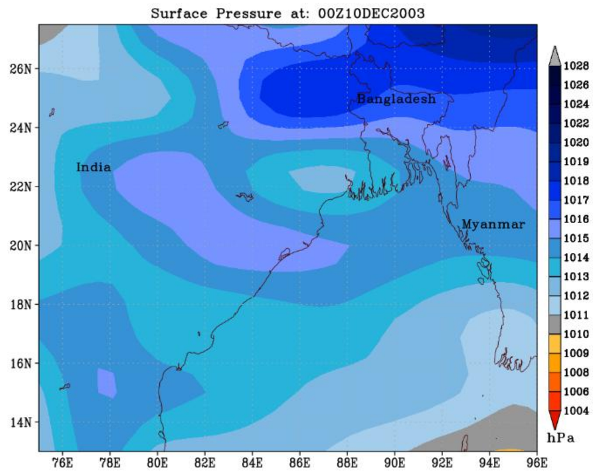
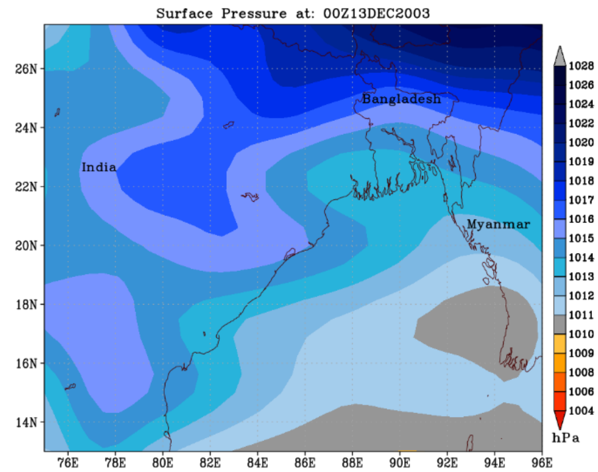


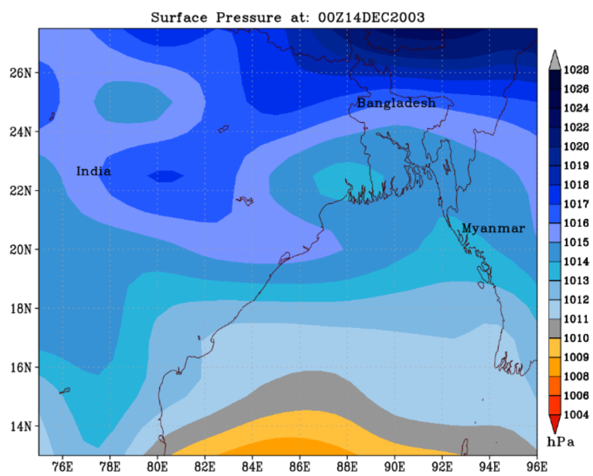
Fig.9: Wind flows at 1000hPa level in 1982 and 2014

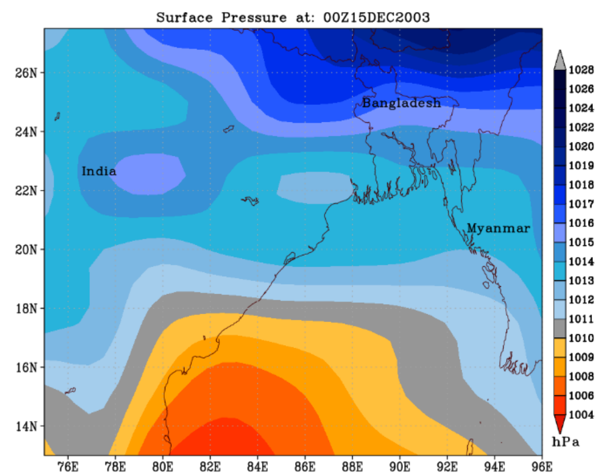
3.9.3 Mean sea level pressure analysis for setup of winter lately at Rangpur 1000hpa at 2003 and 2017

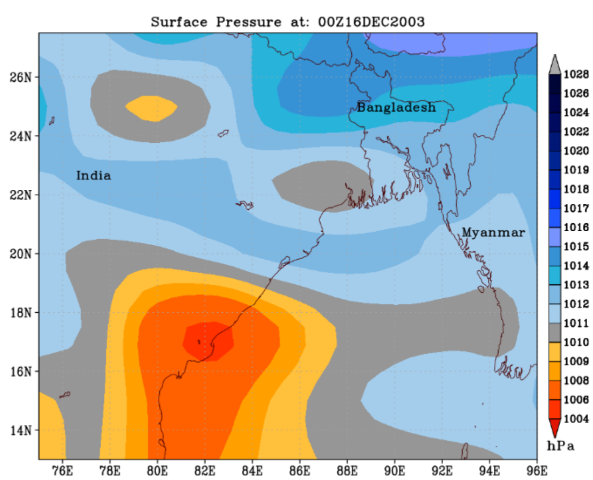
In 2003 a low pressure area formed over west central Bay and the adjoining area on 13th December which extended up to Bangladesh. Due to these two weather systems, there were North/Northwesterly dry air flow at surface level was originated over northwestern Bangladesh on 29 December 2003. In 2017 a low pressure area formed Northwest Bay of Bengal and adjoining area which extend up to head Bay. Due to this in 2017 winter season has been delayed starting on 26 December 2017.

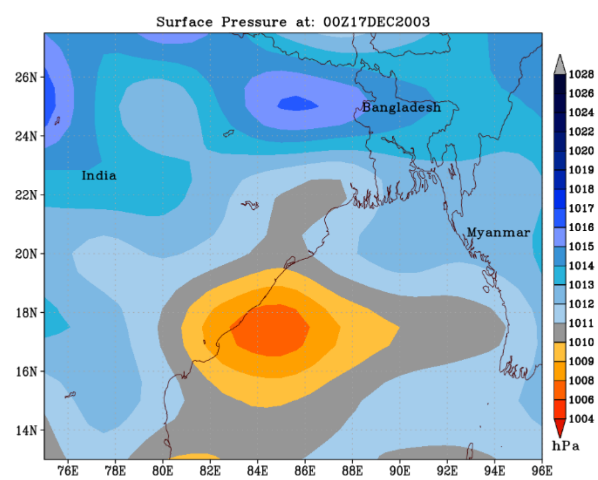












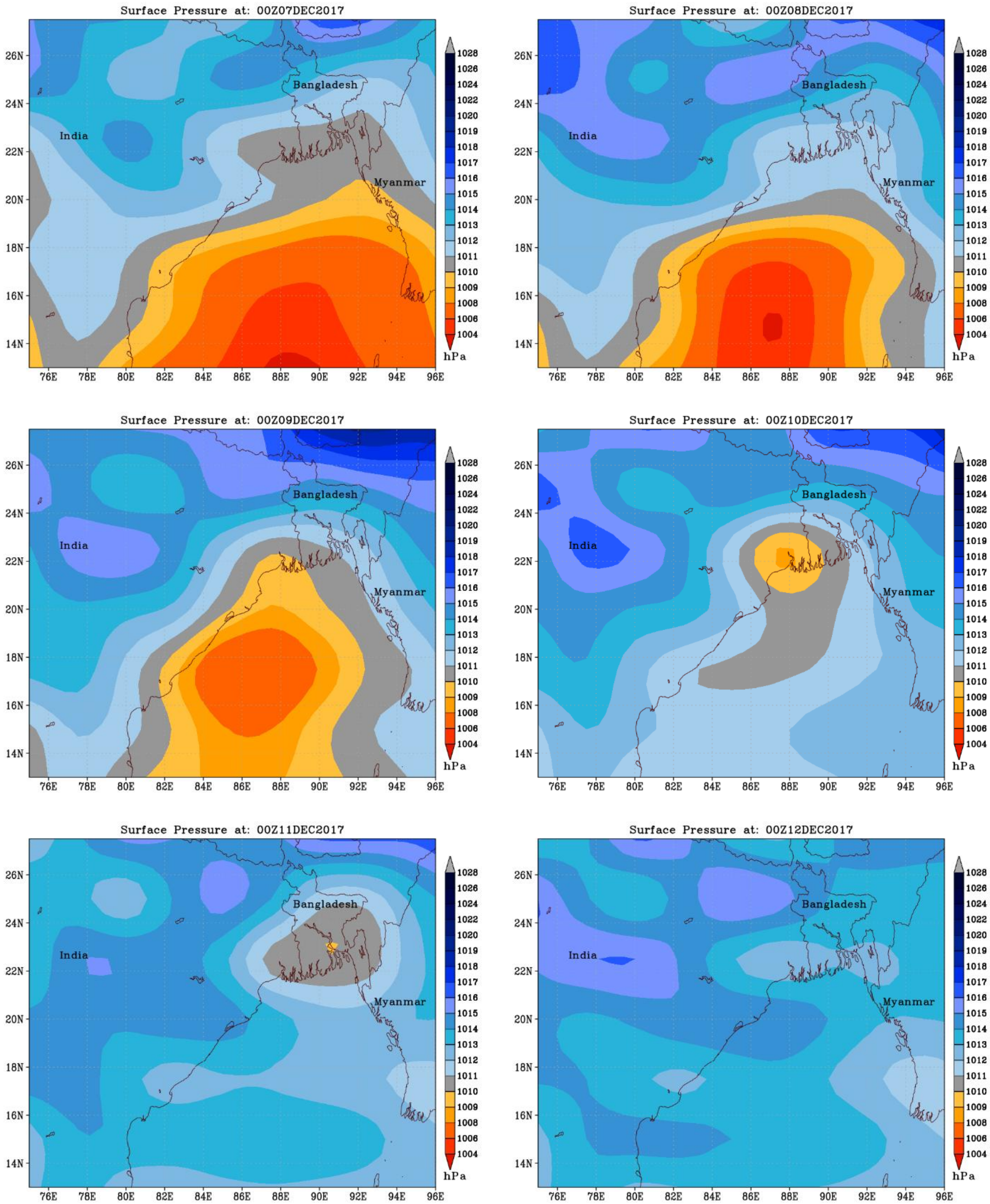
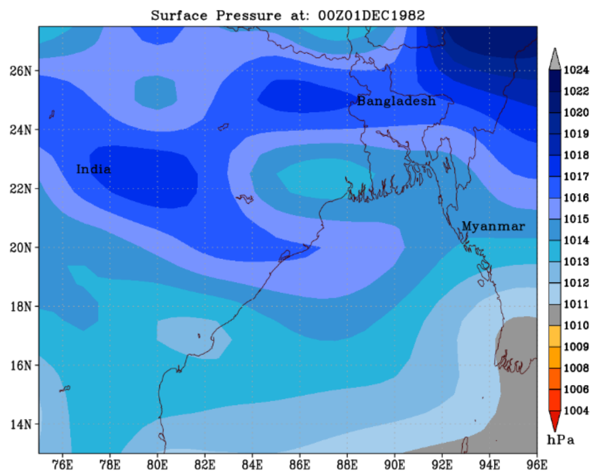
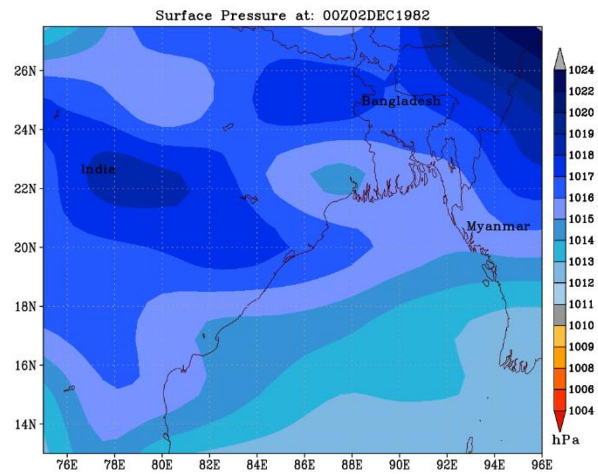


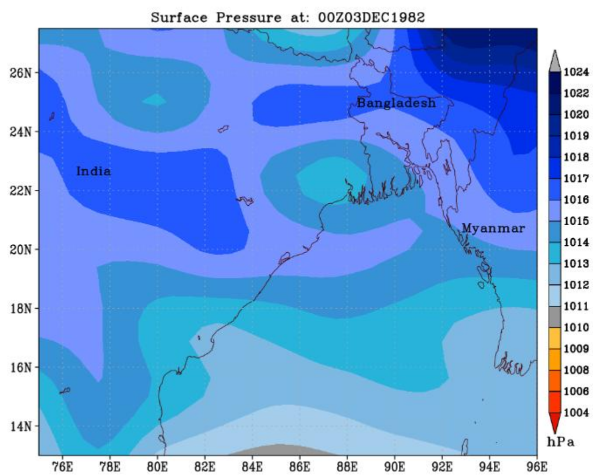
Fig.10: Mean sea level pressure at 0000UTC in 2003 and 2017

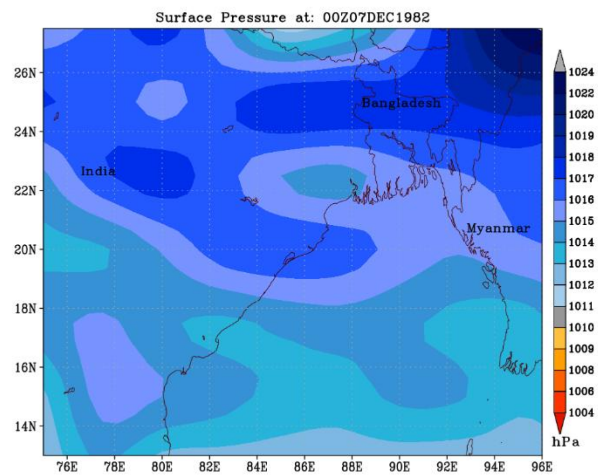
3.9.4: Mean sea level pressure analysis for winter set earlier at Rangpur in1982 and 2014

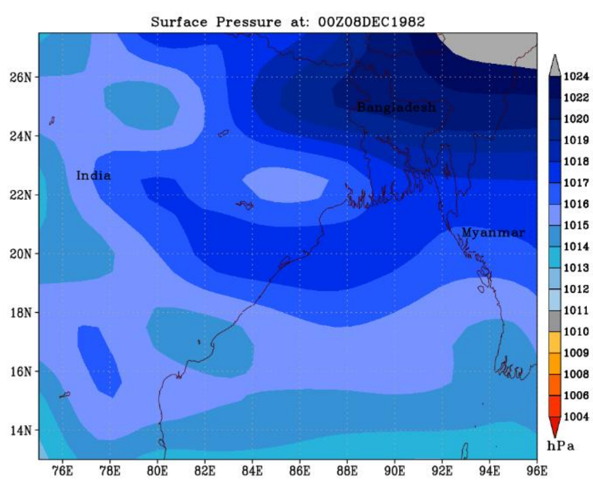
In 1982, a high-pressure region traced out first over Northwestern part of India on 2nd December, as a result there were north/northeasterly flow started in the northern part of Bangladesh. Due to this situation, winter season onset earlier in 1982 season, which was 12 days ahead. In 2014, a high-pressure area appeared first over northwestern/western part of India in the beginning of December, when a seasonal low persisted over South Bay. Favorable conditions persist over the northern part of Bangladesh for the earlier onset of winter during the first quadrant of December i.e on 2nd December in 1982 and on 8th December in 2014 respectively.

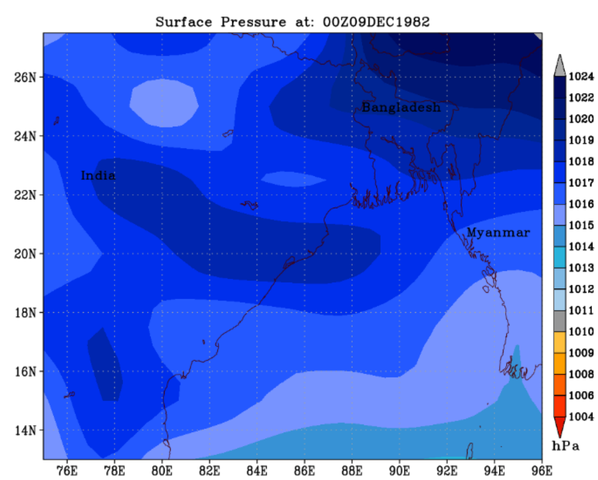












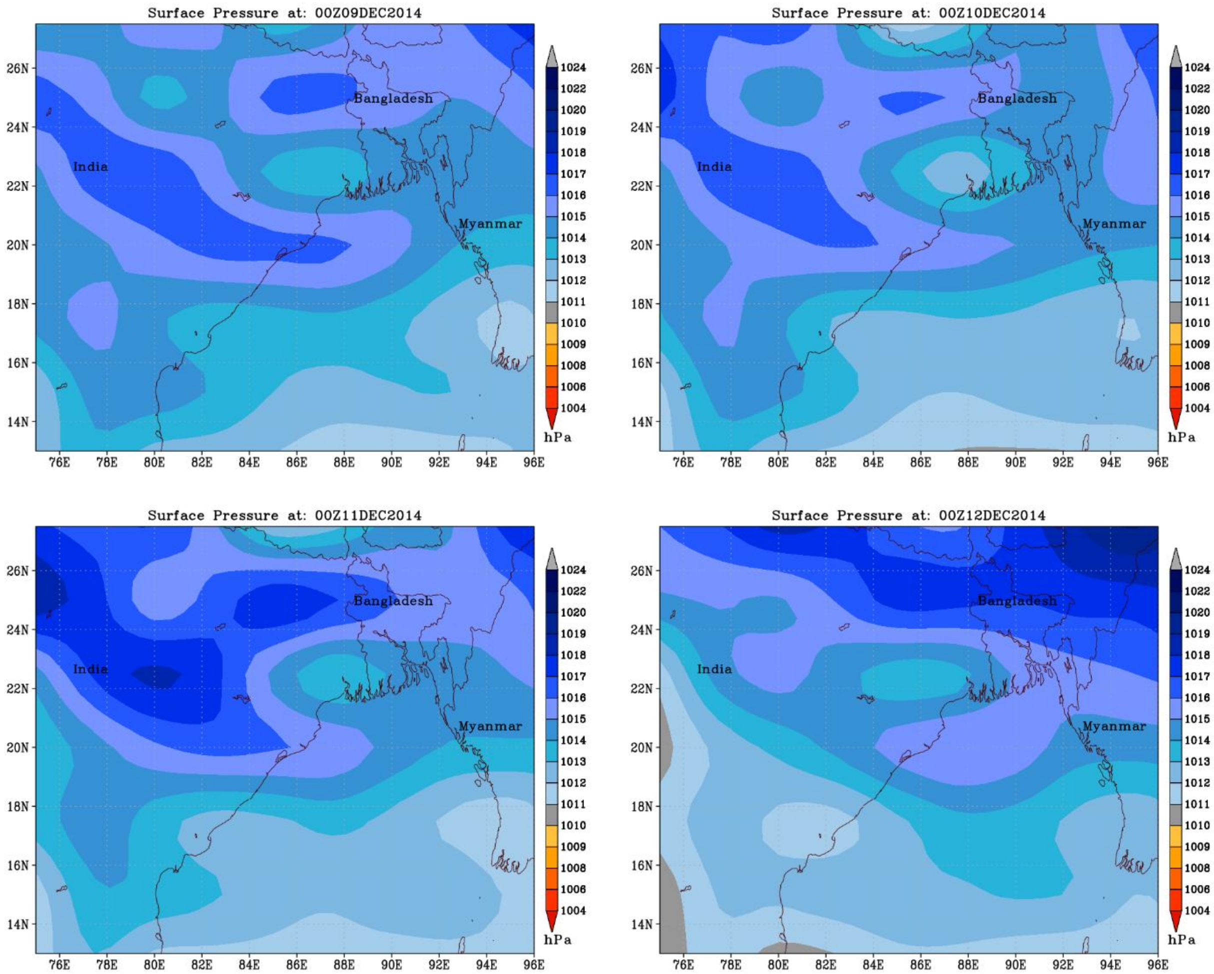


Fig.11: Mean sea level pressure at 0000UTC in 1982 and 2014

4. Discussion

A low pressure system persist over Northwest Bay & adjoining area that's why winter season start to delay in Bangladesh. On the other hand, an anti-cyclonic circulation persist over Northeastern part of India and the same time a low pressure system persist in South Bay that's why winter season startup earlier in Bangladesh. In this study, it is found that Cold wave days for MinT≤15°C, MinT≤15°C and MaxT≤25 & MinT≤20°C are decreasing trend but cold wave days for MaxT≤20°C & MinT≤12.5°C is increasing trend.

The future research plan is to find out why cold wave days for MaxT≤20°C & MinT≤12.5°C is increasing and MinT≤15°C, MinT≤15°C and MaxT≤25 & MinT≤20°C are decreasing.

5. Conclusion

The objective of this study is to evaluate the variability of cold wave situation and the onset of winter monsoon over Rangpur division during the session 1981 to 2021 taking data of Rangpur weather station from climate division of Bangladesh Meteorological Department. It is found that this region has a decreasing trend of minimum temperature 15°C or less during 1981-2021 with the rate of -0.38/year. The research explores that the number of cold wave days is in an augmented level over this region. It is found that deviation of winter from 15th December with maximum temperature≤25°C and minimum temperature≤15 °C in winter season during 1981-2021 follows a decreasing trend of 0.0816/year The study reveal that the average number of days in winter season is 53 in every year and it is following a decreasing rate of -0.082/year. The standard deviation and correlation coefficient shows that the extreme winter has an increasing trend with the rate of 0.085/year, and it is to be assumed easily that these cause a great uneasy condition for the inhabitants of the Rangpur division. Sudden decrease of temperature upto an enduring limit results in a severe health related hazard to most of the peoples especially the old aged, child and women portion.

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From Warning to Action: Evaluating the Effectiveness of Rainfall-Triggered Landslide Early Warning Systems for Hill-Covered Communities at Chattogram in Bangladesh

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Abstract

Rainfall-triggered landslides pose a severe threat to hill-covered communities in Chattogram, Bangladesh, necessitating effective Landslide Early Warning Systems (LEWS). While technical accuracy in rainfall threshold monitoring has improved, a critical research gap persists in understanding why scientific warnings often fail to trigger timely community action. This study evaluates LEWS' effectiveness by examining the transition "from warning to action". Adopting a mixed-methods approach, the research utilized household surveys (n=489), key informant interviews, and focus group discussions across vulnerable sites in Chattogram and Bandarban. Key findings reveal that while technical systems can issue alerts up to five days in advance, their impact is severely constrained by delayed last-mile dissemination, weak institutional coordination, and socio-economic barriers such as fear of property loss. Additionally, gender-disaggregated data shows that women and marginalized groups face higher risks due to unequal access to information. Implications suggest that LEWS must evolve from purely technological solutions into integrated socio-technical systems that prioritize community trust, inclusive communication, and resilient infrastructure to ensure scientific warnings translate into life-saving responses.

Keywords: Landslides, Early Warning Systems, Chattogram, Community Response, Socio-technical Barriers

Introduction

Landslides are among the most significant hydro-meteorological hazards affecting hilly and mountainous regions worldwide. In Bangladesh, the city of Chattogram (formerly Chittagong) and its surrounding hill-covered communities are particularly vulnerable due to a combination of fragile geological conditions, rapid urbanization, and intense monsoonal rainfall (Ali et al., 2014; Ahmed, 2015). The region's terrain is largely composed of loose, weathered Tertiary sedimentary rocks, which, when coupled with deforestation, hill cutting, and unplanned settlements, create highly unstable slopes prone to failure. In recent decades, these risk factors have intensified, resulting in frequent and catastrophic rainfall-triggered landslides that cause significant loss of life, displacement, and infrastructure damage (Ahmed, 2021).

Rainfall remains the primary triggering factor for landslides in Chattogram, with short-duration, high-intensity precipitation events increasing pore-water pressure and reducing soil shear strength (Sarkar et al., 2017). Empirical studies have identified critical rainfall thresholds—such as 100 mm within 3 hours or cumulative rainfall exceeding 250 mm over five days—as key indicators for landslide initiation in the Chattogram Metropolitan Area (Ali et al., 2014; Ahmed et al., 2020). As climate change continues to alter rainfall patterns, the frequency and intensity of such extreme events are expected to increase, further exacerbating landslide risks and underscoring the urgent need for effective disaster risk reduction strategies. In response, Rainfall-Triggered Landslide Early Warning Systems (LEWS) have been introduced as non-structural measures aimed at reducing risk through timely hazard detection and communication. These systems range from automated rain gauges with SMS-based alerts to advanced Web-GIS platforms that integrate real-time rainfall data with landslide susceptibility mapping (Ali et al., 2014). While such technological

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advancements have improved the precision and timeliness of warnings, the effectiveness of LEWS extends beyond technical accuracy. It depends critically on how warnings are communicated, perceived, and acted upon by at-risk communities.

A persistent challenge lies in the gap between receiving a warning and initiating appropriate action. Despite improvements in monitoring and forecasting, barriers such as delayed dissemination, weak institutional coordination, limited community awareness, and socio-economic constraints often hinder timely evacuation (Sarkar et al., 2017; Alam & Ray-Bennett, 2021). For many hill-dwelling residents, decisions to evacuate are influenced by concerns over livelihood security, property protection, and lack of accessible shelters. Additionally, marginalized populations frequently face limited access to reliable communication channels, reducing the reach and inclusivity of early warning systems (Sultana, 2020). Therefore, the effectiveness of LEWS in Chattogram must be understood as a socio-technical system, where technical reliability, communication mechanisms, institutional coordination, and community behavior interact. While meteorological precision and rainfall threshold accuracy form the foundation of these systems (Froude & Petley, 2022), their ultimate success depends on the ability to translate scientific warnings into timely, trusted, and actionable responses at the community level. Against this backdrop, this research aims to evaluate the effectiveness of rainfall-triggered landslide early warning systems in Chattogram, with a particular focus on the transition “from warning to action.” By examining both technical performance and community-level responses, the study seeks to identify key socio-technical barriers and generate actionable insights to strengthen the resilience of hill-covered communities against landslide hazards.

Methodology

This study adopts a mixed-methods research design, integrating both qualitative and quantitative approaches to evaluate the effectiveness of rainfall-triggered Landslide Early Warning Systems (LEWS) in Chattogram. The design is primarily descriptive and evaluative, focusing on the socio-technical dimensions of early warning systems, including system accuracy, communication flow, and community response. A case study approach is employed to capture the real-world dynamics of hill-covered communities, enabling an in-depth understanding of the gap between warning generation and action.

Data was collected through a combination of primary and secondary sources. Primary data include household surveys (n = 489, of which 238 in Chattogram and 251 in Bandarban), key informant interviews (KIIs) (n = 18 KIIs), and focus group discussions (FGDs) (n = 16 FGDs) with community members, local leaders, and disaster management state and non-state stakeholders. In addition, field observations were conducted to assess the condition of infrastructure, communication channels, and evacuation practices. Secondary data were gathered from Bangladesh Meteorological Department (BMD) bulletins, rainfall records, previous research studies, and institutional reports, providing insights into rainfall thresholds, warning dissemination, and historical landslide events.

The study focuses on hill-covered communities within landslide-prone areas of Chattogram, where rainfall-triggered landslides are frequent. Respondents were selected from vulnerable households, community volunteers, and representatives of local disaster management committees (DMCs). The sample includes diverse socio-economic groups to capture variations in perception, awareness, and response behavior, particularly among marginalized populations such as women, elderly individuals, and persons with disabilities.

A purposive sampling strategy was used to select study sites and respondents based on their exposure to landslide risks and involvement in early warning systems. This was complemented by a stratified two-stage cluster sampling method to ensure representation across different demographic groups (e.g., gender, age, disability, occupation, and geographic locations). Key stakeholders, including government officials and NGO representatives, were selected through key informant sampling to provide expert insights on system performance and institutional coordination.

Quantitative data from surveys were analyzed using descriptive statistics, including frequency distribution, percentages, and cross-tabulation to assess awareness, response patterns, and system effectiveness. Qualitative data from interviews and FGDs were analyzed through thematic analysis, identifying key patterns related to communication gaps, behavioral responses, and institutional challenges. In addition, comparative analysis was applied to evaluate differences between technical system performance (e.g., lead time, accuracy) and community-level response outcomes.

Ethical Considerations

The study adheres to standard ethical research practices. Informed consent was obtained from all participants prior to data collection, ensuring that participation was voluntary. Respondents were assured of confidentiality and anonymity, and no personal identifiers were disclosed in the analysis or reporting. Special attention was given to vulnerable groups, ensuring that interviews were conducted in a respectful and culturally sensitive manner. The research also ensured that findings would not harm participants but instead contribute to improving community safety and disaster preparedness.

Results

To assess the present study, the authors employed a range of indicators, including system accuracy and reliability, communication and information flow, behavioral response, gender-disaggregated concerns, infrastructure resilience, socio-economic impacts, cost–benefit analysis, and community response. The subsequent sections examine these indicators by synthesizing existing scientific literature alongside observed field realities in the study areas.

System Accuracy and Reliability

a. Threshold Validation

Rainfall threshold validation remains one of the most critical determinants of accuracy in landslide early warning systems. Empirical and physically based models typically derive thresholds by analyzing historical rainfall–landslide relationships, often using intensity–duration (I–D) curves or cumulative rainfall approaches. For example, research in Chattogram identified that 5-day cumulative rainfall between 71–282 mm can trigger landslides, highlighting the importance of localized threshold calibration rather than adopting generalized global thresholds (Ahmed et al., 2018). However, literature shows that threshold models are inherently uncertain due to spatial variability in soil conditions, slope characteristics, and antecedent moisture, which can lead to false alarms or missed events (Xing et al., 2026). Recent advancements, such as multi-threshold and 3D threshold systems incorporating antecedent rainfall or soil moisture, aim to reduce false alarms while maintaining predictive accuracy (Nocentini et al., 2024). Besides, according to the Special Warning Bulletin for Landslide (Issued 21 August 2025, 21:00 BST) or Heavy Rainfall Warning (Issued 28 April 2026) for landslide by the Bangladesh Meteorological Department (BMD-www.bmd.gov.bd) in Chattogram found that 4-day (96 hours) cumulative rainfall above 88 mm can trigger landslides (BMD, 2025 & BMD, 2026). In real-world contexts like Chattogram, where hill cutting and heterogeneous geology are prevalent, failure to continuously validate thresholds with updated landslide inventories and rainfall data significantly reduces system reliability.

b. Lead Time Analysis

Lead time is a key operational parameter that determines whether warnings can effectively translate into action. Rainfall-triggered landslide systems generally provide lead times ranging from a few hours to several days, depending on forecasting capability and threshold sensitivity. In the Chattogram context, the Web-GIS-based early warning system demonstrated the potential to issue alerts up to five days in advance using forecast rainfall data (Ahmed et al., 2018). However, literature emphasizes that increasing lead time often reduces accuracy due to uncertainty in rainfall prediction and slope response dynamics (Hsu et al., 2018). Additionally, the effectiveness of lead time is not only technical but also institutional; delays in administrative dissemination can significantly shorten actionable warning time at the community level. Real-time examples from Bangladesh indicate that even when forecasts are available, delayed communication and limited preparedness reduce the practical utility of early warnings, highlighting a gap between “technical lead time” and “effective lead time.”

c. Spatial Precision

Spatial precision refers to the system’s ability to accurately identify specific locations at risk, which is particularly challenging in complex hill environments like Chattogram. Modern landslide early warning systems increasingly integrate GIS-based susceptibility mapping with rainfall thresholds to improve spatial targeting. For instance, the Chattogram model combines multi-factor susceptibility maps (e.g., slope, geology, land cover, drainage) with rainfall thresholds to generate location-specific warnings (Ahmed et al., 2018). Despite these advancements, literature highlights that spatial accuracy is often constrained by coarse-resolution data, limited monitoring networks, and variability in local terrain conditions (Ali et al., 2025). Many systems still operate at regional scales, which may overlook micro-level risks such as localized hill cuts or informal settlements, common in Chattogram. As a result, warnings may be too generalized, reducing trust and response effectiveness. Enhancing spatial precision requires high-resolution data, continuous monitoring, and integration of community-level observations to capture localized hazard dynamics.

Communication and Information Flow

Effective communication and information flow are central components of any rainfall-triggered landslide early warning system (EWS), yet they often represent the weakest link between forecast generation and community action. Literature emphasizes that even when accurate forecasts are produced, gaps in communication can significantly reduce the usability of warnings at the community level. In Bangladesh, this gap is particularly evident, where national-level meteorological information does not always translate into actionable messages for at-risk populations. In the context of Chattogram, although rainfall thresholds and hazard zonation have been scientifically developed, the flow of information from technical systems to local communities remains fragmented. For instance, early warning systems developed using Web-GIS platforms can generate alerts several days in advance, but the effectiveness of these alerts depends heavily on how clearly and quickly they are communicated to end users (**Ahmed et al., 2018**). However, the Bangladesh Meteorological Department (BMD) disseminates its Special Warning Bulletin for landslides and heavy rainfall to approximately 46 state and non-state stakeholders, including the Prime Minister's Office, relevant ministries and departments, research organizations, print and electronic media, and district administrations. While this structured communication flow ensures that warnings efficiently reach the final tiers of government, a critical challenge remains how these institutions effectively transmit timely and actionable information to last-mile communities in disaster-prone areas. Therefore, communication should not be viewed solely as a technical process; it is fundamentally a socio-institutional challenge shaped by clarity, timeliness, trust, and accessibility.

a. Dissemination Channels

Dissemination channels refer to the pathways through which warning messages are transmitted from authorities to communities. Research highlights that multi-channel dissemination, such as SMS alerts, email notifications, community volunteers, religious institutions, and local leaders, is essential for ensuring redundancy and wider reach (Thapa et al., 2019). In Chattogram, early warning systems have utilized digital tools such as email notifications and online platforms capable of issuing alerts up to 4–5 days in advance (Ahmed, 2015). However, reliance on digital communication alone is insufficient in many hill-covered communities where internet access and smartphone penetration are limited. Real-world experiences from Cox's Bazar and Chattogram show that community-based dissemination, through mosque announcements, volunteers, and door-to-door communication, remains critical, especially during extreme rainfall events. The literature consistently stresses that warnings must be "simple, clear, and usable" to ensure that communities understand and act upon them (Thapa et al., 2019). Thus, integrating both high-tech and low-tech dissemination channels is essential for effective last-mile communication.

b. Comprehensive Levels (Multi-Level Communication System)

A comprehensive early warning system requires coordination across multiple administrative and institutional levels—national, regional, local government, and community. Studies indicate that effective landslide warning systems depend on strong interconnection and data-sharing among these levels, ensuring that information flows seamlessly from forecasting agencies to local responders (Thapa et al., 2019). In Bangladesh, institutions such as the Meteorological Department, Disaster Management Committees (DMCs), and local authorities operate at different levels, but coordination among them is often weak, leading to delays and inconsistencies in messaging. For example, while rainfall-based thresholds can trigger alerts at the national or city level, these warnings may not be adequately translated into localized action plans at the ward or community level in Chattogram. Furthermore, previous community-based EWS initiatives (e.g., in Cox's Bazar) demonstrated that a lack of long-term institutional integration and follow-up resulted in system inactivity despite initial success (Ahmed et al., 2018). This highlights that a comprehensive, multi-level communication framework must not only exist structurally but also function operationally with clear roles, responsibilities, and accountability across all levels.

Behavioral Response

a. Evacuation Rates

Despite the availability of early warning systems, evacuation rates in Bangladesh remain inconsistent and often low, particularly in rapid-onset hazards like landslides. Studies show that even when warnings are issued, many people delay or refuse evacuation due to risk perception, trust deficits, and previous false alarms. For instance, research on disaster events in Bangladesh indicates that "people stayed put despite obvious alerts," highlighting a gap between warning dissemination and actual response behavior (Shah et al., 2022). In landslide-prone areas such as Chattogram, short lead times and limited warning dissemination further reduce timely evacuation, making anticipatory action less effective (Save the Children, 2025).

b. Barriers to Action

Multiple structural, socio-economic, and institutional barriers constrain effective response to early warnings. Literature highlights that economic insecurity, fear of asset loss, lack of accessible shelters, and weak communication systems significantly hinder evacuation decisions. Social hierarchies and governance limitations also reduce individual agencies, while limited coordination among institutions leads to confusion in messaging. In Bangladesh, studies show that bureaucratic inefficiencies, inadequate infrastructure, and inconsistent communication undermine the effectiveness of evacuation strategies (Masud-All-Kamal et al., 2025). In the context of rainfall-triggered landslides, additional barriers include very short lead times and limited anticipatory protocols, especially in remote hill communities (Save the Children, 2025).

Gender-Disaggregated Concern

Gender plays a critical role in shaping early warning reception and response. Women, children, the elderly, and persons with disabilities often face higher vulnerability due to unequal access to information, mobility restrictions, and decision-making power. Evidence from Bangladesh shows that women are less likely to receive timely warnings directly, as information is often mediated through male household members (Mathathu and Khan, 2022). Cultural norms, caregiving responsibilities, and safety concerns in shelters further limit women's ability to evacuate. Moreover, gender-blind early warning systems fail to address these disparities, leading to unequal outcomes despite similar exposure to hazards (UN Women, 2023). In landslide-prone communities of Chattogram, women and children are often excluded from preparedness and decision-making processes, reinforcing their heightened risk (Save the Children, 2025).

Infrastructure Resilience

Infrastructure resilience in landslide-prone areas of Chattogram remains critically challenged due to the combined effects of intense monsoon rainfall, unplanned urbanization, and weak slope stabilization practices. Studies show that landslides in the Chittagong Hill Tracts frequently damage roads, drainage systems, and utility networks, disrupting both mobility and emergency response capacity (Ahmed, 2021). Although rainfall-triggered early warning systems (EWS) using real-time rain gauges and SMS alerts have been developed, their effectiveness depends heavily on the reliability of physical infrastructure such as roads, communication towers, and power supply (Ali et al., 2018). In practice, heavy rainfall events (often exceeding 150–250 mm) not only trigger slope failure but simultaneously weaken infrastructure systems, limiting the ability of communities to act upon warnings, highlighting a critical gap between early warning generation and actionable response.

a. Shelter Accessibility

Shelter accessibility remains a significant constraint in translating early warnings into life-saving actions. In many hill-covered communities, especially informal settlements and refugee camps, shelters are either insufficient, distant, or located in areas with limited safe access routes. Evidence from Cox's Bazar and surrounding hill regions shows that dense settlements on unstable slopes and poor road connectivity restrict timely evacuation during heavy rainfall events (Kamal et al., 2022). Even when warnings are issued several days in advance based on rainfall thresholds, physical access barriers, such as narrow, muddy, or landslide-prone pathways, reduce evacuation efficiency. Real-world events in Chattogram demonstrate that vulnerable populations often delay evacuation due to distance, lack of transport, and fear of losing assets, ultimately increasing casualties despite the presence of early warning information.

b. Infrastructure Stress

Infrastructure systems in Chattogram experience cumulative stress during prolonged or intense rainfall, which directly undermines the effectiveness of early warning systems. Research indicates that landslides are often preceded by multiple days of heavy rainfall (up to 4–5 days), which progressively saturates soil and destabilizes slopes (Ahmed et al., 2018). This prolonged rainfall also weakens drainage systems, erodes road networks, and overloads communication infrastructure, creating cascading failures. For example, during extreme monsoon events, road collapses and blocked access routes delay emergency services and evacuation, while power outages and network disruptions hinder warning dissemination. Such compound stress highlights that early warning systems must be integrated with resilient infrastructure planning; otherwise, warnings alone cannot translate into effective risk reduction.

Socio-Economic Impact

Rainfall-triggered landslides in the Chattogram region have significant socio-economic consequences, particularly for low-income and hill-settled communities. Studies show that landslides in areas like Chattogram and Cox's Bazar have caused substantial loss of life, displacement, and destruction of housing and infrastructure, often linked with deforestation and unplanned settlements (Ahmed et al., 2020). Early warning systems (EWS), especially rainfall-threshold-based systems, can reduce these impacts by enabling timely evacuation and protection of assets. Evidence from Bangladesh indicates that early warnings help households safeguard livelihoods, including land, housing, and livestock, thereby reducing disaster-induced poverty and enhancing resilience (Zayed et al., 2025). However, effectiveness depends heavily on community awareness, trust, and the ability to act on warnings.

Cost-Benefit Analysis

Existing literature strongly supports the economic viability of early warning systems in Bangladesh. A recent study on flood early warning systems shows that benefit–cost ratios can range from 79 to over 200, indicating extremely high returns compared to investment costs (Islam et al., 2024). Importantly, extending lead time significantly increases economic benefits; for example, just a two-day increase in warning lead time can enhance savings by over 20 times (Islam et al., 2024). Similar principles apply to landslide early warning systems, where even short lead times (e.g., 3–5 days rainfall threshold alerts) can prevent casualties and reduce infrastructure damage (Ahmed et al., 2018). Thus, investment in rainfall-triggered landslide EWS in Chattogram is likely to yield high socio-economic returns through avoided losses and improved preparedness.

Community Response

Table 01: Precautionary measures while people are facing a warning or bulletin from BMD

Category	Action	Avoid
Immediate Response	Evacuate immediately (if rainfall exceeds the BMD threshold (e.g., 100 mm in 24h).	Don't wait for the rain to stop; most landslides occur during or shortly after peak intensity.
Communication	Activate 'Last-Mile' warning. Use local mosques, sirens, and community volunteers to reach hill-dwellers.	Don't assume everyone has a smartphone or access to the digital bulletin.
Environmental	Clean drainage paths to prevent waterlogging, which increases pore-water pressure in the soil.	Don't cut into the hills or clean vegetation during the monsoon season; this destabilizes the slope.

Safety	Identify 'Safe Spaces' on flat, stable ground previously mapped by authorities.	Don't seek shelter in Katcha Houses or structures directly at the foot of steep slopes.
Monitoring	Watch for 'Warning Signs'. New cracks in the ground, tilting trees, or sudden muddy (earthen) water flow.	Don't ignore minor soil shifts; they are often precursors to a massive failure.
Keep provision for special category people, like children, the elderly, pregnant women, and PwDs	Family members should keep with them. The situation should be observed and brought into a safe space. Possibly arrange accessible devices, like a stretcher, a bar for bearing elderly people, and so on.	Don't be anxious in front of them; children don't move or keep to strangers.
Preserve valuable and bearable resources, like land documents (dolil), ornaments (gold),	Bring them covered by a water-protected bag or keep relatives at a safe house who are safe for themselves and live away from landslide hazards.	Don't keep these in the vacant house, because these are possibly stolen.
Livestock	Bring them into the safe space.	Livestock cannot be tied up. If you can't take them to a safe place, you must set them free.
Bring Safety measures, like fire boxes, candles, tents (tarpaulin), warm cloth, oral saline, bearable drinking water, and dry foods.	Bring these safety measures covered by a water-protected bag	Disconnect the electricity switch before leaving the residence, and don't leave home with a fire burning. Don't bring huge clothes and goods when going into a safe space.

Source: Compiled by Authors, 2026, considering qualitative checklist findings.

Discussion

The findings of this study highlight a critical disconnect between the technical generation of landslide early warnings and the actual behavioral response at the community level in Chattogram. While rainfall-triggered Landslide Early Warning Systems (LEWS) demonstrate reasonable effectiveness in detecting hazard thresholds and issuing alerts, their impact is significantly constrained by delays in dissemination, weak communication channels, and limited community preparedness. The results suggest that warning messages often lose their effectiveness as they pass through multiple administrative layers, reducing actionable lead time. Additionally, socio-economic realities, such as fear of property loss, livelihood insecurity, and lack of trust in warnings, play a decisive role in shaping community response. This indicates that the effectiveness of LEWS is not solely dependent on technical accuracy but is deeply embedded within social, institutional, and behavioral contexts. These findings are consistent with existing literature emphasizing the "last mile" challenge in early warning systems. Previous studies (e.g., Froude & Petley, 2022; Sarkar et al., 2017) have highlighted that even highly accurate forecasting systems fail if warnings do not translate into timely action. Similar to the observations in this study, Alam & Ray-Bennett (2021) found that socio-economic vulnerabilities, particularly among informal hill settlers, often lead to delayed or reluctant evacuation decisions. Furthermore, Sultana (2020) identified communication gaps and limited access to inclusive dissemination channels as major barriers in Bangladesh's disaster early warning systems. The issue of institutional fragmentation observed in this study also aligns with global findings that a lack of coordination among agencies leads to inconsistent messaging and reduces public trust. Therefore, the results reinforce the broader understanding that early warning systems must function as integrated socio-technical systems rather than purely technological solutions. The study has several important implications for policy, practice, and future system design. First, there is a need to strengthen last-mile communication mechanisms, ensuring that warnings are disseminated rapidly and in locally understandable formats using multiple channels such as community volunteers, mosques, and localized alert systems. Second, enhancing community awareness and trust through regular drills, awareness campaigns, and participatory approaches is essential to improve response behavior. Third, the findings highlight the importance of institutional coordination, suggesting that agencies such as meteorological departments, local government bodies, and community organizations must operate within a unified framework to deliver consistent and actionable messages. Fourth, the study underscores the necessity of inclusive early warning systems, particularly tailored for vulnerable groups such as women, elderly individuals, and persons with disabilities. Finally, integrating socio-economic considerations, such as safe shelter availability and livelihood protection, into warning systems can significantly improve evacuation compliance and overall resilience.

Limitations of the Study

Despite its contributions, this study has several limitations. First, the research is geographically focused on selected hill-covered communities in Chattogram, which may limit the generalizability of findings to other regions with different socio-economic and environmental contexts. Second, the study relies partly on qualitative perceptions and self-reported responses, which may introduce bias or variability in interpretation. Third, the analysis primarily examines rainfall-triggered warning systems and does not fully incorporate other contributing factors such as soil characteristics, land-use changes, or real-time geotechnical monitoring. Additionally, the limited availability of long-term empirical data on warning effectiveness and response outcomes constrained the ability to conduct a more quantitative evaluation. Future research could address these limitations by incorporating larger datasets, comparative regional studies, and mixed-method approaches to provide a more comprehensive assessment of LEWS effectiveness.

Conclusions

This study demonstrates that the effectiveness of Rainfall-Triggered Landslide Early Warning Systems (LEWS) in Chattogram is not determined solely by technical accuracy, but by the ability to translate warnings into timely, inclusive, and coordinated community action. **T**he findings reveal a persistent gap between warning dissemination and community response. Although rainfall-based thresholds and monitoring systems can reliably detect landslide risks, delays in communication, weak institutional coordination, limited community awareness, and socio-economic constraints significantly reduce the effectiveness of early warnings. Vulnerable populations, particularly hill-dwelling and low-income communities, often face additional barriers such as livelihood insecurity and limited access to safe evacuation options. **T**he study highlights that LEWS must function as an integrated socio-technical system rather than a purely technological solution. Strengthening last-mile communication, enhancing trust in warnings, and ensuring inclusive outreach are essential for reducing landslide risk in rapidly urbanizing hill areas like Chattogram. The findings are also relevant for other climate-vulnerable cities facing similar challenges of informal settlements and disaster exposure. **T**his research contributes to disaster risk reduction literature by shifting the focus from “warning generation” to “warning effectiveness,” emphasizing the critical transition from warning to action. It provides empirical insights into socio-technical barriers that limit LEWS performance in a real-world, high-risk urban context. **F**uture research should incorporate real-time monitoring data, expand geographic coverage, and apply mixed method approaches to better quantify behavioral responses to warnings. There is also a need to explore digital, community-led, and AI-supported communication systems for improving last-mile dissemination and response efficiency. **S**trengthening landslide resilience in Chattogram requires urgent investment in integrated early warning systems, improved inter-agency coordination, and community-centered preparedness programs. Policymakers, practitioners, and local institutions must prioritize inclusive, actionable, and trusted warning mechanisms to ensure that scientific forecasts effectively translate into life-saving actions.

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Assessing spatiotemporal pattern of Temperature and Rainfall and Its Implications for Flash Flood Risks in Northeastern Bangladesh

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Abstract

The northeastern region is one of the most flash flood-prone areas in Bangladesh, where regular flash floods have tremendous impact on the lives, property and livelihoods of the people living in the region. Long-term rainfall trends were analyzed using linear regression and the Student's *t* test to assess statistical significance over a 71-years period (1948-2019) based on data obtained from the Bangladesh Meteorological Department. This study also examined monthly temperature and rainfall pattern in during the pre-monsoon and monsoon seasons over the last decade (2014-2025) using satellite-derived Land Surface Temperature (LST) dataset from MODIS, and the CHIRPS daily rainfall dataset. The findings indicate a gradual increase in rainfall across the northeastern region, particularly in Sylhet due to strong orographic influence. Although most rainfall trends were not statistically significant, pre-monsoon rainfall in Sylhet showed a significant increasing trend at a rate of approximately 6 mm per year. This trend is alarming because intense pre-monsoon rainfall during April and May contribute to earlier and more frequent flash flood in *Haor* (wetland) region (located Northeastern Bangladesh), threatening farmers during the *Boro* rice harvesting season. The *Haor* region contributes nearly one-fifth of the national rice production, making it highly vulnerable to climate-induced flooding. At the same time, most station in the region showed declining post-monsoon rainfall trends, which may assist faster recession of floodwaters and facilitates for land preparation and seedbed establishment during November. Future climate projections by IPCC suggest increasing monsoon rainfall and greater climate variability in South Asia, which may further intensify flood risk in the future. Since the *Haor* region is one of the major producer of *Boro* rice in Bangladesh, increasing floods and heavy pre-monsoon rainfall pose significant threats to agricultural production, rural livelihoods, and regional food security.

Keywords: Pre-monsoon, Flash flood, Northeast region, and Rainfall trend.

1. INTRODUCTION

Bangladesh, a relatively small country with an area of 145,452 km², extends from 20°45′N to 26°40′N latitude and from 88°05′E to 92°40′E longitude (Ahmed and Kim, 2003; Salahuddin *et al.*, 2006; Sarker, 2021). Located in South Asia, Bangladesh lies between the Himalayas to the north and the Bay of Bengal to the south (Messerli and Ives, 1984).The country is predominantly composed of flat alluvial plains, except for the hilly regions in the southeast (Brammer, 2000) , and the majority of the country lies at elevations below 10 m above mean sea level (Sarker and Bigg, 2010; Sarker, Bigg and Zimmerer, 2010; Sarker, 2015, 2021, 2022). One of the major impacts of climate change and variability in Bangladesh is the effect on water resources. The Ganges–Brahmaputra–Meghna River System (GBM) has a discharge greater than all river systems globally except the Amazon and Congo (Rasheed, 2008). Heavy rainfall and flooding in northern Bangladesh often occur during the break monsoon period, when the monsoon trough shifts toward the foothills of the Himalayas (Ahmed and Kim, 2003). Monsoon rainfall affect hydrological processes, leading to drying trends in the northwest due to declining rainfall (Sarker, 2005, 2009, 2021), as well as increased flooding in central regions and flash floods in the northeast due to topography and orographic rainfall (Ahmed and Kim, 2003; Quadir *et al.*, 2003; Sarker, 2005, 2021). Bangladesh experiences flooding almost every year. Most floods are regular seasonal inundations that submerge land without causing significant damage to crops or property and are commonly referred to as "normal floods (Brammer, 1997). In contrast, "disastrous floods" cause extensive damage to crops, infrastructure, and property (Brammer, 1997). Among these hazards, flash floods are one of the most destructive and rapidly occurring natural disasters in northeastern Bangladesh, particularly in Sylhet Division (Hossain and Haq, 2026). Although flash floods occur in several regions of Bangladesh, they are especially frequent in the northeastern region, including

Sylhet Division (Haque, 2026). For example, in 2024, a severe flash flood affected Feni and Noakhali districts, impacting approximately seven million people. But *Haor* region it is common, the *Haor* wetlands of northeastern Bangladesh remain inundated for four to seven months (June-Nov) each year (Hossain *et al.*, 2023; Bokhtiar *et al.*, 2024; Haque, 2026), increasing the vulnerability of local communities. Despite the significance of the Sylhet region, relatively few studies have focused on this area. Bhuiyan and Paul (2024), investigated the 2022 flash flood in the *Haor* region, particularly in Sunamganj, using a descriptive qualitative approach. The study identified major causes of the flood and highlighted its impacts, including loss of life and property, infrastructure damage, and disruptions to education and social life (Bhuiyan and Paul, 2024). More recently, Khan and Islam, (2025) generated flood extent maps for Sylhet Division using Sentinel-1 SAR imagery from 25 May, 5 June, and 19 June 2024, capturing both major flood waves. However, the present study extends beyond flood mapping by incorporating rainfall and temperature analysis using meteorological datasets.

The study focuses on the pre-monsoon, monsoon and post monsoon seasons. In Bangladesh, the pre-monsoon hot season from March to May, followed by the summer monsoon from June through September and a short and mild autumn (Post-monsoon) season from October to November (Asian Development Bank, 1994; Ahmed, 2003, 2004; Rasheed, 2008; as noted by Sarker, 2009). The analysis encompasses the broader northeastern region of Bangladesh, covering the *Haor* basin, which is larger than administrative boundary of Sylhet Division. In addition, this research investigates seasonal rainfall trends and temperature dynamics to understand the meteorological impact on the region and to assess whether the climate of northeastern Bangladesh is changing over time.

2. EXPERIMENTAL SET-UP & METHODOLOGY

2.1 STUDY AREA: **NORTHEASTERN REGION OF BANGLADESH**

The northeastern region of Bangladesh was selected as the study area because of its unique hydrological, geological and topographical characteristics, which contribute to its environmental and socio-economic importance. It shares border with Indian states of Meghalaya to the north, Assam to the east and Tripura to the south. The region is situated at the foothills of the Meghalaya Plateau in northeastern India (Khan and Islam, 2025). The upstream catchments are relatively steep, and intense rainfall over the Meghalaya, Barak, and Tripura basins rapidly drains downstream, frequently triggering flash floods in the low-lying Sylhet region (Khan and Islam, 2025). The region contains extensive permanent water bodies and wetlands, locally known as *Haor*, which occupy the central basins (Brammer, 1997). The Sylhet Basin is a vast depressed area, much of which remains inundated even during the dry season (Brammer, 1997; Rasheed, 2008). The lowest parts of the basin lie below five meters above sea level (Rasheed, 2008). See figure 1 for the study area and figure 2(a) for river network 2(b) elevation map of study area. Three meteorological stations—Sylhet, Sreemangal, and Mymensingh—were selected to examine climatic variability, particularly pre monsoon and monsoon rainfall patterns, across the region.

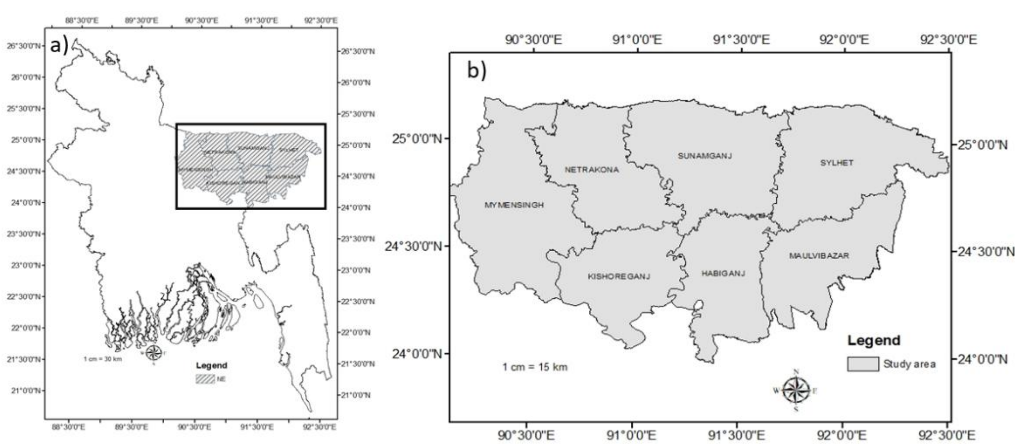

Figure 1: Study area a) Bangladesh b) Northeast region.

2.2 DATA AND METHOD

Monthly rainfall data were obtained from the meteorological stations from Bangladesh Meteorological Department (BMD). A continuous time series of 71 years (1948–2019) was used for analysis. The selected stations include Sylhet, Mymensingh, and Srimangal. Linear regression analysis was employed to trend analysis using the following formula, y=max+c, Here, x represent time (year) as the independent variable and y represent the dependent variable (temperature, rainfall), slope of the regression line (m), denote magnitude of the trend (see also (Sarker, 2021). To determine whether the observed trends were statistically significant, the Student's *t*-test was applied using the null hypothesis (H_0: $m = 0$), indicating no trend, and the alternative hypothesis (H_1: $m \neq 0$), indicating a significant trend. This methodology has been described in detail by (Sarker, 2021).

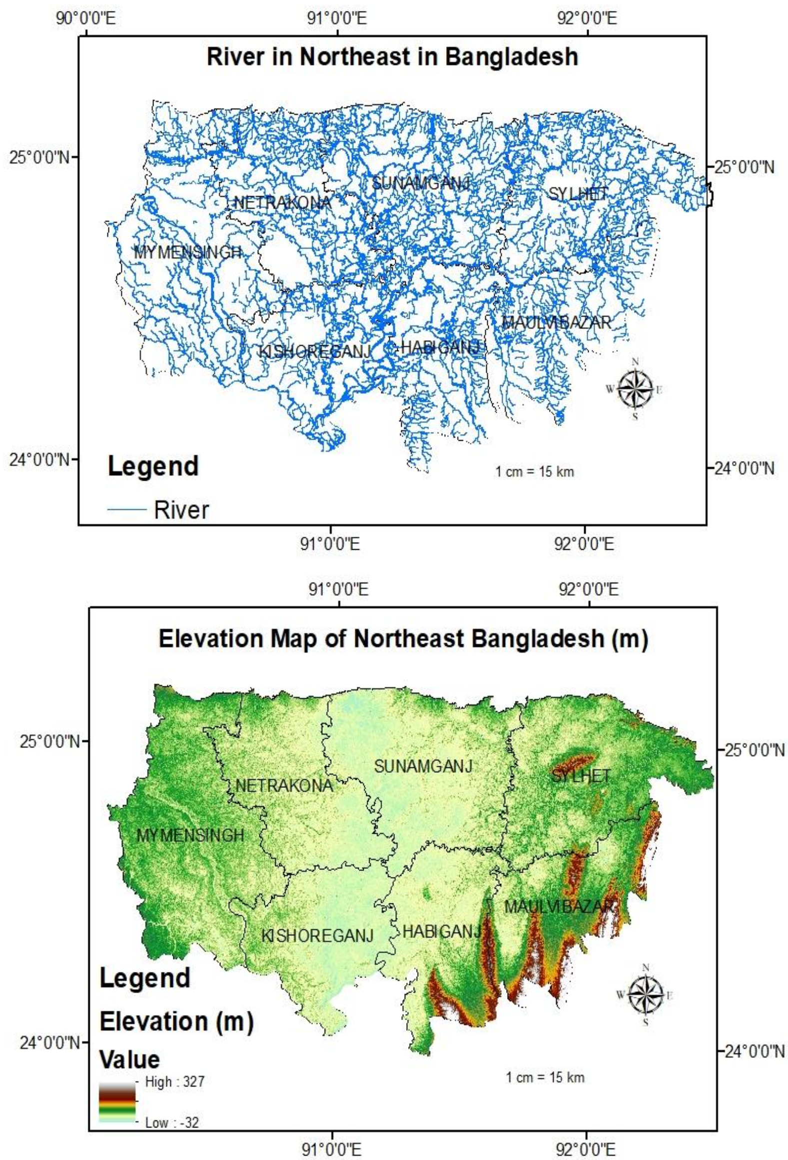

Figure 2 (a): River network b) Elevation map of Northeast region.

As the study area is larger than the Sylhet division and includes additional districts such as Mymensingh, the Northeast region of Bangladesh was selected for this study, and a new Shapefile for the region was created using ARC GIS software. For satellite-based temperature analysis, data were obtained from the MODIS Land Surface Temperature and Emissivity Daily Global 1 km product (MOD11A1 Version 6.1) [ee.ImageCollection("MODIS/061/MOD11A1")]. The MOD11A1 V6.1 product provides daily land surface temperature (LST) and emissivity measurements derived from the MOD11_L2 swath product and gridded into a 1200 × 1200 km tile system. The dataset offers consistent observations suitable for long-term temperature monitoring and spatial analysis. For satellite-based analysis of average temperature, MODIS data were collected from the MOD11A1 V6.1 dataset [ee.ImageCollection ("MODIS/061/MOD11A1")]. The MOD11A1 V6.1 product provides daily land surface temperature (LST) and emissivity data derived from the MOD11_L2 swath product within a 1200 × 1200 km grid. Rainfall analysis was conducted using the Climate Hazards Group InfraRed Precipitation with Station Data (CHIRPS) Daily dataset. This dataset has an approximate spatial resolution of 5 km, with precipitation values expressed in millimeters (mm). Daily rainfall data from 2014 to 2025 were analyzed to assess recent rainfall variability across the study area. Daily mean rainfall maps for April, May, and June were generated for the study period, with particular emphasis on the years 2020, 2022, and 2024. Special attention was given to the April–June periods of 2022 and 2024 because severe flood events occurred in the Northeast region during these years. Similarly, temperature data for the period 2014–2025 were analyzed, with a particular focus on 2024. This emphasis was justified by the findings of the World Meteorological Organization, which reported that 2024 was the warmest year on record globally. Monthly mean rainfall and average temperature values were calculated for each month, while seasonal mean values were generated for the monsoon period (June–September). All spatial analyses and map visualizations were produced using Google Earth Engine (GEE) code.

3. RESULT AND DISCUSSION

3.1. TEMPERATURE PATTERNS

Figures 3 and 4(a-c) clearly show that temperatures during April and May were higher than in June, while rainfall gradually increased from April to June. From the beginning of June 2024, rainfall gradually increased across the northeastern region, particularly in Sylhet. The findings suggest that prolonged heavy rainfall and flash flooding contributed to lower-than-expected temperatures across northeastern Bangladesh. Consequently, temperatures during June were lower than those recorded in April and May. On 8 June 2024, Sylhet recorded 257 mm of rainfall according to BMD observations (Figure 5b). Similar date temperature fall. Correspondingly, satellite-derived LST maps for the same period showed a noticeable decline in surface temperature. BMD data further indicated that the mean maximum temperature was approximately 32°C in Sylhet and 31.04°C in Sreemangal, whereas Ishwardi in the northwestern region recorded a substantially higher maximum temperature of 37.5°C. This is because the atmospheric moisture content and cloud cover absorb the outgoing long wave radiation very efficiently, and thereby they trap the heat decrease the temperature is slightly lower than expected (Ahmed, 2005; Sarker, 2005, 2021). As Temperature continue to rise in this reason (Sarker, 2005, 2009, 2015, 2021), the intensity and frequency of tornado are projected to increase (Bokhtiar *et al.*, 2024). An analysis of daily rainfall distribution (mm) and temperature patterns during in the northeastern region of Bangladesh, using data from satellite-derived rainfall and land surface temperature (LST) datasets, indicates a strong inverse relationship between rainfall intensity and temperature variation in this region.

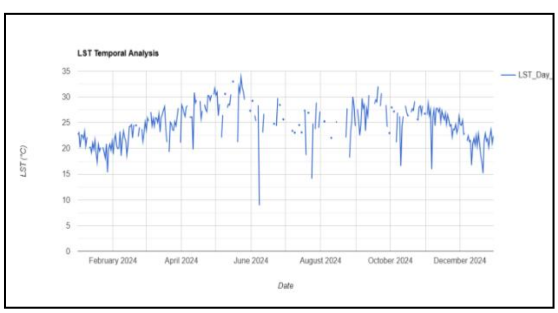

Figure 3. Daily mean temperature for the year 2024.

Figures 4(a-c) clearly show that temperatures during April and May were higher than in June, while rainfall gradually increased from April to June and temperature decreased. Figure 4(d) shows the mean monsoon land surface temperature (LST) during 2014-2025, repressing spatial temperature behavior across the study area during the summer monsoon season.

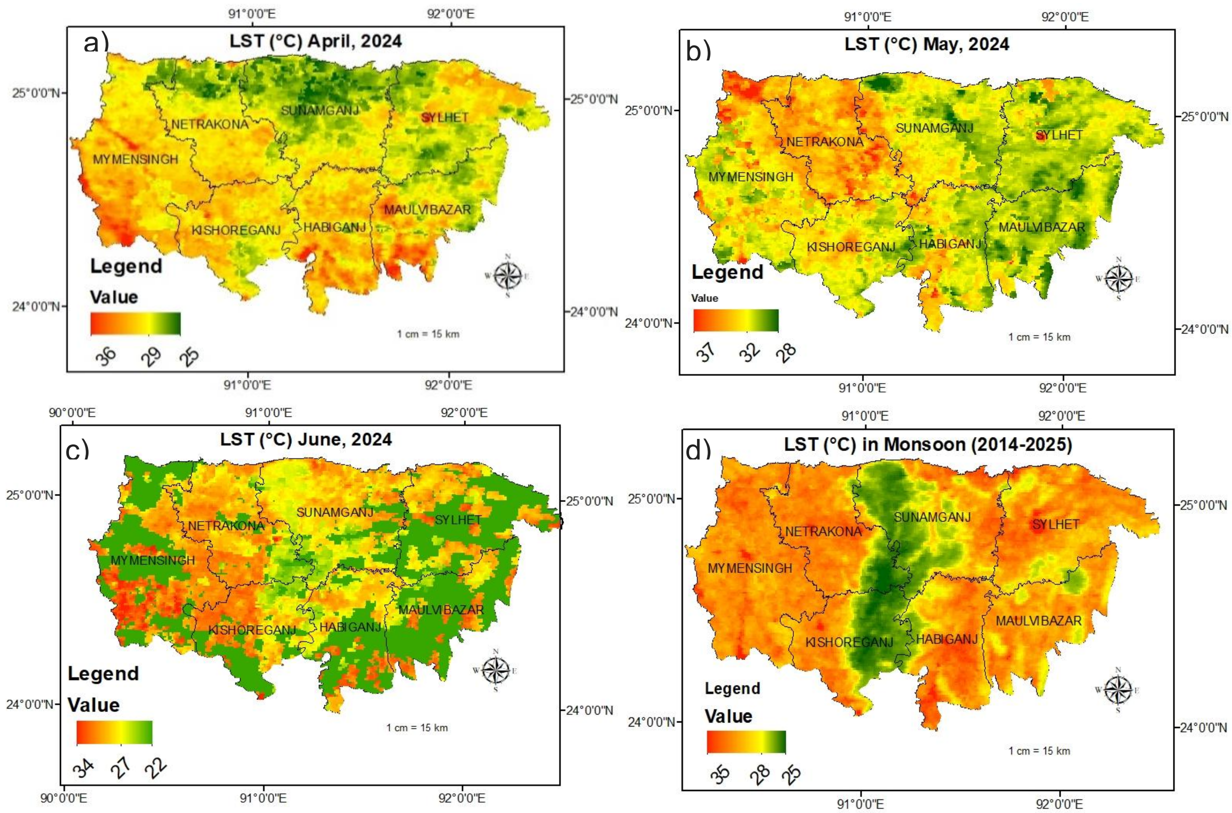

Figure 4: Mean land surface temperature for a) April, b) May, c) June, 2024 and d) Monsoon (2014-2025).

3.2 SEASONAL RAINFALL TREND

Linear regression and the Student's *t*-test were employed to explore the long-term rainfall dataset. The analysis found that most of the stations rainfall is increasing but statistically non-significant, except for the pre-monsoon rainfall increasing in Sylhet with increasing at the rate at a rate of approximately 6 mm per year (Table 1 and Figure 5(a) , which may lead to earlier flash floods in the region and adversely affect *Boro* farmers and agricultural production. Nevertheless, most stations in the northeast region showed increasing rainfall trends, except during the post-monsoon season. Sylhet demonstrated strong average rainfall in all seasons and annually due to the orographic effect, and the rate of increase was also comparatively higher, with an annual increase of about 9 mm per year. Similarly, rainfall in Sreemangal also showed an increasing trend, particularly for annual rainfall. However, none of these trends were statistically significant enough to conclusively confirm that rainfall is increasing. Overall, the comparative analysis suggests that rainfall in the northeast region of Bangladesh is gradually increasing 4.9 mm per year (but not significant), with the highest rate of increase observed in Sylhet due to its strong orographic influence (see section 3.4).

3.3 SATELLITE-BASED ANALYSIS OF RAINFALL (2014-2025)

Figure 5(b) illustrates the comparison of mean monthly rainfall among the three selected stations during June, indicating that Sylhet consistently recorded higher rainfall than the other stations. Figure 6, derived from the CHIRPS Daily rainfall dataset, further demonstrate that rainfall during June was substantially higher than in April or May during the major flood years of 2022 and 2024.

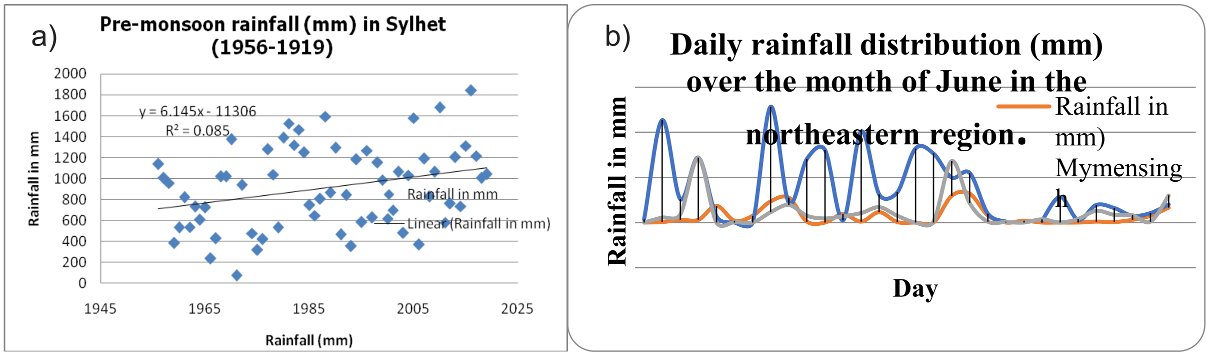

Figure 5: a) Pre-monsoon rainfall trend in Sylhet (left), b) Daily rainfall distribution at three stations in June 2024 (right)

Consequently, the flash floods of 2022 and 2024 occurred during the early monsoon period and caused widespread destruction across the region. In contrast, an unusually early rainfall event for April 2026 severely affected for farmers and regional food security, as a significant portion of the country's rice production originates from the *Haor* region. Regarding the 2022 flood event, Atiqul Haque stated that "the flooding is the worst in 122 years in the Sylhet region" (as noted by Gupta and Mogul, 2022). The data further indicate that in years such as 2014, 2016, and 2018, the region experienced relatively early and intense rainfall during May, which negatively affected agricultural activities in the following production cycle. Many farmers suffered economic losses because they were unable to harvest their *boro* rice fields before flooding occurred. Although July and August are generally considered the peak flood months in Bangladesh, the timing of monsoon onset is particularly critical in the Sylhet division. Early or delayed monsoon rainfall strongly influences agricultural activities, especially the harvesting period of *boro* rice, which usually occurs between April and early May. Most farmers begin harvesting in mid-April to minimize the risk of damage from pre-monsoon flash floods. If heavy rainfall begins during April or May, standing *boro* crops can be severely damaged, as observed in several recent years. In contrast, when the monsoon begins in June, farmers generally have more time to complete harvesting; however, extreme flooding events can still result in substantial losses of life, property, agriculture, and livelihoods. For example, the major flash floods of 2022 and 2024 occurred in mid-June and caused extensive damage throughout the region.

Table 1: Mean rainfall variation and slope from the linear regression analysis of rainfall measured seasonally, annually over the period of 1948-2019.

Northeast region	**Seasonal rainfall (mm) pattern**									
Stations	Winter (Dec-Feb)		Pre-monsoon Mar-May		Monsoon June-Sept		Post-monsoon Oct-Nov		Annual Jan-Dec	
	Slope	Mean	Slope	Mean	Slope	Mean	Slope	Mean	Slope	Mean
Mymensing	-0.04	32	+2.5	439	+0.3	1434	-0.4	196	2.4	2284
Sylhet	+0.15	51	+6.2*	910	+3.3	2034	-0.18	244	9	3238
Srimongal	+0.14	52	+3.5	692	+3	1339	-0.5	200	7.07	2100
Northeast (study area)	-0.18	68	+4.2	680	+1.02	1600	-0.16	215	+4.9	2550

*Refer to statistically significant at 95% confidence level; **Refer to statistically significant at 95% confidence level

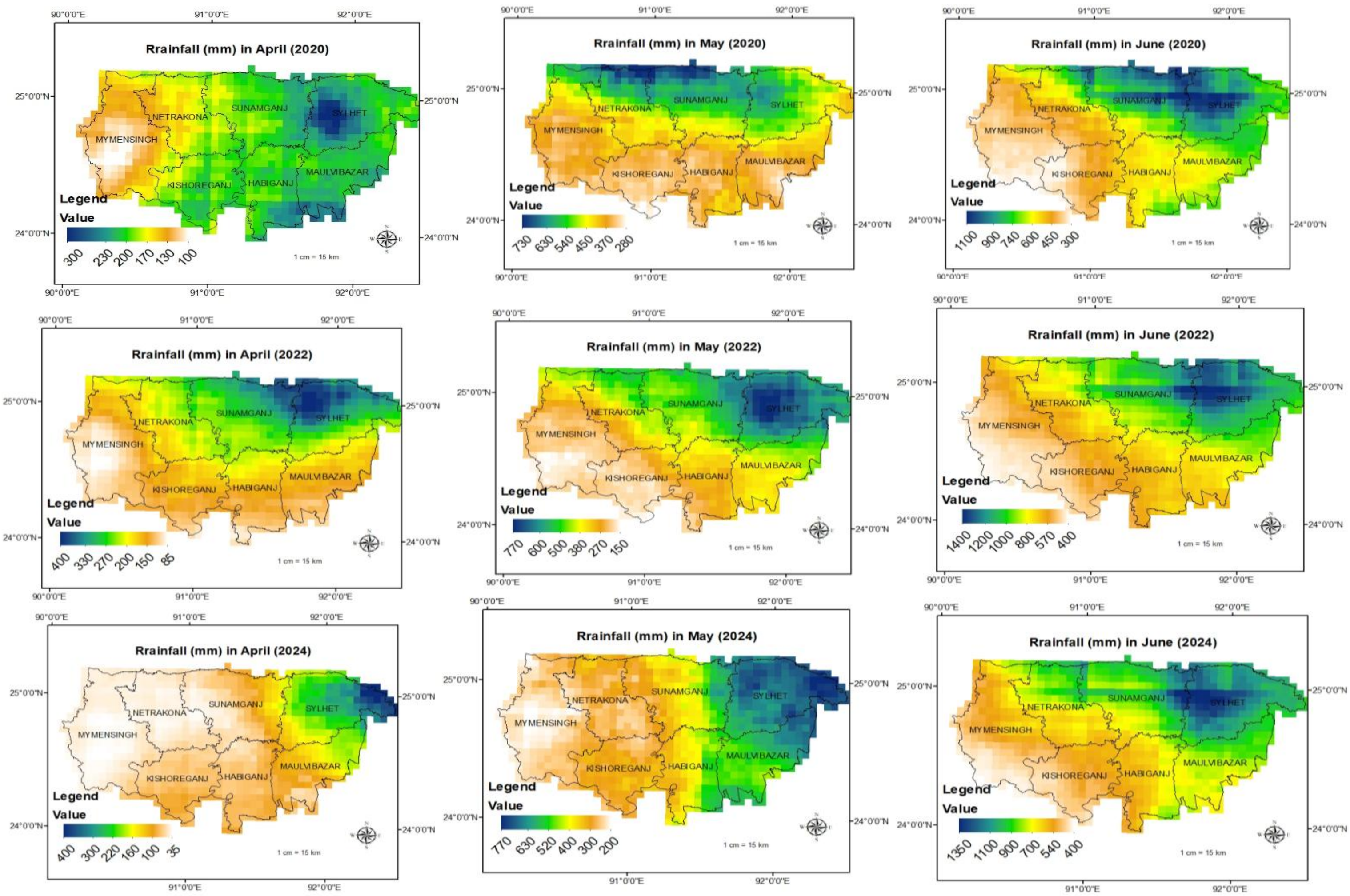

Figure 6. Rainfall during April, May, and June in different years (2020, 2022, and 2024).

3.4 LOCATION-SPECIFIC HYDRO-METEOROLOGICAL CHARACTERISTICS AND FLASH FLOODS

The northeastern region of Bangladesh lies at the foothills of the Meghalaya Plateau, and Sylhet is located very close to Indian state of Meghalaya (Ahmed & Kim,2003; Ahmed,2004; Sarker,2005,2009,2021). Notably, Cherrapunji, situated in the mountainous region adjacent to northeastern Bangladesh, receives some of the highest annual rainfall in the world, averaging around 11,000 mm due to strong orographic precipitation (Quadir *et al.*, 2003). Owing to its unique topographic and climatic conditions, the northeastern region of Bangladesh, particularly Sylhet, receives the highest annual rainfall in the country, averaging approximately 4,200 mm (Sarker, 2005, 2009, 2021). Several previous studies have also reported exceptionally high rainfall in the northeastern region of Bangladesh (Ahmed and Kim, 2003; Ahmed, 2004; Sarker, 2005, 2009, 2021; Sarker and Bigg, 2010; Sarker, Bigg and Zimmerer, 2010). Consequently, the region is highly vulnerable to flash floods (Islam, 2024). The present study also demonstrates that monsoon rainfall is considerably higher in Sylhet compared to other stations in the northeastern region as well as the rest of Bangladesh (Table 1; Figure 7 a-c). Although monsoon rainfall is generally associated with widespread flooding in Bangladesh, heavy pre-monsoon rainfall has a particularly strong relationship with flash flood occurrence in the northeastern region. Short-duration intense rainfall events, combined with rapid runoff from the surrounding hilly catchments, frequently trigger flash floods in the region. Analysis of rainfall data from 1995–2022 indicates that extreme rainfall events in Meghalaya and Sylhet are closely associated with severe flash floods, which are increasingly linked to climate change (Islam, 2024). Moisture influx from the Bay of Bengal is a major driver of rainfall variability in Bangladesh, particularly in the Northeast region. Sarker (2021) reported that pre-monsoon sea surface temperature (SST) in the northern Bay of Bengal has been increasing at a rate of approximately 0.6°C per year, with a 99% confidence level. Rising SSTs can enhance evaporation and atmospheric moisture content, thereby increasing the moisture supply available for precipitation over the Northeast region. This warming trend may enhance moisture availability and atmospheric water vapor transport toward the Northeast region, potentially leading to increased rainfall. Consequently, the frequency and intensity of flash flood events may increase in the future. In recent years, the Northeast region has already experienced several severe flash floods, highlighting its growing vulnerability to climate-induced hydro meteorological hazards. For instance, during the pre-monsoon of 2017, intense rainfall triggered an early flood in the northeast region, causing extensive damage to boro rice. According the government of Bangladesh 8000000 MT of Boro rice damaged (Goverment of Bangladesh, 2017). Analysis of satellite-derived rainfall data indicates that pre-monsoon rainfall exceeded 2,200 mm in parts of the region, highlighting the exceptional magnitude of the event. The northeastern region experienced another severe flooding in June 2024. This intense rainfall, combined with runoff from upstream catchments, triggered widespread flash flooding across the region. On 18 June 2024, the Surma River was flowing 131 cm above the danger level (IFRC, 2024). According to the Bangladesh Water Development Board (BWDB), rainfall recorded during the previous 24 hours (18 June 2024) included 333 mm in Lalakhal, Sylhet; 327 mm in Jaflong; 191 mm in Kanaighat and Zakiganj; 159 mm in Laurer Garh, Sunamganj; and 95 mm in Sunamganj city and Chhatak upazila (IFRC, 2024). The northeastern region experiences two major types of flooding: flash floods and regular seasonal floods. In most parts of Bangladesh, major flooding generally occurs during July and August. In contrast, flash floods in the northeastern region usually occur during the pre-monsoon and early monsoon seasons, particularly between April and June, due to intense short-term rainfall. Unlike normal river floods, flash floods occur suddenly with little or no warning (Montz and Gruntfest, 2002) and often cause severe damage to human lives, property, agriculture, and the environment (Hossain and Haq, 2026).

3.5 RECENT IMPACTS OF FLASH FLOODS (2022–2026)

The 2022 flash floods inundated approximately 94% of Sunamganj District and more than 84% of Sylhet District, causing extensive damage to agricultural land and severely affecting housing infrastructure, particularly in Comanyjanj *upazila* where homes were destroyed beyond repair (Haque, 2026). As a coping strategy, a large number of affected residents temporarily migrated to city in search of wage labor opportunities (Haque, 2026; Jabin and Atiqul Haq, 2026). Since the flooding occurred during the early monsoon season rather than the pre-monsoon period, crop damage was comparatively lower (Khan and Islam, 2025). However, severe inundation affected major urban centers, including Sylhet and Sunamganj, resulting in substantial impacts on densely populated areas (Khan and Islam, 2025). In contrast, the early flash flood event of 2026 had a greater impact on *boro* rice cultivation because it occurred during the harvesting season. Northeast region experienced severe flooding in June 2024. Sylhet and Sunamganj districts were among the worst affected areas, where more than 3 million people experienced displacement and livelihood disruption due to severe flooding (United Nation, 2024). The excessive rainfall caused widespread inundation, significantly damaging agriculture, infrastructure, and local economic activities (United Nation, 2024).

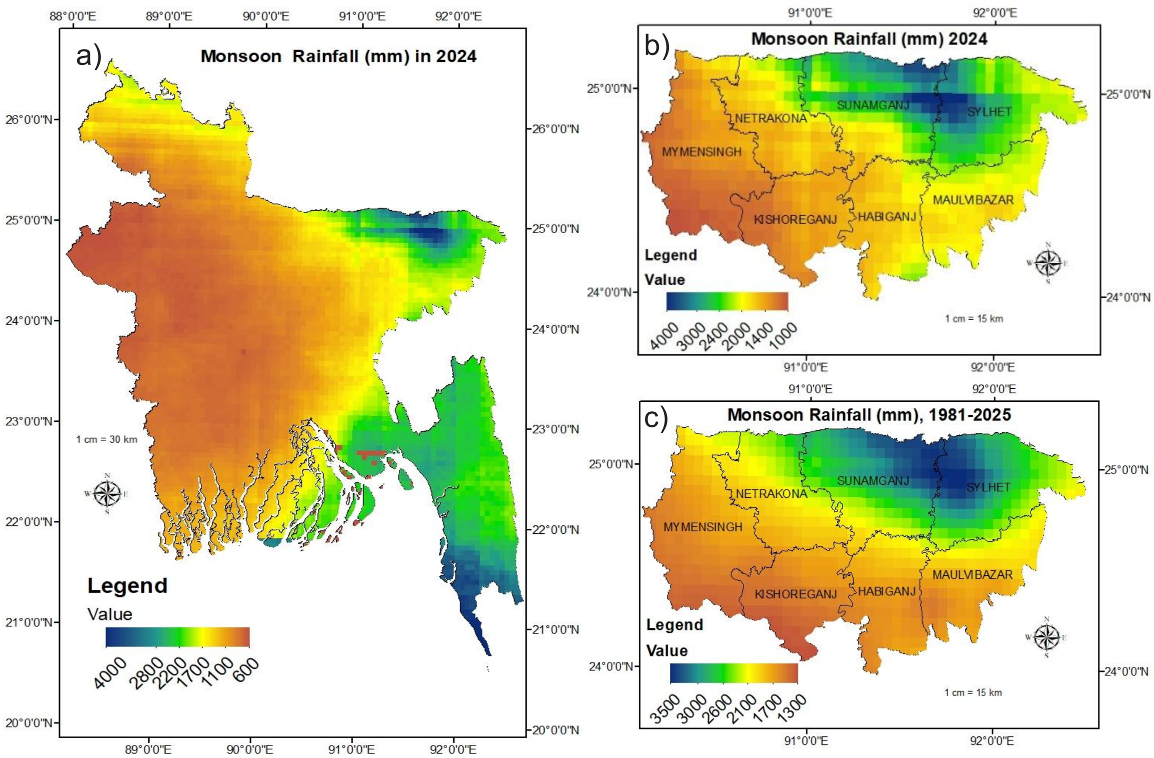

Figure 7: a)Total Monsoon Rainfall (mm) distribution in 2024 entire Bangladesh b) Northeast region c) Monsoon Rainfall over the period of 1981-2025.

4. CONCLUSION

The Northeastern *Haor* region of Bangladesh is highly vulnerable to flash floods, which frequently cause server damage to local communities, livelihoods and property. Historical analysis indicate that rainfall has generally increased across most seasons and meteorological stations in the region. In particular, both pre-monsoon and monsoon rainfall exhibit increasing trends over time, with rainfall in Sylhet remaining considerably higher than in other parts of the region. This trend is likely to intensify flash flood risks in northeastern Bangladesh. The situation is particularly alarming because the region is highly sensitives to early rainfall events during April and May, which coincide with the harvesting period of *Boro rice.* In recent year, such as 2026, excessive early rainfall and flash floods severely disrupted *Boro* paddy harvesting, resulting in substantial economic losses for farmers. *Boro* rice is the principal rice crop in Bangladesh, contributing approximately half of the country's total rice production (Shahrier and Hasan, 2025; Alim, 2026). The seven *Haor* districts alone account for nearly 18–20% of national *boro* rice production; however, these areas are increasingly vulnerable to climate-induced hazards, particularly heavy pre-monsoon rainfall and flash floods (Alim, 2026). At the same time, most stations in the region showed declining post-monsoon rainfall trends, which may facilitate faster recession of floodwaters and create more favorable conditions for land preparation and seedbed establishment during November. According to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (2022), both annual and summer monsoon precipitation in South Asia are projected to increase throughout the 21st century, accompanied by greater inter-annual variability. This suggests that flash flood frequency and intensity may further increase in the future. Moreover, the *Haor* Basin is a tectonic depression formed by the collision between the Indian and Eurasian plates, resulting in continuous subsidence at a rate of approximately 2–4 mm per year (Kamruzzaman and Shaw, 2018). This ongoing subsidence is expected to increase both the extent and frequency of annual flooding in the region (Kamruzzaman and Shaw, 2018). Since the *Haor* region is one of the major producers of *boro* rice in Bangladesh, increasing flash floods and heavy pre-monsoon rainfall pose significant threats to agricultural production, rural livelihoods, and regional food security.

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We declare that this manuscript represents our original research and writing. AI tools were used exclusively for proofreading and language enhancement, including corrections to grammar and spelling and did not contribute to the study’s content or findings.

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Trend, Variability, Change-Point Analysis and SARIMA-Based Forecasting of Rainfall and Temperature in Northeastern Bangladesh

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ABSTRACT

This study investigates the long-term variability, trend, and change-point characteristics of rainfall and temperature in the Sylhet and Sreemangal regions of northeastern Bangladesh using observed data from 1990 to 2024. The analysis incorporates descriptive statistics, the Pettitt test for change-point detection, autocorrelation analysis, and the Mann–Kendall (MK) and Modified Mann–Kendall (MMK) tests for trend assessment, along with Sen's slope estimator to quantify trend magnitude. Results show strong seasonal variability, with peak rainfall occurring during the monsoon season, while temperature exhibits a clear annual cycle with relatively stable variability. Pettitt test results indicate multiple structural shifts in both rainfall and temperature, with more significant and consistent breakpoints in temperature around 2015–2016, suggesting the onset of a persistent warming phase. Autocorrelation analysis reveals weak and insignificant serial dependence in rainfall but strong positive autocorrelation in temperature, justifying the use of MMK for temperature trend detection. Trend analysis demonstrates that rainfall patterns are largely non-significant and irregular, whereas temperature shows statistically significant increasing trends across multiple months and seasons, indicating consistent warming in the region. Furthermore, SARIMA-based forecasting suggests the continuation of seasonal patterns in both rainfall and temperature for the period 2025–2034, with increasing uncertainty over time. Overall, the findings highlight an asymmetric climatic response characterized by stable rainfall but significant warming, which has important implications for water resources, agriculture, and climate adaptation strategies in northeastern Bangladesh.

Key Words: Rainfall variability; Temperature trends; Change-point detection; Pettitt & Mann–Kendall test; SARIMA forecasting.

1. INTRODUCTION

Bangladesh is recognized as one of the most climate-sensitive countries in the world due to its geographical location, monsoon-dominated climate, dense population, and dependence on climate-sensitive sectors such as agriculture and water resources **[1].** Variations in rainfall and temperature significantly influence the hydrological cycle, crop production, ecosystem stability, and socio-economic activities throughout the country. In recent decades, increasing climate variability and global warming have altered regional climatic characteristics, resulting in irregular rainfall distribution, rising temperatures, prolonged dry periods, and extreme weather events. These climatic changes are particularly important in northeastern Bangladesh, where both natural ecosystems and human livelihoods are highly dependent on seasonal rainfall and temperature patterns.

The Sylhet region, located in northeastern Bangladesh, possesses unique physiographic and climatic characteristics that distinguish it from other parts of the country. The region consists of numerous hills and hillocks locally known as tilas, extensive wetlands or haors, and high floodplains. Parts of the foothills of the Meghalaya Plateau extend into this region, contributing to its complex topography and high rainfall variability. Several important rivers, including the Surma and Kushiyara, flow through Sylhet after originating from the Barak River system in India. These rivers later merge with the Meghna River before draining into the Bay of Bengal. Due to its topographic setting and exposure to moisture-laden monsoon winds, Sylhet receives some of the highest annual rainfall totals in Bangladesh and frequently experiences flooding and waterlogging during the monsoon season. Sreemangal, another important area within the region, is well known for its tea gardens, forest ecosystems, and comparatively lower temperatures during winter. The climatic conditions of these areas strongly influence agriculture, fisheries, wetlands, biodiversity, and local livelihoods.

Bangladesh experiences four major meteorological seasons: pre-monsoon (March–May), monsoon (June–September), post-monsoon (October–November), and winter (December–February). The pre-monsoon season is characterized by high temperatures and convective rainfall, while the monsoon season contributes more than 70% of the country's annual rainfall. Post-monsoon acts as a transitional period between the wet monsoon and dry winter seasons. Winter is generally cool and dry, with very limited rainfall. Seasonal rainfall and temperature variability across Bangladesh are controlled by large-scale atmospheric circulation, monsoon dynamics, local topography, and land–atmosphere interactions (bmd met-report). However, recent climate studies indicate increasing irregularities in seasonal rainfall patterns and continuous warming trends across South Asia, including Bangladesh. Changes in rainfall intensity, shifting monsoon onset, and rising temperatures have become major concerns for climate researchers and policymakers **[2]**.

Rainfall and temperature are among the most important climatic variables used to assess climate variability and climate change. Previous studies reported that global warming has intensified the hydrological cycle, leading to fluctuations in rainfall frequency, intensity, and distribution. Increasing temperature trends have also been observed in many tropical and subtropical regions. In Bangladesh, several studies have identified increasing temperature trends and irregular rainfall variability, which directly affect agricultural productivity, water availability, flood occurrence, and ecosystem sustainability. Although national-scale climate assessments are common, regional analyses remain limited, particularly for northeastern Bangladesh, where topographic complexity and monsoon influences create localized climatic behavior. Therefore, understanding long-term climatic trends and variability in Sylhet and Sreemangal is essential for climate adaptation planning and sustainable resource management.

To investigate long-term climatic changes, several statistical and time-series techniques are commonly used in climatological research. The Pettitt test is a widely applied non-parametric method for detecting abrupt change points or structural breaks within a time series. It identifies the probable timing of sudden shifts in climatic variables without requiring normally distributed data, making it suitable for rainfall and temperature analysis. Autocorrelation analysis is another important approach used to examine the persistence and serial dependence of climatic observations over time. Detecting autocorrelation is necessary because serially correlated data may influence the reliability of statistical trend tests. Among trend detection techniques, the Mann–Kendall (MK) test is one of the most widely used non-parametric methods for identifying monotonic increasing or decreasing trends in hydro-climatic time series. However, climatic datasets often exhibit serial correlation, which can affect the significance of the MK test. To overcome this limitation, the Modified Mann–Kendall (MMK) test adjusts the original MK approach by accounting for autocorrelation effects, thereby providing more robust trend estimates. Sen's slope estimator is frequently used alongside MK and MMK tests to quantify the magnitude and direction of climatic trends. In addition to historical trend analysis, time-series forecasting models such as Seasonal Autoregressive Integrated Moving Average (SARIMA) are increasingly applied to predict future climatic behavior**[3],[4].** SARIMA models are particularly effective for climatic data because they can capture both temporal trends and seasonal variations simultaneously **[5–8].**

Many researchers used the SARIMA model for forecasting and predicting climatic parameters. Despite the growing number of climate-related studies in Bangladesh, comprehensive investigations combining trend analysis, change-point detection, autocorrelation assessment, and future forecasting for northeastern Bangladesh remain limited. Most previous studies focused either on rainfall or temperature individually, while integrated assessments covering both variables at regional scales are comparatively scarce. Furthermore, limited attention has been given to the detection of structural climatic shifts and future seasonal forecasting using advanced statistical approaches such as SARIMA. Therefore, this study aims to fill these research gaps by conducting a detailed analysis of long-term rainfall and temperature variability in Sylhet and Sreemangal using robust statistical and forecasting techniques. Therefore, the specific objectives of this study are:

1. To analyze the long-term trends and seasonal variability of rainfall and temperature in Sylhet and Sreemangal during the period 1990–2024 using the Mann–Kendall (MK), Modified Mann–Kendall (MMK), and Sen's slope methods.
2. To detect abrupt climatic shifts and serial dependence in rainfall and temperature data using the Pettitt change-point test and autocorrelation analysis.
3. To forecast future rainfall and temperature patterns for the period 2025–2034 using Seasonal Autoregressive Integrated Moving Average (SARIMA) models and evaluate their potential implications for climate adaptation in northeastern Bangladesh.

2. METHODOLOGY

2.1 Study Area

The study area is located in the northeastern part of Bangladesh, covering the Sylhet region and including the meteorological stations at Sylhet and Sreemangal. Geographically, the area extends approximately between 24°30′N to 25°15′N latitude and 91°30′E to 92°30′E longitude. Sylhet city is located at about 24.89°N latitude and 91.87°E longitude, while Sreemangal lies around 24.31°N latitude and 91.73°E longitude. Topographically, the region consists of low-lying floodplains interspersed with elevated hill ranges, with elevations ranging from about −21 m to 335 m above sea level. The southern and eastern parts, particularly around Sreemangal, are characterized by hilly terrain and tea garden landscapes, while the central and northern parts are dominated by alluvial plains. The region is strongly influenced by the nearby Meghalaya Plateau, which enhances orographic rainfall, making it one of the wettest regions in the country. This combination of geographic location, elevation variability, and monsoonal climate makes the area highly significant for rainfall and temperature trend analysis.

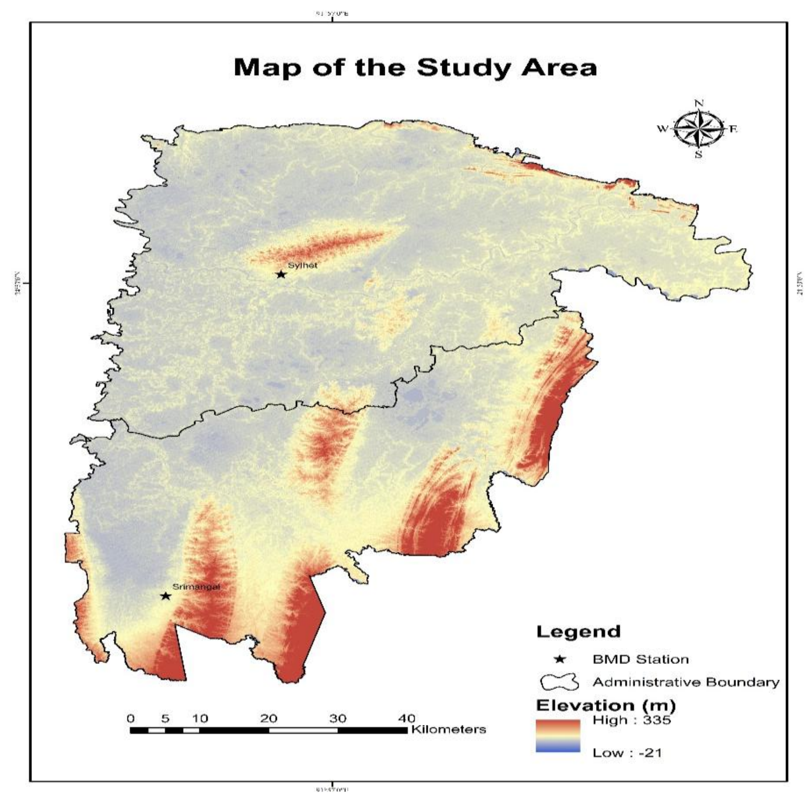

Fig. 1 Map of the study area

2.2 MK/MMK test

The MK test is a non-parametric statistical method commonly used to detect increasing or decreasing trends in climatic time-series data such as rainfall and temperature**[6].** Since the method does not require normally distributed data, it is widely applied in hydro-climatological studies. In this study, the MK test was used to analyze monthly, seasonal, and annual trends of rainfall and temperature. Before conducting the MK test, lag–1 autocorrelation was examined because serial correlation can affect the significance of trend results **[9].** Where significant autocorrelation was detected, the Trend-Free Pre-Whitening (TFPW) method proposed by Yue and Wang**[10]** was applied to reduce autocorrelation effects. The standardized test statistics (Z) was calculated to determine the significance of the detected trends:

$$Z=\begin{cases} \frac{S-1}{\sqrt{\mathrm{Var}(S)}}, & \text{if } S>0 \\ 0, & \text{if } S=0 \\ \frac{S+1}{\sqrt{\mathrm{Var}(S)}}, & \text{if } S<0 \end{cases} \tag{5}$$

The MMK test is an improved version of the MK test that accounts for autocorrelation in climatic time-series data, making trend results more reliable **[8]**. It was used in this study for rainfall and temperature trend analysis where serial dependence was detected in the dataset. In this study, both 5% and 10% significance levels were used to assess rainfall and temperature trends. A positive Z value represents an increasing trend, whereas a negative Z value indicates a decreasing trend over time. Similar methodologies have been widely adopted in climatological and hydrological studies for long-term trend analysis and climate variability assessment **[11]**.

2.3 Sen's slope

Sen's Slope estimator is a non-parametric method used to quantify the magnitude of monotonic trends in time-series data such as rainfall and temperature **[12].** It provides a robust estimate of the rate of change per unit time and is widely used alongside the MK/MMK test. In this study, the method was adopted based on the study established by Nadim et al**.[13].**

2.4 SARIMA Model

The Seasonal Autoregressive Integrated Moving Average (SARIMA) model was used in this study to forecast future rainfall and temperature patterns. This model is capable of capturing both seasonal and non-seasonal components of time-series data, making it suitable for climatic variables with strong seasonal fluctuations. The SARIMA approach was applied to generate projections for the period 2025–2034, providing an indication of possible future variability and long-term trends in rainfall and temperature in the study area.

3. RESULTS AND DISCUSSION

3.1 Climatology

The integrated analysis of rainfall and temperature patterns demonstrates in Sylhet and Sreemangal is illustrated in Fig. 2. Rainfall shows strong seasonal variation, with very low values during winter (DJF) and a rapid increase from March, indicating the onset of the pre-monsoon period. Peak rainfall occurs in June during the monsoon season, reaching about 850 mm in Sylhet and around 450 mm in Sreemangal. After June, rainfall gradually decreases and becomes minimal. Rainfall variability is highest during the monsoon months, especially in June when Sylhet records SD values of about 340 mm. CV values remain very high during winter and late autumn (often exceeding 150–200%), indicating irregular and unreliable rainfall, whereas during June–August CV falls below 40%, reflecting stable precipitation. Sylhet receives higher rainfall and shows greater variability than Sreemangal, suggesting stronger monsoonal influence and higher exposure to extreme rainfall and flood risk.

Mean temperature patterns also exhibit clear seasonal contrasts (Fig.1b, d, and f). Mean temperature is lowest in January and February (about 16–19°C) and increases steadily to reach maximum values of around 28–29°C during June to August (Fig. 1b). After the monsoon (JJAS), temperature gradually declines toward December. Sylhet remains slightly warmer than Sreemangal throughout most of the year. Mean temperature variability is highest during winter and early spring, with SD and CV values peaking in January (CV up to about 8% in Sylhet), indicating unstable atmospheric conditions. During the monsoon season, temperature variability decreases significantly, with CV values falling to around 1.5–2%, reflecting stable thermal conditions due to cloud cover and high humidity. Compared to rainfall, temperature remains relatively stable throughout the year.

The results indicate the seasonal rainfall and mean temperature distributions for Sylhet and Sreemangal (Fig. 3). The results show a strong dominance of the monsoon season, followed by clear contrasts among the other seasons. During the pre-monsoon period, Sylhet receives about 380 mm of rainfall, while Sreemangal records around 240 mm, indicating early moisture buildup before the onset of the main monsoon. The highest rainfall occurs in the monsoon season, with Sylhet recording approximately 680 mm and Sreemangal about 350 mm, confirming the strong influence of monsoonal circulation in the region. In the post-monsoon season, rainfall decreases sharply to around 90 mm in Sylhet and 75 mm in Sreemangal, reflecting the retreat of monsoon systems. Winter rainfall remains minimal in both areas, with values below 25 mm, indicating a pronounced dry season. Seasonal mean temperature variations show clear thermal contrasts among different seasons in both study areas. During the pre-monsoon season, the mean temperature reaches about 26°C in both Sylhet and Sreemangal, reflecting increasing solar radiation and surface heating. The highest temperatures are observed in the monsoon season, with values around 28–28.5°C, indicating warm and humid conditions associated with persistent cloud cover and high atmospheric moisture. In the post-monsoon period, temperature declines to about 23°C in Sylhet and 22°C in Sreemangal, marking the transition toward cooler conditions. The lowest temperatures occur in winter, with mean values of approximately 19.5°C in Sylhet and 18°C in Sreemangal.

The results indicate that Sylhet exhibits stronger monsoon intensity, higher rainfall totals, and greater variability, making it more vulnerable to hydrological hazards, while Sreemangal shows relatively moderate climatic conditions with lower extremes. In addition, monsoon months provide reliable rainfall and stable mean temperatures suitable for agriculture and water resource recharge, while high rainfall variability in Sylhet increases flood vulnerability, and high winter CV values indicate uncertainty in dry-season water availability. These results are reported with the previous study by **[14–16].** patterns highlight the strong control of monsoonal circulation and local geographic conditions on the climate of northeastern Bangladesh.

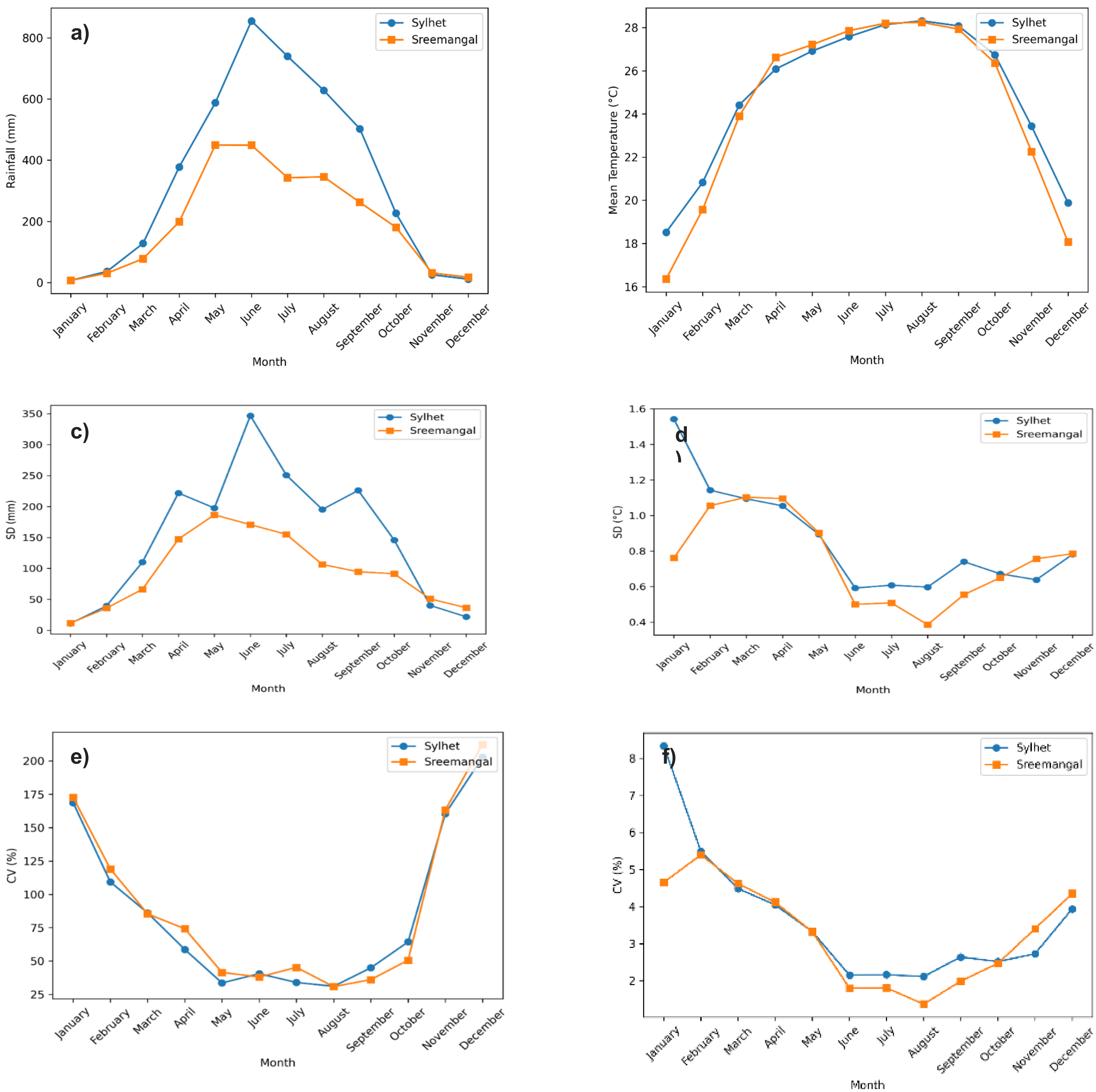

Fig. 2 Mean, SD (%), and CV of rainfall (a,c,e) and mean temperature (b,d,f) in Sylhet and Srimangal

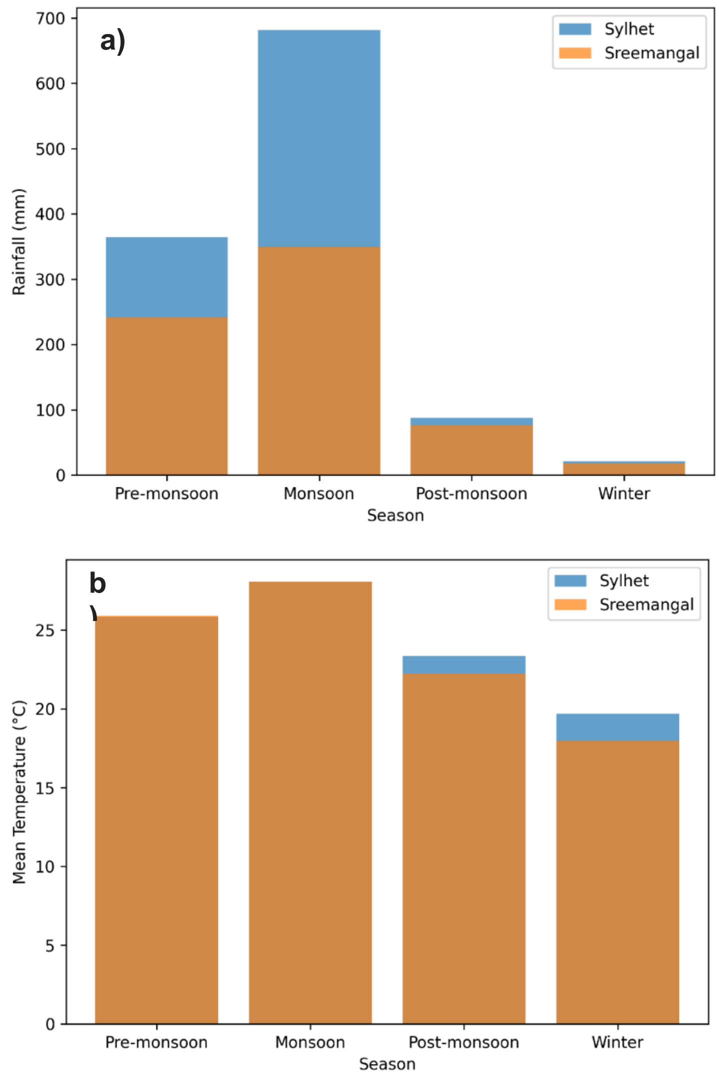

Fig. 3 Seasonal rainfall (a) and the mean temperature (b) plots in the study stations

3.2 Pettit test

Table 1 represents the results of the Pettitt test applied to monthly, seasonal, and annual rainfall and mean temperature series for Sylhet and Sreemangal to identify possible changes in long-term climatic patterns. The analysis reveals several structural shifts in both rainfall and mean temperature, particularly after the early 2000s, indicating increasing climate variability in northeastern Bangladesh. For rainfall, Sylhet shows noticeable breakpoints mainly after 2000. Significant shifts were detected in July (2017, $p = 0.002$) and September (2015, $p = 0.011$), suggesting major changes in peak monsoon rainfall behavior. At the seasonal scale, the most prominent change was observed during the monsoon season in 2020 ($p = 0.486$) and the pre-monsoon season in 2015 ($p = 1.443$), although these were not statistically significant at the 5% level. However, the annual rainfall series of Sylhet indicates a breakpoint in 2015 ($p = 0.486$), reflecting a recent transition toward more variable rainfall conditions. In Sreemangal, rainfall breakpoints were detected earlier, particularly in March (2004), June (2000), and July (1993), reflecting early monsoon instability. Although most rainfall breakpoints in Sreemangal were statistically insignificant, the monsoon season (2022) and annual rainfall (2000) suggest a shift toward altered precipitation regimes since the early 2000s. On the other hand, mean temperature records exhibit more statistically significant changes than rainfall, especially after 2010. In Sylhet, significant breakpoints were detected in July (2019, $p = 0.002$), September (2015, $p = 0.011$), October (2015, $p = 0.033$), pre-monsoon (2016, $p = 0.033$), monsoon (2015, $p = 0.001$), post-monsoon (2024, $p = 0.045$), and annual series (2015, $p = 0.004$). These results indicate a major shift in temperature patterns around 2015–2016, marking the beginning of a persistent warming phase. Similarly, Sreemangal also shows significant temperature breakpoints in July (2019, p = 0.002), September (2018, p = 0.010), pre-monsoon (2016, p = 0.033), monsoon (2015, p = 0.002), and post-monsoon (2024, p = 0.040). The consistency of these breakpoints across both stations suggests a region-wide climatic transition rather than localized variability. In annual scale, the mean temperature showed a statistically significant change point in 2015 (p = 0.004).

The analysis further confirms that the Pettitt test results demonstrate that temperature series exhibit greater and more statistically significant structural changes than rainfall. Most significant temperature breakpoints cluster around 2015–2016, which corresponds to the period of intensified warming observed in the anomaly analysis. This indicates that recent decades have experienced a fundamental change in regional thermal conditions. Rainfall series, although showing multiple breakpoints, display weaker statistical significance, suggesting that rainfall variability is more irregular and influenced by short-term climatic fluctuations rather than abrupt long-term shifts.

Table 1 Results of the Pettit test

Month / Season	Sylhet				Sreemangal			
	Rainfall		Mean temperature		Rainfall		Mean temperature	
	Breakpoint year	P-value	Breakpoint year	P-value	Breakpoint year	P-value	Breakpoint year	P-value
Jan	2001	0.2387	2024	0.301	2003	1.365	2024	0.527
Feb	1997	0.1676	2012	0.139	1997	0.341	2024	0.518
Mar	1999	0.3413	2014	0.059	2004	0.341	2014	1.246
Apr	1998	1.1057	2018	0.409	2021	0.601	2021	0.571
May	2005	0.6974	2013	0.601	1999	0.499	2013	0.311
Jun	2022	0.6011	2021	0.129	2000	0.632	2023	0.134
Jul	2017	0.6323	**2019**	**0.002**	1993	1.086	**2019**	**0.002**
Aug	2008	0.7312	2011	0.168	2007	0.421	2024	0.119
Sep	1994	0.8741	**2015**	**0.011**	2006	0.571	**2018**	**0.010**
Oct	2017	0.1191	**2015**	**0.033**	2016	1.046	2014	0.291
Nov	2008	1.4618	2024	0.180	1996	1.126	2013	0.714
Dec	2015	0.4722	2024	0.231	2015	0.556	2016	0.352
Pre-monsoon	2015	1.4426	**2016**	**0.033**	2000	0.397	**2016**	**0.033**
Monsoon	2020	0.4856	**2015**	**0.001**	2022	1.226	**2015**	**0.002**
Post-monsoon	2012	0.1287	**2024**	**0.045**	2016	1.027	**2024**	**0.040**
Winter	1997	0.2307	2006	0.239	2015	0.352	2006	0.238
Annual	2015	0.4856	**2015**	**0.004**	2000	0.541	2024	0.098

Bold color indicates 5% significance level

3.3 Autocorrelation test

The serial dependence (Table 2) analysis indicates that most rainfall series in Sylhet (particularly July, r = 0.124) and Sreemangal (particularly October, r = 0.003) exhibit weak and statistically insignificant autocorrelation, with correlation values ranging from −0.305 to 0.201. This suggests that rainfall variability is largely irregular and random in nature. Therefore, the independence assumption of the MK test is generally satisfied for rainfall data, allowing reliable application of the MK test for rainfall trend detection. In contrast, mean temperature series show relatively strong and significant positive autocorrelation, particularly in Sylhet during post-monsoon (r = 0.499), winter (r = 0.351), and at the annual scale (r = 0.512), and in Sreemangal during July (r = 0.453), monsoon (r = 0.499), and post-monsoon (r = 0.350), with correlation coefficients ranging from 0.350 to 0.512 and significant at the 5% level. This indicates strong temporal persistence and long-term memory in temperature records. Under such conditions, the classical

MK test may overestimate trend significance. Hence, the MMK test, which accounts for serial correlation, is more suitable for temperature trend analysis. Accordingly, this study applies the MK test primarily for rainfall and the MMK test for temperature to ensure robust and reliable trend detection.
Monthly, seasonally, and annually significant autocorrelation in study stations is consistent with the findings of the previous study reported by **[17]** and **[18].** These results highlight the importance of accounting for serial correlation when analyzing climatic time series, ensuring that trend detection is both accurate and reliable across different variables and temporal scales.

Table 2 Results of serial dependence

Month / Season	Rainfall		Mean temperature	
	Sylhet	Sreemangal	Sylhet	Sreemangal
	r	r	r	r
Jan	-0.070	-0.304	-0.189	-0.122
Feb	0.092	-0.022	-0.052	-0.006
Mar	-0.227	-0.171	-0.031	-0.247
Apr	0.065	0.035	-0.057	-0.026
May	-0.275	-0.034	-0.027	0.035
Jun	-0.002	-0.145	-0.003	-0.078
Jul	**0.124**	-0.028	0.301	**0.453**
Aug	-0.135	0.255	0.028	0.205
Sep	-0.126	-0.234	0.319	0.311
Oct	0.236	**0.003**	0.326	0.110
Nov	-0.170	-0.131	0.173	0.093
Dec	-0.008	-0.067	0.242	0.235
Pre-monsoon	-0.091	0.124	0.190	0.255
Monsoon	-0.053	-0.305	0.255	**0.499**
Post-monsoon	0.201	0.164	**0.499**	**0.350**
Winter	0.127	0.030	**0.351**	0.190
Annual	-0.048	0.026	**0.512**	0.298

Bold colour indicates 5% significance level

3.4 Trend analysis

The MK/MMK trend analysis of rainfall in Sylhet and Sreemangal (Table 3) shows that most monthly, seasonal, and annual rainfall series exhibit no statistically significant trends at the 5% level. In Sylhet, none of the months show a significant trend, with October having the highest Z-value ($Z = 0.225$, $p = 0.059$) but still insignificant. In Sreemangal, all months are non-significant, with the highest Z-value in August ($Z = 0.207$, $p = 0.083$). Seasonal analysis indicates that only the post-monsoon season in Sylhet shows a significant increasing trend ($Z = 0.269$, $p = 0.024$, Sen's slope = 5.097 mm/year), while pre-monsoon, monsoon, and winter remain stable. In Sreemangal, no seasons show significant changes, including the monsoon and post-monsoon periods (post-monsoon Sen's slope = 2.533). Annual rainfall also shows no significant trend in both locations (Sylhet $Z = 0.099$, $p = 0.410$, Sen's slope = 12.091 mm/year; Sreemangal

Z = 0.072, p = 0.551, Sen's slope = 5.821 mm/year). Sen's slope values generally reflect minimal changes in rainfall intensity, except for the weak post-monsoon increase in Sylhet.

In contrast, mean temperature trends (Table 4) show strong and statistically significant warming across both Sylhet and Sreemangal. In Sylhet, significant monthly increases are observed in March (Z = 2.406, p = 0.016, Sen's slope = 0.043), July (Z = 3.873, p = 0.001, slope = 0.039 °C/year), September (Z = 3.876, p < 0.001, slope = 0.044 °C/year), and October (Z = 3.291, p = 0.001, slope = 0.035 °C/year), while other months remain non-significant. Sreemangal shows significant increases in July (Z = 3.832, p < 0.001, slope = 0.031 °C/year), September (Z = 3.752, p < 0.001, slope = 0.031 °C/year), and October (Z = 2.079, p = 0.038, slope = 0.025 °C/year). Seasonal trends are significant in both locations during pre-monsoon, monsoon, post-monsoon, and winter, with Sen's slopes ranging from 0.023–0.035 °C/year in Sylhet and 0.023–0.034 °C/year in Sreemangal. Annual mean temperatures also increased significantly (Sylhet Z = 4.675, p < 0.001, slope = 0.029 °C/year; Sreemangal Z = 2.685, p = 0.007, slope = 0.016 °C/year). These results indicate persistent warming with strong temporal persistence and long-term memory, as supported by serial dependence analysis.

Overall, rainfall variability in both regions is largely irregular and random, consistent with serial dependence analysis, suggesting that long-term changes in rainfall are minor and dominated by short-term variability, consistent with **[19].** The results also highlight an asymmetric climatic response: while rainfall remains largely non-significant, mean temperatures are steadily increasing, which is also contradicted by some studies on climate change and variability **[20,21].** These results indicate signaling a clear warming trend with potential implications for agriculture, water resources, and climate adaptation strategies in Sylhet and Sreemangal.

Table 3 Rainfall trend analysis

Month / Season	Rainfall							
	Sylhet				Sreemangal			
	Z	p	Trend	Sen's slope (mm/year)	Z	p	Trend	Sen's slope (mm/year)
Jan	-0.198	0.073	no trend	0	0	1	no trend	0
Feb	-0.182	0.128	no trend	-0.647	-0.155	0.194	no trend	-0.375
Mar	-0.163	0.173	no trend	-1.440	-0.131	0.274	no trend	-0.800
Apr	0.055	0.650	no trend	2.143	-0.064	0.599	no trend	-0.722
May	0.126	0.293	no trend	3.667	0.074	0.541	no trend	1.765
Jun	0.143	0.233	no trend	6.125	0.139	0.244	no trend	3.500
Jul	0.045	0.712	no trend	1.269	0.007	0.966	no trend	0.040
Aug	0.153	0.201	no trend	5.818	0.207	0.083	no trend	3.273
Sep	-0.062	0.609	no trend	-2.130	-0.143	0.233	no trend	-1.739
Oct	0.225	0.059	no trend	5	0.008	0.955	no trend	0.087
Nov	-0.017	0.896	no trend	0	-0.015	0.909	no trend	0
Dec	0.118	0.276	no trend	0	0.084	0.446	no trend	0
Pre-monsoon	0.037	0.766	no trend	2.421	0.034	0.787	no trend	0.148
Monsoon	0.124	0.300	no trend	6.545	0.064	0.599	no trend	1.364
Post-monsoon	0.269*	0.024	increasing	5.097	-0.005	0.977	no trend	2.533
Winter	-0.131	0.274	no trend	-0.458	0.035	0.776	no trend	-0.120
Annual	0.099	0.410	no trend	12.091	0.072	0.551	no trend	5.821

* Indicates 5% significance level

Table 4 Trend analysis of mean temperature

Month / Season	Mean temperature							
	Sylhet				Sreemangal			
	Z	p	Trend	Sen's slope (°C/year)	Z	p	Trend	Sen's slope (°C/year)
Jan	1.409	0.159	no trend	0.025	0.455	0.648514	no trend	0.005
Feb	1.751	0.080	no trend	0.029	0.028	0.977312	no trend	0
Mar	2.406*	0.016	increasing	0.043	-0.042	0.965945	no trend	0
Apr	1.778	0.075	no trend	0.036	1.251	0.210816	no trend	0.027
May	1.580	0.114	no trend	0.025	1.895	0.058027	no trend	0.029
Jun	1.909	0.056	no trend	0.019	1.628	0.103509	no trend	0.013
Jul	3.873*	0.001	increasing	0.039	3.832*	0.000127	increasing	0.031
Aug	1.781	0.075	no trend	0.019	1.700	0.089044	no trend	0.013
Sep	3.876*	0.000	increasing	0.044	3.752*	0.000175	increasing	0.031
Oct	3.291*	0.001	increasing	0.035	2.079*	0.037604	increasing	0.025
Nov	1.863	0.062	no trend	0.022	-0.071	0.943295	no trend	0
Dec	1.665	0.096	no trend	0.024	1.452	0.146265	no trend	0.019
Pre-monsoon	2.018*	0.044	increasing	0.023	2.957*	0.003104	increasing	0.035
Monsoon	2.957*	0.003	increasing	0.035	12.937*	0	increasing	0.034
Post-monsoon	12.937*	0.000	increasing	0.034	3.259*	0.001118	increasing	0.032
Winter	3.259*	0.001	increasing	0.032	2.017*	0.043595	increasing	0.023
Annual	4.675*	0.000	increasing	0.029	2.685*	0.00724	increasing	0.016

* Indicates 5% significance level

3.5 Time series forecasting

Fig 4 presents the monthly rainfall and temperature forecasts for Sylhet and Sreemongal for the period 2025–2034 based on the selected SARIMA models. The historical series (1990–2024) exhibit pronounced seasonal patterns in both rainfall and temperature at the two locations. Sylhet rainfall shows high interannual variability with strong monsoonal peaks, while Sreemongal rainfall follows a similar seasonal structure but with comparatively lower magnitudes. Temperature series for both stations display clear annual cyclical behavior with relatively stable long-term trends. The forecast results indicate the continuation of these seasonal dynamics over the projection horizon, with rainfall maintaining periodic peaks and troughs and temperature preserving its regular annual oscillation. The prediction intervals widen gradually over time, reflecting increasing uncertainty in longer-term forecasts, yet remain consistent with the historical variability structure of the series. Overall, the models capture the dominant seasonal characteristics and provide stable short- to medium-term projections for both climatic variables.

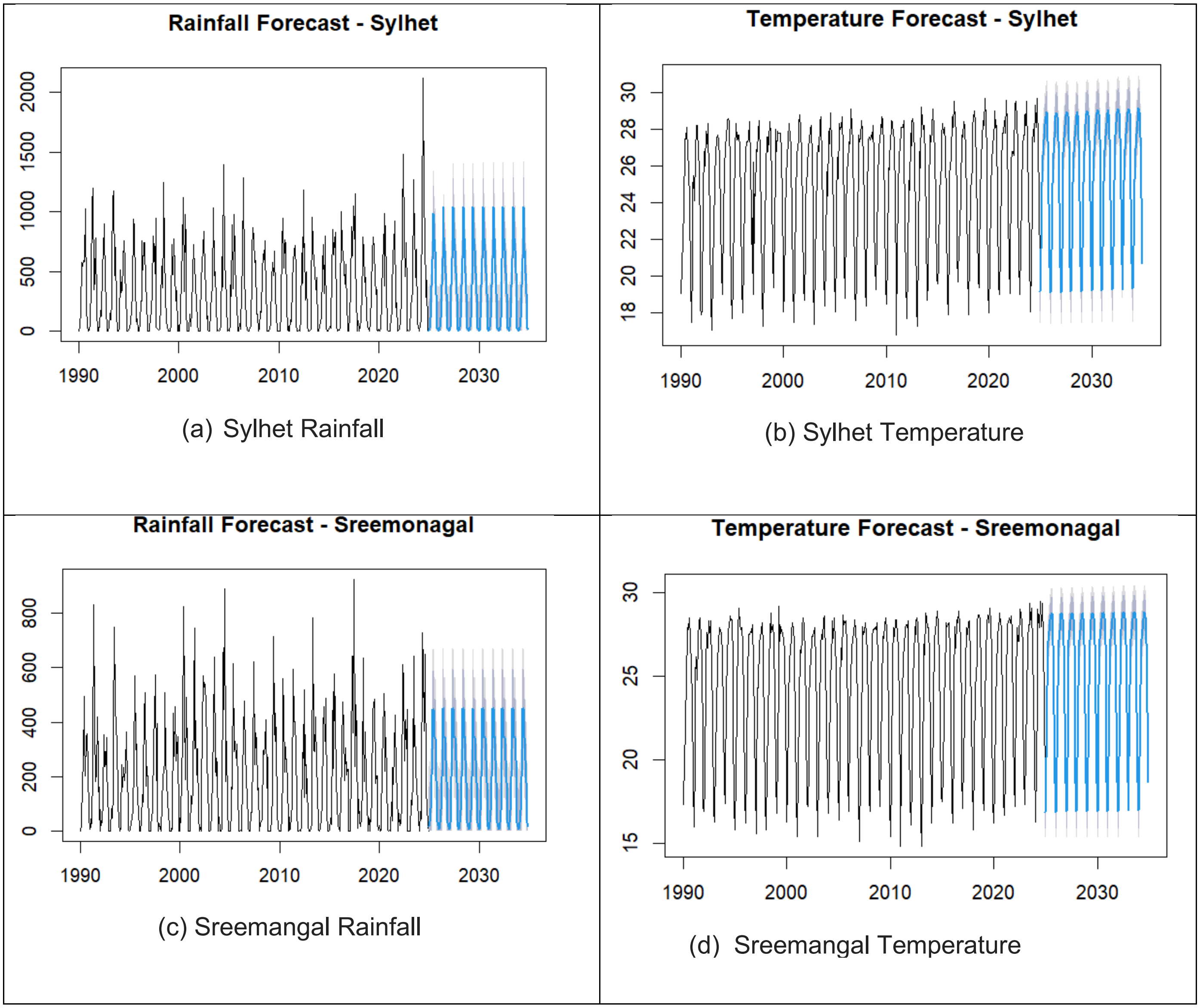

Fig 4: Forecasting (2025-2034) of Sylhet's (a) rainfall, (b) temperature, and Sreemangal's (c) rainfall, (d) temperature

4. CONCLUSION

This study examined the long-term variability, trends, structural changes, and future behavior of rainfall and temperature in Sylhet and Sreemangal, northeastern Bangladesh, using multiple non-parametric statistical approaches and time-series forecasting techniques. The integrated climatological analysis shows that both regions are strongly influenced by seasonal monsoon dynamics, with rainfall highly concentrated during the monsoon period and very low during winter. Sylhet consistently receives higher rainfall than Sreemangal, indicating stronger monsoonal influence and greater exposure to flood-related hazards. Temperature patterns show a clear seasonal cycle with higher values during pre-monsoon and monsoon periods and lower values in winter, while overall temperature variability remains comparatively stable throughout the year. The change-point analysis using the Pettitt test indicates noticeable structural shifts in both rainfall and temperature series, particularly after the early 2000s. However, temperature records exhibit more consistent and statistically significant breakpoints, especially around 2015–2016, suggesting the onset of a sustained warming phase across the region. Autocorrelation analysis further confirms weak and irregular dependence in rainfall data, whereas temperature shows strong positive serial correlation, indicating long-term persistence in thermal conditions. This justifies the use of MMK for temperature trend assessment and

MK for rainfall. Trend analysis reveals that rainfall exhibits mostly non-significant and irregular trends at monthly, seasonal, and annual scales, indicating high natural variability without a clear long-term directional change. In contrast, temperature shows a consistent and statistically significant increasing trend across several months, seasons, and both study stations, confirming persistent regional warming. Sen's slope results further quantify this warming signal, highlighting steady increases in mean temperature over time. SARIMA-based forecasting suggests that the observed seasonal patterns in both rainfall and temperature are likely to continue into the future (2025–2034). While rainfall variability remains highly seasonal with strong monsoon dominance, temperature is expected to maintain its gradual upward trajectory. However, forecast uncertainty increases with time, indicating the inherent unpredictability of long-term climatic projections. The findings demonstrate an asymmetric climatic response in northeastern Bangladesh, where rainfall remains highly variable but largely trend-free, while temperature shows a clear and persistent warming signal. These changes have important implications for agriculture, water resource management, flood risk, and climate adaptation planning in Sylhet and Sreemangal.

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E-Governance for better service delivery in public sector: Experience of implementing National E-Service System (NESS) in the Deputy Commissioners' Office in Bangladesh

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Abstract

This research focuses on e-governance for better service delivery in public sector especially in Bangladesh. The aim of the research is to investigate the role of e-governance regarding service delivery provided by the Deputy Commissioners' office in Bangladesh through National E-Service System (NESS) considering with the experiences of government officials. The objectives of the study are to identify the experience of implementing NESS, to find out the impact of NESS in delivering public services to the citizens and whether e-governance is effective or not for delivering better services to the citizens.

For conducting this research eight respondents have been selected from four Deputy Commissioners' office. The study has been conducted through qualitative method followed by interpretivist philosophy with an inductive approach. The semi-structured interview questions were used and exploratory strategy has been followed by the researcher to collect data from the eight respondents.

The findings and results of this study showed that there were some limitations and challenges of implementing NESS in the initial stage such as lack of knowledge and skills of the employees and infrastructure facilities, attitudinal problem etc. Still there exist some problems in the rural areas for getting full benefits from NESS by the service receivers such as incapacity of rural people to use ICT and intervention of middlemen. But the overall outcomes of NESS are that it is providing a lot of benefits such as increasing transparency, efficiency and accountability; reducing corruption; saving time, cost and visit; improving customer satisfaction; easy access and monitoring etc. to the service receivers as well as the service providers. So, it can be said that NESS is playing a positive and significant role in delivering better services to the citizens of Bangladesh comparing with the traditional system of service delivery.

1.1 Introduction and background of the study

The attempt of the study is to evaluate the experience of implementing National E-Service System (NESS) in Deputy Commissioners' Office in Bangladesh regarding service delivery to the citizens of Bangladesh. In the traditional form of service delivery system in the public administration in Bangladesh was paper based long-term procedures and it dissatisfied the citizens regarding the delay in service delivery and there was also corruption in providing service to the citizen (Karim 2015).

As Bangladesh is an over populated country so it is very difficult for the service providers to ensure better service following the traditional method which is paper based long term bureaucratic system. Because the traditional system is inflexible and labour intensive so it takes long time to provide services and due to shortage of sufficient staffs as well as infrastructural facilities government offices are not capable to satisfy the increasing demand of services from the growing population (a2i 2013).

To improve that situation of service delivery Bangladesh government has taken the initiatives for providing better services to the citizens through e-governance system using online. For providing better services to the citizens of Bangladesh National e-Service System (NESS) in the District e-Service Centre (DESC) located in the Deputy Commissioner's (DC) office that facilitates one stop service delivery (a2i 2013).

The 64 DESCs located all over the country was inaugurated on 14 November, 2011 and DESC has been designed to improve the accessibility and transparency of public service delivery system at the district level to attain some objectives which includes: ensuring service delivery to the citizens within a shortest possible time, keeping the rights to information of citizens through wide-ranging information stream and reducing corruption and increasing accountability through transparent processes (a2i 2013).

In Bangladesh District Administration, that means Deputy Commissioner's office is providing government services for the rural and urban people on behalf of central government over the past 200 years. The services that are provided by the DC office are: control and supervision of revenue; maintenance of public order and security; magisterial functions; control of fire arms; administration of jails; licence and certificates; land acquisitions; press and publications; census; election matters; relief and rehabilitation; social wellbeing; transport and traffic affairs; education and conduct of public examinations; public amusement; public grievances and enquiries; pension matters; inter agency matters; treasury and stamp; training functions; minority matters; family planning etc. (Cabinet division 2016).

ICT is an effective instrument that helps to provide effective service delivery to the citizens or public. UNDP (2007 cited by Salam and Islam 2013) describes that for providing sustainable delivery of services e-governance can play an important role for poor society and keep accountable both the policy makers and service providers.

1.2 Aim

The aim of the research is to investigate the role of e-governance regarding service delivery implemented by the Deputy Commissioners' Office in Bangladesh through NESS with considering the experiences from government officials.

1.3 Objectives

The objectives of the research are-

- to identify the experience of implementing NESS in the DC office.
- to find out the impact of NESS in delivering public services to the citizens.
- to study about the experience of delivering services to the citizens through NESS.
- to know from the experience whether e-Governance is effective or not for delivering better service to the citizens.

1.4 Research questions relating to level of service delivery

The study has tried to answer the following research questions:

- How promptly public services are provided by the DC office through NESS in considering with traditional system?
- Has NESS made a significant impact on better service delivery through the DC office in Bangladesh?

1.5 Rational or justification of the research

The research has some justifications or rationalities. The justifications are as given below:

i. **Academic:** This study will help the academicians for obtaining knowledge and gathering some ideas regarding service delivery through e-governance projects. Kasubiene and Vanagas (2007) said that, e-governance is a new scope of research and the aspect of service quality of e-governance is even more important for research. So, this study will help the researchers to conduct further research relating to this area.

ii. **Business/Practitioner:** The information attained from this study will give proper direction for managers of e-government to improve the implementation of e-governance system for service delivery. This study will also help the government of different countries for taking initiatives of e-governance systems. This study will also help the government employees of Bangladesh for improving efficiency regarding service delivery.

iii. **Personal:** This study will help the researcher to understand about different terms of e-governance and give a lot of ideas of conducting research. It will also help the researcher for doing Ph.D. in future and it will help to build up his career in this sector.

2.1 Concept of E-Governance and E-Government

According to Pani and Mishra (2009) government related to the achievement of public interest of the society while governance describes the link between government and other political, social and administrative environment. Governance is the process through which decisions are made and implemented that means it is related with the policy formulation and execution. On the other hand, government is one of the actors in governance.

2.2.1 E-Governance

E-Governance means the use of information and communication technology by the government to ensure transparency, accountability, effectiveness and efficiency in the government organisations for delivering better services to the citizens (Alam 2012).

Drucker (2001 cited by Rokhman 2011) said that E-governance is the application of information and communication technology that helps government and public administration to perform their activities.

The aim of establishing e-governance is to ensure good governance and good governance is categorised by involvement, accountability and transparency. E-governance is performed by IT in order to enable an efficient, prompt and translucent process of circulating information to the public and other agencies (UNESCO 2005).

Budhiraja (2003 cited by Naz 2009) defined e-governance as the application of IT to the organisational functions of government for the purpose of ensuring Simple, Moral, Accountable, Responsive and Transparent governance. She also called it SMART governance. So, e-governance is the combination of three things, which are people, information technology and government.

Typically, e-governance relating to delivery of public services to the citizens through electronically. Delivery of public services exist between the government representatives and the general people to whom the government services are provided to. Any mechanism of effective delivery of public service must eventually indicate to good governance (Salam and Islam 2013).

Jain and Ramani (2005) said that, e-governance is the involvement of citizen with the activities and services of government and it covers the activities and services for almost all segments of the society. They also said that e-governance improve the transparency, integrity and efficiency of the government functions and services to the citizen by ensuring the easy access to the information.

Pani and Mishra (2009) said that e-governance related with the delivery of public services and information to the public through electronically and e-governance applies ICT to the process of administration and it does not mean that computerisation of the total administration but means a fundamental change in operation of government.

2.2.2 E-Government

E-government is a narrower term considering with e-governance. Pani and Mishra (2009) said that e-government is considered with a narrower discipline that deals with the development of online services to the citizen which includes e-tax, e-health, e-procurement, e-transportation etc.

Fraga (2001 cited by Nkwe 2012) said that e-government is the transformation of relationships between internal and external sector of government through internet, information technology and communications in order to improve the constituency participation and the delivery systems of service by the government to its society.

2.3 Domains of E-governance Application

Productive use of information and communication technology has been facilitated by e-governance that establish relationship among the citizens, businesses and different organs of government. According to Heeks (2001), there are three main domains of e-governance which includes e-Administration; e-Citizens and e- Services; and e-Society. The main objective of e-administration is to improve the working capacity of public sector by reducing process costs, to improve the internal performance, making strategic communications within different government organs and creating empowerment through transferring power, authority and resources. E-service helps to improve the communications with the citizens by talking to citizens and listening to citizens. It also helps to improve the delivery of public services regarding with quality, convenience and cost. E-Society helps to build external interactions and relationships between government organisations and other institutions. It also helps to work better with government and business, developing communities and building partnerships through institutional relationships (Heeks 2001).

2.4 Components of E-Governance

E-governance interacts with different groups and organisations. According to Backus (2001) e-governance interact with three different groups, including (i) government to citizens (G2C) that improves relationship between the government and citizens, (ii) government to government (G2G) that improves inter groups or organisations' relationships and (iii) government to business (G2B) that establishes effective relationship between the government and business enterprises. The component of e-governance creates a link between the government and citizens for the purpose of ensuring better and efficient delivery of public services and it helps citizens to get more benefit from it. In G2C government provides one-stop, on-line access to information and services to the citizens. It also helps to increase the availability and openness of getting public services and try to improve the quality of public services. The primary objective of this activity is to create friendly environment between the government and citizens regarding delivery of public services.

2.5 A Four Phase Model of E-Governance

Backus (2001) said that a four-phase e-governance model was developed by an international e-business research consultancy firm named Gartner in 2000. This model has four phases which linked with the development of computer technology, networking of computers and communication systems. This model shows that e-governance will mature after fulfilling these four stages. The delivery of online services and use of information and communication technologies in government functions serve one or more of the features of e-governance in each of the four phases. These phases include information, interaction, transaction and transformation. The universal e-governance maturity stages and its meaning are as shown below using a table.

Stages	Meanings
Information	In this phase the relevant information is provided to the general public through websites and it is similar with the brochure or leaflet. It improves transparency and accountability in service delivery through ensuring quality of service delivery; easy accessibility and availability.
Interaction	In this phase, the e-government provides interaction between government and citizens with various applications. In this stage citizens can search any kind of information related with the government services, download any types of government forms or documents, and ask any questions to the public servants through online via email or website. In this stage the general public also apply online for jobs and different services that saves time and cost. This also helps to achieve efficiency and effectiveness because most of the services are processed through online.
Transactional	In this phase, technological complexities are increased and dealings can be made without going to the office, for example online passport and visa application, online voting etc. In this stage government provides safe transactions with a high level of authorization through online process which saves time, money and paper.
Transformational	In the transformational phase all information is integrated or gathered at one counter where public can get all services which saves time, cost and visit and will ensure transparent, better and effective delivery of public services. In this stage the government or public services are made available online to stakeholders around the clock.

2.6.1 Opportunities and Benefitsof E-Governance

According to Ndou (2004) there are a lot of benefits or opportunities of e-governance and these are the same in developing countries and developed countries although many imminent benefits are not utilised by the developing countries because of limited use of e-governance. She identified the following main opportunities of e-governance.

i. It reduces cost and ensures efficiency
ii. It ensures excellence of service delivery for customers and businesses
iii. Improve accountability and transparency by reducing corruption
iv. Increase the capability of government
v. It creates new and reliable network for the community
vi. Help to improve the perfection of making decision
vii. Encourage other sectors of the society to use ICT

After assessing the results of 12 e-government projects in developing countries Bhatnagar (2004) found that e-governance has provided substantive benefits by reducing corruption, increasing transparency, improving service delivery, enhancing economic goals of good governance through empowering people.

John et al. (2005 cited by Kettani and Moulin 2014) said that by implementing e-governance development targets, Malaysia is becoming a role model of developing nation.

Bertucci and Alberta (2003) said that e-governance can reform the governance system and public administration by effective and efficient public management that ensure more access and provide quality information to the citizen to build participative and interactive partnership of governance through better service delivery.

According to Kettani and Moulin (2014) by reducing the required amount of input resources, e-government effects the value chain of government organizations which ensures less physical effort from more limited workforce that reduce time regarding delivery of services, increasing output by increasing number of services and improving outcomes by improving the quality of delivery of services.

United Nations (2008) describes a number of internal and external gains generated from e-governance which includes the following:

Internal gains generated by e-governance

- It helps to avoid duplication
- Reduce transaction costs
- Shorten bureaucratic process
- Provide improved efficiency
- Ensure better communication and coordination
- Enriched transparency
- Help to sharing information among agencies
- Ensure information management security

External gains generated by e-governance

- Quicker delivery of service
- Greater efficiency
- Ensure flexibility of delivering service
- Invention in service delivery
- Greater involvement
- Better empowerment of citizen
- participation of citizen

2.6.2 Challenges and Risks ofe-governance

There are different challenges and risks of successful implementation of e-governance initiatives. According to Ndou (2004) the main challenges of development and implementation of e-governance includes the following:

i. Lack of infrastructural facilities which includes insufficient IT equipment, computer literacy, e-readiness etc.
ii. Improper rules, regulations and other policy issues.
iii. Shortage of development of human capital and ultimate learning which includes education, skills, technical capabilities and learning.
iv. Showing negative attitude to change management and resistance to change.
v. Weak collaboration and partnership with public or private organisations and community and fail to create network among them.
vi. Wrong vision, mission and strategy.
vii. Leadership role is not appropriate to influence, motivate, support and involve the participants.

Hanna (2010 cited by Kettani and Moulin 2014) identified a number of risks of e-governance which includes the following:

- Attitudinal positions of government officials with respect to information and communication technology.
- Underestimate the organizational performances and consequences of ICT decisions.

- Lack of organizational capacity and capability to manage effectively of public-private partnerships (PPP).
- Lack of managerial strengths.
- Participatory approaches implemented poorly.
- Inherent risks to a supply-driven e-government context.

Alshehri and Drew (2010) said that for implementing e-government we face different barriers and challenges that can delay the progress. They categorised these barriers as technical, organisational, social and financial which includes ICT infrastructure, security and privacy, resistance to change to electronic ways, support of top management, collaboration, lack of skilled personnel and training, culture, digital divide and other financial barriers.

Heeks (2003 cited by Dada 2006) argued that in developing countries most implementations of e-government have failed and the rate of total failure is 35% because of limited number of resources they have and wastefully spend large amounts of money for these projects.

2.7 Other critical views of e-governance

There are also some other critical views of e-governance which are found from different researches.

Ciborra (2005) said that receiving of e-governance in developing countries is highly questionable and, in these countries, good governance is not always the outcome of e-government. He argued that transparency and accountability will not come automatically from the military or bureaucratic administrations. Using a case study on e-government implementation in Jordan he wonders that developing countries are not ready to treat the citizens as customers but in these countries the citizens of privileged areas may have access to the service more easily and in the form of bribery or favouritism corruption may be continued and offered to new intermediaries.

Baptista (2005) argued that e-government has the possibility to transform governance and to establish the relationship between state, citizens and organisations. But the overall performance to good governance usually remains unclear in terms of public services and also return on investment. Because a considerable amount of government funds is invested in e-governance projects.

Basu (2004) said that despite of the availability of infrastructure in developing countries many people do not have any access to IT because of a large gap between educated people who have the ability to use technology and the uneducated poor people who do not have any ability to use technology.

2.8 E-Governance: Service Delivery Approaches

There are two types of service delivery approaches of e-governance including agency-centric approach and citizen-centric approach. Shapiro (1999) said that the modern governments are shifted from the traditional agency-centric approach to citizen-centric approach for delivering of public services. Salam and Islam (2013) stated that citizen-centric approach is more realistic approach for providing public services and it creates an opportunity to interact between the government and citizens.

Agency-Centric Approach

Another name of agency-centric approach of e-governance is department-centric approach. In agency centric approach it is necessary for the citizens to interact with each department separately that creates inefficiency and inconvenience for getting service and it requires separate approval from each department that time consuming and expensive for getting proper service (Al-Khouri 2011).

Citizen-Centric Approach

Citizen-centric approach helps government to be efficient for the purpose of providing better service to the citizens that creates citizen satisfaction and improve the quality of life for getting government services (Mehra 2004).

Gronlund (2002) said that providing service through citizen-centric approach government can able to increase trust, transparency and accountability from the view of citizens and in this approach, government thinks about the process of service delivery through citizens' view point rather than operational or any other means.

Citizen-centric approach helps to avoid duplication for delivery of services. It is concerned with the rethinking of service delivery system through citizen perspective that reduces time and minimizes long bureaucratic procedures or hierarchies of government (Salam 2012 cited by Salam and Islam 2013).

2.9 Empirical Studies on E-governance for better service delivery

Many researchers have conducted different studies regarding e-governance and tried to assess the effectiveness of e-governance for delivering better public services both developed and developing countries. Some studies relating to this issue are as discussed below.

2.9.1 E-Governance and Public Service Delivery

E-governance related with the delivery of public services that are provided through electronically. It creates a relationship between the government entities and the citizens. It also provides different government related information and services to the citizens in more transparent way and facilitates citizen empowerment and simplifies the delivery of public services (Bhatnagar 2014).

Tapscott and Caston (1993) said that information and communication technology has initiated change in delivery of public service both in principles and mode. Paper based documentation and face to face interaction of bureaucratic system has moved to electronic interchange and non-interpersonal interaction. Impartiality, standardization and equity principles have been established by user customization.

Harris (2000 cited by Salam and Islam 2013) argued that ICT plays a key role to support good governance as it increases accountability, transparency and thus help to minimize the operational expense of government.

2.9.2 Service Quality and Customer Satisfaction

E-service facilitates easy flow of information that provides different experience to the customers regarding better service from the government organisations. Different studies have conducted by the researchers regarding traditional service versus e-service to find out quality dimensions of providing public service.

Field et al. (2004) said that for providing better services to the citizens e-service can play a crucial role that increase customer satisfaction, building trust and ensure competitive success for the organisations.

Dabholkar (1996) conducted research work on the quality of e-service which is very much interrelated with web site design and he identified seven basic elements that helps to increase the quality of e-service, including design of the website, accessibility, reliability, ease of use, enjoyment, delivery and control.

With the comparison of the quality of traditional service delivery to the electronic service delivery system Cox and Dale (2001) find out six criteria that helps to improve the quality of online service delivery including appearance of website, accessibility, ease of communication, availability, credibility and understandable to the customers.

Saha and Zoha (2005 cited by Doost and Ashrafi 2014) said that one of the major issues of every organisation is to provide better quality of service that ensure customer satisfaction. They also said that customer satisfaction is the combination of psychological relations to the experience of consumption or adaptability with a product or service, customers' evaluation and perception.

Kalsi et al. (2009) mentioned that citizens may be directly benefitted from the initiatives of e-government as they have direct transactions with the services provided by the government.

A study was conducted by Al-Tarawneh (2012) on quality of e- service and customer perception, which indicates that customer's perception of quality of e-service is influenced by website design, ease of use, responsiveness, security and personalization.

Salam and Islam (2013) said that, better delivery of public service is the key foundation of any popularly elected government for their existence and they take several programs for bringing changes within their prevailing conventional and procedural governmental systems and for the purpose of achieving the reliance from its citizens they try to deliver better public services.

3.1 Methodology

Research methodology is a systematic and scientific process including different steps that helps to solve any research problem. Every researcher should know not only the techniques or methods of research but also about the methodology of research (Kothari 2004).

According to Collins and Hussey (2003), methodology is the key factor for conducting any research. Methodology highlights the principles and methods of the scope of research through critical discussion and where principles can be considered as the fundamental philosophy of the research (Horn 2012).
Saunders et al. (2009) said that research methodology is a process which has different outside and inside layers looks like an onion including research philosophies, approaches, strategies, choices of methods, time horizons and the research techniques and procedures that has been followed step by step by the researchers to conduct research.

3.2 Research philosophy

Research philosophy is important for any kind of research because it shows the way in which the researcher views the world. Saunders et al. (2009) said that research philosophy can influence the particular view of the researchers regarding the relationship between the knowledge and the process by which the research developed. According to Johnson and Clark (2006 cited by Saunders et al. 2009) researchers should be aware of the philosophical commitments because it has significant impact on the study that they are investigating. There are different philosophical perspectives of conducting research such as positivism, realism, pragmatism and interpretivism (Saunders et al. 2009).
This study has been conducted through interpretivism philosophy because the aim of this philosophy is to understand the meanings and realities regarding participation of the members in the social processes who are working in a social group and also to understand their views and intentions to generate social actions (Orlikowski and Baroudi 1991). Saunders et al. (2009) said that interpretivism philosophy helps the researcher to understand the roles of individuals as social actors and it is useful for in-depth investigations where small samples are taken for the purpose of qualitative research. They also argued that for business and management research especially in the field of human resource management, organisational behaviour and marketing this type of philosophy is highly appropriate.
As the study has been conducted to find out the real situation, in-depth investigations and the roles of government officials regarding service delivery in the Deputy Commissioners' Office in Bangladesh through NESS that is why interpretivism philosophy has been followed.

3.3 Research Approach

There are two types of research approach. These are- inductive approach and deductive approach. Inductive approach has been applied in this research because this approach helps to find out the real situation of the research field and helps to understand the better scope of the problem (Saunders et al. 2009). This approach is opposite from the deductive approach and also called the bottom-up approach. According to Flick (2011), inductive approach is applied where interviews are conducted concerning particular phenomena and data are being examined for arrangements among respondents. Inductive approach underlines to gain an understanding of the meanings where humans are attached to a specific event and this approach is more appropriate where a small number of samples are used for conducting research (Saunders et al. 2009).
This study has been conducted through inductive approach because in this research the researcher has been tried to find out the real situation of e-governance system regarding service delivery from the experience of government officials who are working in the Deputy Commissioner's office in Bangladesh. In addition to that as this study has been conducted with a small number of samples that is why inductive approach has been applied.

3.4 Research Method

There are two main methods of business and management research such as quantitative method and qualitative method. In this research qualitative method has been chosen to investigate the role of e-governance regarding service delivery implemented by the Deputy Commissioners' Office in Bangladesh through NESS with considering the experiences from government officials.

Daymon and Holloway (2011) said that in qualitative study respondents are participated not only to furnish data but also in some extent to interpret it and in case of interviews in qualitative study the researcher can encourage and penetrate the participants to tell something details about the topic.

Qualitative research presumes that human beings understand and tends to narrate things from their mind cognitively. Qualitative methods allow people to express their assumptions, opinions, understandings, desires and beliefs. This method facilitates to deliver perspectives, such as one-to-one interviewing by which the respondents can express their assumptions and understandings. Analysis of such data requires to explain these assumptions, understandings and beliefs in a broader social perspective (Horn 2012).

Holloway and Wheeler (2010) argued that qualitative research facilitates to describe, understand and interpret the social spectacles assumed by cultures, groups or individuals. This method is applicable to discover the experiences, feelings and behaviour of people which is an integral part of their lives.

According to Bryman and Bell (2011) qualitative research gives emphasis to the words rather than quantification of data which predominantly gives priority on inductive approach between theory and research.

In this study qualitative approach has been applied because of finding, understanding and exploring the beliefs, assumptions, and experiences of government officials of implementing NESS for providing public services to the citizens through DC office. In qualitative approach the respondents have some freedom to give arguments of a certain topic which is conducted through in-depth interview. So, for generating idea regarding delivery of public services through NESS provided by the DC office this approach has helped the researcher to find out the real situation. By applying qualitative approach through interview method, the respondents have been got more benefits and flexibility for giving their opinion regarding implementing NESS for the purpose of providing better service and they have also given their arguments according to their individual experiences whether e-governance system in the public sector is appropriate or not for providing better service delivery to the citizens.

3.5 Research Strategy

Research strategy is a general plan followed by the researcher to gather data for the purpose of answering research questions that meet the research objectives and providing results. Saunders et al. (2009) described three types of research strategies which include exploratory, descriptive and explanatory. They also described different types of strategies for generating research data including survey, experiment, action research, case study, ethnography, grounded theory, archival research etc. Bryman and Bell (2011) said that it is necessary for the researcher to apply appropriate research strategy so that it can make a connection with the research philosophy, research approach and methods of the research that has already been selected by the researcher and to give emphasis on the research aims, objectives and research questions.

In this study exploratory strategy has been followed by the researcher and considered more effective to explore the actual situation of e-governance regarding service delivery provided by the Deputy Commissioner’s office in Bangladesh. Exploratory strategy has been followed because it helps the researcher to find out what is happening inside, seeking new insights, asking questions and assessing phenomena in a new light (Robson 2002 cited by Saunders et al. 2009). Saunders et al. (2009) said that there are three main ways of conducting exploratory research which includes searching of literature, conducting interview with the subject experts and the focus group.

3.6 Method of data collection

For conducting any types of research, it is necessary to collect relevant data. There are two types of data including primary data and secondary data. Primary data is the first-hand information that is collected through interview, survey, census etc. Secondary data are collected through journal articles, books, internet or website, research documents etc.

In this research both types of data have been collected for conducting the research properly. The secondary data has been used for the purpose of literature review and generating research themes which has also been developed through interview. The primary data of this research has been collected through semi-structured questions.

According to Bryman and Bell (2011), semi-structured question usually refers to a situation in which the interviewer has a series of questions that are in the general form of interview schedule but is able to vary the sequence of questions. Saunders et al. (2009) said that there are three types of interviews including structured, semi-structured and unstructured or in-depth interviews which are used for collecting primary data.

In this study semi-structured interview method has been chosen by the researcher for collecting primary data because semi-structured interview is referred for qualitative research and in this type of interview the researchers have a list of themes and questions where the sequence of questions may vary from interview to interview depending on the situation, organisational context and the flow of conversation (Saunders et al. 2009). Semi-structured interview also provides opportunity to the researchers to probe answers and it allows the interviewees to give explanation on a certain topic and also gives flexibility for answering questions that helps the researcher to generate themes and it is useful for exploratory research where interpretivist philosophy has been followed (Saunders et al. 2009).

As this study is a qualitative, exploratory study and follow interpretivism to find out the actual situation of service delivery through NESS provided by the Deputy Commissioner's Office in Bangladesh so, semi-structured interview method has been applied. The semi- structured interview has been conducted by the researcher with the respondents through one-to-one interview via mobile phone or Skype because the interviewees are working in Bangladesh and it was convenient for both the interviewer and interviewees in terms of time and cost and it was also useful for recording data promptly and easily. The conversation of each interview took 30 to 40 minutes.

For collecting data interview method seems to be more suitable and effective for this study because the aim of the study is to investigate the role of e-governance regarding service delivery from the experiences of government officials who are working in the DC office in Bangladesh rather than test a theory. The interview method has also helped the researcher to collect narrative data to generate themes and to interpret the facts and findings easily.

3.7 Language and design of questions

The questions have been designed to fulfil the research aim and objectives and to get answers of the research questions and also to explore the key themes of the research that will be explored through interview. The language of questions was in English language because the respondents who have been selected are good at English and high academic qualification that means all respondent has Master's degree from renowned universities.

3.8 Sampling Design and Technique

Sampling design and technique is very much important for conducting research as it is not possible to collect data from the entire population. The appropriateness and effectiveness of data collection from the representative sample of population depends on the selection of appropriate sampling technique (Saunders et al. 2009). There are two major types of sampling technique including probability sampling and non-probability sampling and each type divided into different categories.

There are 8 Administrative Divisions and 64 Districts in Bangladesh (Bangladesh National Portal 2016). Each 64 district has one Deputy Commissioner's Office called District Administration. In this research out of 64 Deputy Commissioner Offices operating in 8 Divisions in Bangladesh first of all 4 Divisions have been selected which are Dhaka, Rangpur, Sylhet and Rajshahi and then from 4 Divisions out of 33 DC offices 4 DC offices have been selected through multi stage random sampling method respectively to conduct the study. The selected districts were Dhaka, Rangpur, Sylhet and Naogaon from the divisions of Dhaka, Rangpur, Sylhet and Rajshahi respectively.

In district administration a number of government officials work as a representative of central government headed by the Deputy Commissioner (DC). There are some Additional Deputy Commissioners (ADC) and some Assistant/Senior Assistant Commissioners (AC/SAC) with specific tasks work in the DC office. All the officers come from the Bangladesh Civil Service Administration cadre where ADCs assist DC and

AC/SACs assist DC through ADCs. In this study for selecting respondents from the government officials of DC office purposive sampling method has been followed. Because the respondents who took part as service provider and directly involved with ICT operation have been preferred and who have come from Bangladesh Civil Service and posted as Additional Deputy Commissioner and Assistant Commissioner in the DC office equivalent to Deputy Secretary/Senior Assistant Secretary and Assistant Secretary to the government.

Saunders et al. (2009) said that purposive sampling is used where a very small number of samples are taken by the researcher and where the respondents are very much involved with specific tasks that help them to give answer of the questions in the time of interviewing. This type of sampling helps the researcher to collect data to answer research questions and meet the requirement of research objectives and themes. In this study 8 respondents have been selected from 4 Deputy Commissioners' Office. That means, in every DC office one Additional Deputy Commissioner (ADC) and one Assistant Commissioner (AC) have been selected as respondents.

3.9 Pilot Study

A pilot study has been taken by the researcher to eliminate any ambiguity about the questions and to understand how it works with the aims and objectives of the research. After that the researcher decided to proceed on and conducted the main study.

3.10 Data analysis

According to verbatim the conversations with the interviewees has been transcribed. After that the collected data has been analysed according to the aim and objectives of the study through coding method to answer the research questions and then common codes have been selected for analysis. The relevant theories have also been considered for interpreting the data to make the result more appropriate and reliable.

3.11 Validity and Reliability

Every researcher should be more careful about the validity and reliability of data that they are collecting because it is very important for conducting research. In this study the researcher has always given priority to the relevancy of data. The primary data of this study has been collected and analysed within a very short time for ensuring reliability and validity. As the respondents of this study were government employees and worked in the relevant field of this research and also had maximum educational qualification so, they answered the questions easily, smoothly and confidently. The secondary data of this study has been collected from the reliable sources like renowned journals, reference books, relevant websites etc. to develop literature review of this study and avoided those types of data that made confusion regarding with relevancy. So, in this research the researcher was always careful about the validity, reliability and quality of data.

3.12 Ethical Consideration

Every researcher should be careful about the ethics for conducting any type of research including ethical concern of the respondents when they collect data. Saunders et al. (2009) said that research ethics related with the questions about how a researcher formulate and clarify research topic, research design, methods of data collection, process, store and analyse, and how to write research findings and preparing research results. In this study, before conducting interview, the interviewees have been informed by the interviewer about the purpose of the study and it has been conducted with the prior consent from them and after collecting data the researcher stored and analysed it very carefully for the purpose of maintaining maximum reliability. The BU Research Ethics Code of Practice has also been followed and complied in this research.

3.13 Limitations

There are always some limitations for conducting any type of research (Yin 2012) and this study is not the exception from that idea. The limitations may include regarding time, quality, budget, availability of resources, insufficient knowledge about the research area etc. In this study there were also some limitations. For example, this study has been conducted only in the DC office but there are so many government offices in Bangladesh which are implementing e-governance. Besides this, there were also a limitation of time to conduct the research.

In summary it can be said that in this study the researcher has followed interpretivism philosophy with an inductive approach, applied qualitative method, exploratory strategy and semi-structured interview questions for collection of data. The sampling technique of this study was multi stage random sampling for selecting Division and District of Bangladesh respectively and purposive sampling for selecting the respondents. A pilot study was also conducted by the researcher before going to the final study.

4.1 Research Findings

From the interviews a number of key themes have been derived. In this study the researcher has conducted eight interviews with the eight participants those are working in four different Deputy Commissioners' office in Bangladesh. Before conducting final interview, the researcher also conducted a pilot interview to understand how the interview questions work to fulfil the aims and objectives of this study and then he decided to proceed on and conducted final interviews.

A number of key themes have been developed by the researcher for the purpose of presenting the results of this study and the key themes of this research have been developed under the consideration of research objectives and from the common codes of the answers of the interviewees. There are fifteen key themes have been developed in this study which are as follows:

1. Increased efficiency, transparency and accountability
2. Improved customer satisfaction
3. Reducing corruption
4. Saving time, cost and visit
5. Prompt delivery of services
6. Improve quality of decision making
7. Breaking long bureaucratic system
8. Citizen centric service
9. Building trust
10. Easy access and monitoring
11. Incapacity of rural people to use ICT
12. Intervention of middlemen
13. Lack of knowledge and skills of the employees
14. Lack of infrastructure facilities
15. Attitudinal problem

The following table shows the linking of key themes with the related interviewees with percentage of respondents:

Sl. No	Key themes	Serial no. of related interviewees from where the themes derived	Total no. of interviewees	Percentage
1	Increased efficiency, transparency and accountability	1,2,4,5,6,7,8	7	87.5%
2	Improved customer satisfaction	1,2,3,5,6,8	6	75%
3	Reducing corruption	1,2,5,6,7,8	6	75%
4	Saving time, cost and visit	1,2,3,4,5,7,8	7	87.5%
5	Prompt delivery of services	1,2,3,4,5,7,8	7	87.5%
6	Improve quality of decision making	1,2,3,4,6	5	62.5%
7	Breaking long bureaucratic system	1,2,3,5,6	5	62.5%
8	Citizen centric service	1,2,3,4,5,6,7	7	87.5%
9	Building trust	1,3,4,5,6	5	62.5%
10	Easy access and monitoring	1,2,4,5,7,8	6	75%
11	Incapacity of rural people to use ICT	1,2,3 ,6,7,8	6	75%
12	Intervention of middlemen	1,3,4,5,6	5	62.5%
13	Lack of knowledge and skills of the employees	1,2,4,5,6,7	6	75%
14	Lack of infrastructure facilities	1,2,3,5,6,7,8	7	87.5%
15	Attitudinal problem	1,3,4,5,6,7,8	7	87.5%

Table: Linking of key themes with related interviewees

The description of these key themes is as given below:

4.1.1 Increased efficiency, transparency and accountability

The important objectives of e-governance are to increase efficiency, transparency and accountability for the purpose of providing better service to the citizens. As NESS has applied in the means of e-governance in the Deputy Commissioner's office in Bangladesh so the main motto of NESS is to increase efficiency, transparency and accountability to deliver better public services to the citizens. In this study out of 8 participants 7 participants that means around 88% of the interviewees have given their opinion that NESS has ensured efficiency, transparency and accountability.

4.1.2 Improved customer satisfaction

Now a day's customer satisfaction is one of the major issues of service provider because every organisation wants to improve customer satisfaction by providing better service because it helps to improve the goodwill as well as improve the reputation of the organisation. To improve customer satisfaction e-governance system is a useful tool. In this study 6 participants that mean 75% of the total participants said that by applying NESS in the DC office service receivers get hassle free services that make them satisfied.

4.1.3 Reducing corruption

In developing country like Bangladesh corruption is one of the main problems in government offices. In the traditional form of service delivery, the lower-level employees and the middlemen tried to earn money in the form of bribe from the service seekers to give services. But by introducing NESS this type of corruption has been minimised because as this system is fully computerised and internet based so there is no physical meeting is required for getting a service.

Out of 8 interviewees 6 interviewees that mean 75% of the interviewees have given their arguments that in traditional form of service delivery the corrupted staffs were very much interested about the files from where they get illegal benefit rather than normal file. As a result, general people did not get their service in time and in that system, there was no effective monitoring system that ensures to keep in touch all the files by the higher authority. But in this system for effective monitoring this type of corruption has been minimised.

4.1.4 Saving time, cost and visit

One of the objectives of e-governance is to provide better services by reducing cost. Among the 8 interviewees 7 interviewees that means almost 88% of the total respondents have mentioned that as in this system people can apply through online from everywhere and can get necessary information from the websites of the concerned office so it is not mandatory and necessary to come in the office physically which has reduced their conveyance cost and as well as other process costs. They also said that in traditional system people came to office first for getting the information and procedure to get a specific service and after collecting that information they again came to office with necessary document and then applied for concerned service. But by the use of NESS it has become easier for them to collect information and to apply online which ultimately has saved the time of the applicants, reduced cost and number of visits in the government office.

4.1.5 Prompt delivery of services

The precondition of better service is to prompt delivery of services. Among the interviewees 7 interviewees that means almost 88% of the interviewees have mentioned that by introducing e-governance in the form of NESS, the Deputy Commissioner's office has abled to provide faster delivery of services. Because in this system the employees can log in from anywhere and can see the file through online and give proper decision within short time which may accelerate the file disposal system. But in traditional system if the concerned employee stayed outside from the office for official visit or other purposes then the file was hanged until the officer came back to the office.

4.1.6 Improve quality of decision making

For disposing any file timely and successfully quality of decision making is important for the employees. There are 5 interviewees out of 8 interviewees that means around 63% of the respondents have given argument that by using NESS in the DC office the quality of decision making has been improved by the employees because they can get necessary information, circular, rules and regulation from the website and can see easily the previous decision regarding the same matter which can help them to decide and give opinion quickly.

4.1.7 Breaking long bureaucratic system

There are 5 interviewees that means around 63% of the total interviewees said that in traditional system the government organisations in Bangladesh followed long bureaucratic system which took long time to process a file or service and, in that system, customers were not satisfied about the procedure of getting a service. But in the present system of service delivery that means by applying NESS the government employees can give their decision on a matter from anywhere by using internet. Although it follows the bureaucratic system but with the help of technology they can give their decision quickly.

4.1.8 Citizen centric service

Out of 8 respondents 7 respondents that mean almost 88% of the respondents have mentioned that NESS has created positive relationship between the government employees and the service recipients because one of the major objectives of NESS is to satisfy the citizens. Since people are getting timely service and government is always trying to provide better service so, certainly it is a citizen centric service system.

4.1.9 Building trust

Now a day's, it is one of the toughest tasks to build trust among the people. In this study out of 8 interviewees there are 5 interviewees that means around 63% of the total interviewees said that NESS replaced the traditional system of service delivery because of building trust and ensure customer satisfaction by giving better service in the easiest way. As this system is transparent and informative so people has accepted it from their heart.

4.1.10 Easy access and monitoring

Among the respondents there are 6 respondents that mean 75% of the total respondents said that in e-governance system access and monitoring is easier than any other system. They said that as e-governance that means NESS in the DC office is operated by ICT so, one can easily access to his/her account by login and can see the overall situations of dashboard and can give proper direction and feedback to the concerned officials about the file disposal. In addition to that customer can easily track about the position of their esteemed service or can collect necessary information easily from the website.

4.1.11 Incapacity of rural people to use ICT

Out of 8 respondents there are 6 respondents that means 75% of the total interviewees said that in the rural area of Bangladesh a considerable number of people do not know how to use computer or internet. They also said that because of poverty in Bangladesh most of the rural people have no ability to buy computer or use internet.

4.1.12 Intervention of middlemen

Among the interviewees there are 5 interviewees that mean around 63% of the respondents said that in the rural area of Bangladesh so many people are illiterate and poor and they do not know how to get a service from the DC office. As a result, they try to get help from other persons and fall into the trap of middlemen which may create some problems.

4.1.13 Lack of knowledge and skills of the employees

Out of 8 respondents there are 6 respondents that mean 75% of the interviewees said that at the initial stage the staffs in the DC office have some lacking of knowledge and skills to operate computer and internet properly. That is why on that time their performance was not up to the mark but after a certain period of time when they took training on ICT then their performance has been increased.

4.1.14 Lack of infrastructure facilities

Infrastructure is very much important to introduce a new system. In this study among the respondents there are 7 respondents that mean almost 88% of the participants said that at the very beginning they didn't have proper infrastructure facilities to implement NESS. They had shortage of computer, low speed of internet and insufficient power supply which hampered their service although it has improved now.

4.1.15 Attitudinal problem

It is human nature to show negative attitude when they found that a new system is coming up and they have to implement it. Because everybody think that they are used to the present system and it is easier to them so why they will accept a new one. In this study the same thing was happened at the initial stage. Among the respondents there are 7 respondents that means around 88% of the total respondents said that at the beginning of introducing NESS the lower-level employees showed their negative attitude about NESS.

4.2.1 Themes related with the opportunities and benefits

The following themes show the opportunities and benefits of e-governance in the form of NESS:

1. Increased efficiency, transparency and accountability
2. Improved customer satisfaction
3. Reducing corruption
4. Saving time, cost and visit
5. Prompt delivery of services
6. Improve quality of decision making

7. Breaking long bureaucratic system
8. Citizen centric service
9. Building trust
10. Easy access and monitoring

In this study the researcher has found that in implementing NESS most of the respondents said that they are getting and providing these opportunities and benefits from e-governance in the form of NESS.

If we consider these themes with the relevant literature, then we find similarities. Ndou (2004) said that there are a lot of benefits or opportunities of e-governance and these are the same in developing countries and developed countries although many potential benefits are not utilised by the developing countries because of limited use of e-governance. The opportunities that are identified by her includes cost reduction and efficiency gains, transparency, anticorruption and accountability, quality of service delivery to business and customers, improve the quality of decision making, increase the capacity of government, network and community creation, promote use of ICT in other sectors of the society.

Gronlund (2002) said that providing service through citizen-centric approach government can able to increase trust, transparency and accountability from the view of citizens and in this approach, government thinks about the process of service delivery through citizens' view point rather than operational or any other means.

In this study most of the respondents said that by introducing NESS in the form of e-governance they are getting more benefit comparing with traditional system which has increased their efficiency, transparency and accountability, and improved the quality of decision making. So, the findings of this study are very much similar with the findings of Ndou (2004) and Gronlund (2002).

Another researcher Backus (2001) said that e-governance creates a link between the government and citizens for the purpose of ensuring better and efficient delivery of public services and it helps citizens to get more benefit from it. In the component of government to citizen government provides one-stop, on-line access to information and services to the citizens. It also helps to increase the availability and openness of getting public services and try to improve the quality of public services. The primary objective of this activity is to create friendly environment between the government and citizens regarding delivery of public services.

Heeks (2001) said that e-service helps to improve the communications with the citizens by talking to citizens and listening to citizens. It also helps to improve the delivery of public services regarding with quality, convenience and cost.

Field et al. (2004) said that for providing better services to the citizens e-service can play a crucial role that increase customer satisfaction, building trust and ensure competitive success for the organisations.

Mehra (2004) argued that citizen-centric approach helps government to be efficient for the purpose of providing better service to the citizens that creates citizen satisfaction and improve the quality of life for getting government services.

In this study most of the respondents said that NESS has provided all these opportunities to the citizens and now the citizens are getting quick services which can save their time, cost and visit and as a result they become more satisfied. This also has created a trust between government and citizens. So, the findings of Backus (2001), Heeks (2001), Field et al. (2004) and Mehra (2004) are very much similar with the findings of this study.

4.2.2 Themes related with the challenges and risks

The following key themes show the challenges and risks of e-governance in the form of NESS:

1. Incapacity of rural people to use ICT
2. Intervention of middlemen
3. Lack of knowledge and skills of the employees
4. Lack of infrastructure facilities

5. Attitudinal problem

The findings of the study show that at the initial stage most of the lower-level employees have negative attitude about NESS because of their lacking of knowledge on ICT and there was also some lacking of infrastructure facilities. The respondents also mentioned some critical aspects in the rural area of Bangladesh including incapacity of rural people to use ICT and intervention of middlemen that may hamper the aim of NESS.

Ndou (2004) said that the main challenges of development and implementation of e-governance are ICT infrastructure, computer literacy, resistance to change etc.

Hanna (2010 cited by Kettani and Moulin 2014) identified a number of risks of e-governance which includes attitudinal positions of public officials with respect to ICT, organisational practices, lack of managerial strengths, participatory approaches implemented poorly etc.

Alshehri and Drew (2010) also mentioned these types of risks of e-governance which includes lack of skilled personnel, ICT infrastructure, resistance to change, financial barriers etc.

Ciborra (2005) said that developing countries are not ready to treat the citizens as customers but in these countries the citizens of privileged areas may have access to the service more easily and in the form of bribery or favouritism corruption may be continued and offered to new intermediaries.

Basu (2004) said that despite of the availability of infrastructure in developing countries many people do not have any access to IT because of a large gap between educated people who have the ability to use technology and the uneducated poor people who do not have any ability to use technology.

In this study most of the respondents said that at the initial stage in implementing NESS they faced some problems which includes with the lacking of knowledge and skills of employees and infrastructure facilities and negative attitudes of the lower level employees and still now they are facing some challenges in the rural area which includes incapacity of rural people to use ICT and intervention of middlemen and these challenges and risks are very much similar with the findings of Ndou (2004), Hanna (2010), Alshehri and Drew (2010), Ciborra (2005) and Basu (2004).

5.1 Outcomes and results

From the findings it has been found that National E-Service System (NESS) is playing a positive role in delivering better services to the citizens comparing with the traditional system. Because in this study most of the respondents said that NESS has provided a number of benefits to the citizens as well as the government. The most common benefits that are provided by NESS includes: increasing efficiency, transparency and accountability, improving customer satisfaction, reducing corruption, saving time, cost and visit, ensuring prompt delivery of services, improving quality of decision making, breaking long bureaucratic system and building trust with the citizen. If we consider these benefits with the objectives of e-governance, it is said that it ensures better services to the citizens effectively.

Although there were some challenges found in this study at the beginning of implementation of NESS which includes lack of knowledge and skills of the employees, lack of infrastructure facilities, negative attitude of the employees etc. but the government is trying to minimise these problems. In this study the respondents also mentioned some problems in the rural areas that considered as barriers for the service receivers in getting service by NESS which are incapacity to rural people to use ICT and intervention of middlemen.

The respondents mentioned some suggestions to implement NESS effectively. These suggestions are- to develop infrastructure facilities, to arrange ICT training regularly, taking necessary steps based on the feedback, to give recognition for performance etc. They said that if the government takes proper measures, then NESS will function smoothly.

But the overall findings show that NESS has a positive and significant impact to provide better services to the citizens and by NESS citizens are getting prompt services considering with traditional system.

5.2 Recommendations for practitioners

From this study the researcher has found some suggestions from the respondents to implement NESS as well as e-governance effectively specially in the public sector and if the practitioners consider these suggestions, then it will help them to get proper outcome from e-governance. The recommendations for practitioners are as given below:

5.2.1 To develop infrastructure facilities
For the purpose of proper implementation of e-governance it is necessary to develop infrastructure facilities. Without the development of infrastructure, it is difficult to get satisfactory outcome from e-governance. So, the practitioners should consider the development of infrastructure so that they can implement e-governance properly.

5.2.2 To arrange ICT training regularly
As e-governance is run by information and communication technology so it is necessary to know ICT for all level of employees so that they can handle ICT properly. For this purpose, regular training on ICT should be arranged and provided by the management to the employees and the practitioners should consider this to run e-governance effectively.

5.2.3 Taking necessary steps based on the feedback
It is necessary to collect time to time feedback from the service providers and service receivers for taking corrective measures considering on feedback. If the practitioners follow this, then it will help them to take necessary steps and to ensure better performance of e-governance.

5.2.4 To introduce recognition system for better performance
Everybody wants recognition for his performance and it is also a motivational tool to satisfy an employee to make committed to his job. If the practitioners introduce recognition system for the best performer in their organisation, then it will be easier for them to make committed of the employees and as well as to implement e-governance effectively.

5.2.5 Rules and regulations should be revised and updated
Every country has some rules and regulations on ICT and for the proper implementation of e-governance it is necessary to update these rules and regulations time to time. So, the practitioners should consider the rules and regulations related with ICT.

5.2.6 To take some initiatives on public awareness
Public awareness is very much important to introduce a new system. As e-governance is a new system for the developing countries so it is necessary for the practitioners to increase public awareness about this matter specially, in the rural area so that the rural people can get proper benefit from it.

5.3 Recommendations for further research
This study has some limitations so it can provide opportunities for the future researchers to conduct further research. As this study has conducted specially in the Deputy Commissioner’s office in Bangladesh to find out the impact of e-governance in the form of NESS for providing public services to the citizens so, there are a lot of scopes to conduct researches on e-governance in different organisations including public and private organisations and in different countries. In addition to that as this study has conducted by highlighting on e-services but other researches can be conducted on different areas of e-governance for example, e-administration, e-society etc. Besides these, further research can also be conducted by taking larger samples, following quantitative method and by taking respondents from the service providers and service receivers.

Conclusions
Finally, from this research it can be said that although there were some limitations at the initial stage of implementing National E-Service System (NESS) in the Deputy Commissioners’ office in Bangladesh and although the employees are still facing some barriers in the rural areas but NESS is ensuring better and prompt delivery of services to the citizens of Bangladesh considering with the traditional system of service delivery and it has a positive and significant impact of delivery of public services to the citizens.

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Variability and Trend of rainfall over Bandarban district

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Abstract

Bandarban, located in southeastern Bangladesh, is a mountainous district with complex topography that receives high amounts of rainfall due to the combined influence of the southwest monsoon from the Bay of Bengal and orographic uplift. This study investigates the long-term rainfall characteristics, variability, and trends in Bandarban using the Climate Hazards Group InfraRed Precipitation with Station Data (CHIRPS) dataset for 1981–2025. Results show a strongly seasonal rainfall regime, with the monsoon contributing 76.3% of the annual rainfall and an average annual rainfall of approximately 3,120 mm. Light rainfall events account for nearly 50% of all events, whereas heavy rainfall events (≥44 mm day^{-1}) comprise only 5.2% but pose significant risks of flash floods and landslides. Trend analysis indicates increasing rainfall during the monsoon and pre-monsoon seasons, although these trends are not statistically significant. In contrast, the Precipitation Concentration Index (PCI) exhibits a statistically significant increasing trend, indicating that rainfall is becoming more concentrated into fewer, more intense events. Despite this, near-normal rainfall conditions dominate approximately 70% of the study period, with extreme wet and dry years occurring infrequently. Comparison of 2001–2025 with the 1981–2000 baselines further reveal increases in mean rainfall and the frequency of extreme precipitation events, highlighting the growing influence of climate change on rainfall patterns in Bandarban.

Keywords: Rainfall, Monsson, PCI, Variability, Bangladesh.

1. Introduction

Rainfall is one of the most important climatic variables influencing the hydrological cycle, agricultural productivity, ecosystem sustainability, and socio-economic development. Variations in rainfall distribution, intensity, frequency, and duration directly affect water resources, food production, flood occurrence, drought conditions, and environmental stability. In recent decades, climate change has significantly altered rainfall characteristics across many regions of the world, resulting in increased hydro meteorological extremes and growing concerns regarding water security and disaster risk management (IPCC, 2023).

Bangladesh, located in the tropical monsoon region of South Asia. Bangladesh receives approximately 70-80% of its annual rainfall during the southwest monsoon season from June to September. The country's climate and economy are highly dependent on rainfall because agriculture, fisheries, and water resources are closely linked to seasonal precipitation patterns. However, changes in rainfall behavior have become increasingly evident in recent decades, with many regions experiencing shifts in rainfall intensity, timing, and variability. These changes have raised concerns regarding flood hazards, drought occurrence, crop production, and climate resilience (Shahid, 2010; Upal, 2020).

The southeastern part of Bangladesh, particularly the Chattogram Region, exhibits unique climatic and geographical characteristics. The region includes Chattogram, Cox's Bazar, Rangamati, Bandarban, and Khagrachhari districts and is characterized by complex topography consisting of coastal plains, hilly terrain, dense forests, and river networks. The Chattogram Hill Tracts (CHT), including Rangamati and Bandarban, receive some of the highest rainfall amounts in Bangladesh due to strong monsoonal influences from the Bay of Bengal and orographic lifting caused by the hill ranges. These factors contribute to substantial spatial and temporal variability in rainfall patterns across the region.

Rainfall variability in Bandarban has become an important research topic because of the increasing occurrence of climate-related hazards such as flash floods, landslides, soil erosion, riverbank instability, and waterlogging. The steep slopes, fragile geological formations, and intense monsoon precipitation make these districts particularly vulnerable to hydro-meteorological disasters. Heavy rainfall events frequently trigger landslides, resulting in significant loss of life, infrastructure damage, and environmental degradation. Studies conducted in the Chattogram Hill Tracts indicate that excessive rainfall is one of the primary triggering factors for landslide occurrence, especially in areas characterized by weak sedimentary rocks and deforested hill slopes.

Several studies have investigated rainfall variability and trends in Bangladesh. Shahid (2010) reported significant spatial variability in rainfall distribution across the country and highlighted the influence of climate change on rainfall patterns. Similarly, Upal (2020) analyzed rainfall data from 27 meteorological stations across Bangladesh and found that although many parts of the country exhibited declining annual and seasonal rainfall trends, southeastern Bangladesh showed increasing rainfall tendencies compared with other regions. This finding suggests that the Chattogram Region may be responding differently to changing climatic conditions due to its geographical location and topographic influences.

Recent research focusing specifically on southeastern Bangladesh has revealed notable changes in rainfall behavior. Rahman et al. (2025) analyzed annual maximum rainfall records from nine stations in the Chattogram Region during 1988–2023 using Mann–Kendall and Modified Mann–Kendall trend tests. Their study identified considerable spatial variability in rainfall trends, with several hilly stations showing decreasing annual maximum rainfall while some lowland stations exhibited increasing tendencies. The study emphasized that rainfall variability in the region is strongly associated with flood and landslide risks and highlighted the need for localized climate assessments.

The Chattogram Hill Tracts have experienced several devastating rainfall-induced disasters in recent years. Intense monsoon rainfall frequently causes flash floods and landslides in Rangamati and Bandarban. For example, severe monsoon rainfall events in southeastern Bangladesh have repeatedly triggered landslides and flooding, resulting in casualties, displacement, and infrastructure damage. Recent assessments indicate that heavy rainfall combined with unstable hill slopes significantly increases disaster vulnerability in these districts.

Fig. 6: Location of Bandarban district in Bangladesh

Climate model projections further indicate that rainfall extremes are likely to intensify across Bangladesh under future warming scenarios. Recent downscaling studies suggest that southeastern Bangladesh may experience substantial increases in extreme rainfall intensity during the twenty-first century. Projections indicate that the magnitude of extreme daily rainfall events could increase considerably by mid-century and late-century periods, thereby increasing the risks of flash floods, landslides, and water-related disasters in the Chattogram Hill Tracts.

Despite the growing number of studies on climate variability in Bangladesh, detailed investigations focusing specifically on long-term rainfall variability in Bandarban remain limited. Most existing studies have concentrated on national-scale rainfall trends or broader regional assessments without adequately addressing the unique climatic characteristics of the hilly southeastern region. Furthermore, comprehensive analyses integrating historical rainfall variability, extreme rainfall events, spatial distribution patterns, and future climate projections are still relatively scarce. Therefore, a detailed study of rainfall variability in Bandarban is necessary to improve understanding of regional hydro-climatic changes and support climate adaptation, disaster risk reduction, water resource management, and sustainable development planning. Attempt has therefore made to investigate the rainfall variability and its trend of Bandarban district.

The findings of such research would contribute significantly to understanding the impacts of climate change on rainfall dynamics in the Chattogram Hill Tracts and provide scientific evidence for policymakers, planners, and disaster management authorities in developing climate-resilient strategies for the region.

2. Methodology

2.1 Rainfall Data Processing

Daily precipitation data for the period 1981–2025 has been obtained from the Climate Hazards Group InfraRed Precipitation with Station Data (CHIRPS) dataset, which provides rainfall estimates at a spatial resolution of 0.05° (~5 km). CHIRPS combines satellite-based infrared precipitation estimates with in-situ rain gauge observations to produce a long-term, high-resolution rainfall dataset suitable for climatological, hydrological, and climate change studies, particularly in regions with sparse meteorological observations (Funk et al., 2015).

The analysis is conducted for Bandarban District (Fig:1), Bangladesh. The administrative boundary of Bandarban is extracted from the GADM Administrative Level-2 boundary dataset and used as the spatial mask for rainfall extraction. Prior to the analysis, the coordinate reference system (CRS) of the district boundary has been verified and matched with that of the CHIRPS raster data to ensure accurate spatial alignment and overlay. Daily CHIRPS rainfall data (netCDF form) files are processed using the terra package in R. Each raster layer represents the accumulated precipitation for one day. The Bandarban district polygon was overlaid on the CHIRPS grids, and precipitation values from all grid cells intersecting the district are extracted for each daily raster. The extracted pixel values are subsequently used to derive district-scale rainfall statistics representative of the entire study area. The sum of rainfall from all intersecting grid cells, representing the spatially accumulated rainfall over the district has been defined as the total rainfall (mm day^{-1}).

To assess changes in rainfall characteristics between the baseline period (1981–2000) and the recent period (2001–2025), several rainfall indices were derived from the daily rainfall data. Daily rainfall refers to the total precipitation accumulated during a 24-hour period at a given location. In this study, daily rainfall amounts (P_d, mm day^{-1}) were obtained from the CHIRPS dataset and used as the primary variable for all subsequent analyses. Daily rainfall values (P_d, mm/day) were aggregated to monthly and annual totals. Monthly rainfall was calculated as:

$$P_m = \sum_{d=1}^{n} P_d \quad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where P_d is daily rainfall and n is the number of days in a month.

Annual rainfall (AR) was calculated as the sum of daily rainfall amounts within a calendar year:

$$AR = \sum_{d=1}^{N} P_d \quad \ldots\ldots\ldots\ldots\ldots (2)$$

where P_d is the daily rainfall amount (mm) and N is the total number of days in a year. Annual rainfall represents the total precipitation received during a year and is expressed in millimeters (mm). Long-term trends in annual rainfall were evaluated using the non-parametric Mann–Kendall trend test and Sen's slope estimator.

2.1 Rainy-Day Frequency

Rainy-day frequency (RDF) was defined as the number of days within a year with measurable rainfall equal to or greater than 1 mm:

$$RDF = \sum_{d=1}^{N} I\,(P_d \geq 1) \quad \ldots\ldots\ldots\ldots (3)$$

where I is an indicator function that equals 1 when daily rainfall is at least 1 mm and 0 otherwise. This index provides a measure of rainfall occurrence and frequency.

2.2 Wet-Day Intensity

Wet-day intensity (WDI) represents the average rainfall amount on rainy days and was calculated as:

$$WDI = \frac{\sum_{d=1}^{N} P_d}{RDF} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

Where, P_d is the daily rainfall amount on wet days (≥1 mm) and RDF is the annual number of wet days. This index is equivalent to the mean precipitation per wet day and is expressed in mm/day. It is conceptually similar to the Simple Daily Intensity Index (SDII) recommended by the Expert Team on Climate Change Detection and Indices.

2.3 Wet-Day Rainfall Distribution

Wet-day rainfall distribution describes the statistical distribution of rainfall amounts occurring on wet days (≥1 mm). For each climate period, descriptive statistics including the mean, median, standard deviation, minimum, maximum, 95th percentile (P95), and 99th percentile (P99) were calculated from all wet-day rainfall data. This analysis characterizes the variability and intensity spectrum of rainfall events and facilitates the assessment of changes in moderate and extreme precipitation.

2.4 Climate Period Comparison

To evaluate changes in rainfall characteristics, all indices were computed separately for two climate periods: 1981–2000 and 2001–2025. Differences between the periods were assessed using boxplots and non-parametric statistical tests. Summary statistics including the mean, median, standard deviation, minimum, maximum, P95, and P99 were calculated for each rainfall index to quantify changes in rainfall totals, frequency, intensity, and extremes.

2.5 Monthly Rainfall Climatology

The long-term monthly climatology was calculated using the arithmetic mean of monthly rainfall totals over the study period:

$$\overline{P_m} = \frac{1}{N}\sum_{i=1}^{N} P_{m,i} \quad \ldots\ldots\ldots\ldots\ldots (5)$$

where: $P_{m,i}$ is rainfall in month m in year i and N is the total number of years.
The standard deviation (SD) was also calculated to quantify interannual variability:

$$SD = \sqrt{\frac{\sum\left(P_{m,i}-\overline{P_m}\right)^2}{N-1}} \quad \ldots\ldots\ldots\ldots\ldots (6)$$

2.6 Annual Rainfall Trend Analysis

Long-term trends in annual rainfall were assessed using the non-parametric Mann–Kendall (MK) trend test (Mann, 1945; Kendall, 1975), which is widely used in hydro-climatological studies because it does not require data normality
The Mann–Kendall statistic is defined as:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sgn\left(x_j - x_i\right) \quad \ldots\ldots\ldots\ldots (7)$$

Where, $sgn\left(x_j - x_i\right) = \begin{cases} 1, & x_j > x_i \\ 0, & x_j = x_i \\ -1, & x_j < x_i \end{cases}$

The median of all pairwise slopes provides the overall trend magnitude. A positive value indicates an increasing trend, whereas a negative value indicates a decreasing trend.

Sen's Slope

The magnitude of trend was estimated using Sen's slope:

$$Q_i = \frac{x_j - x_i}{j-i} \quad \ldots\ldots\ldots\ldots\ldots (8)$$

The median of all Q_i values represents the trend magnitude.

2.7 Annual Rainfall Anomaly

Annual rainfall anomalies were calculated relative to the long-term mean annual rainfall:

$$A_i = P_i - \bar{P} \quad \ldots\ldots\ldots\ldots\ldots (9)$$

Where, A_i is annual rainfall anomaly, P_i is annual rainfall in year i, and $\bar{P}$ is the long-term mean annual rainfall. Positive anomalies indicate wetter-than-normal years, while negative anomalies indicate drier-than-normal years.

2.8 Precipitation Concentration Index (PCI)

The Precipitation Concentration Index (PCI) is a widely used statistical indicator developed by Oliver (1980) to quantify the temporal distribution and concentration of rainfall within a year. PCI provides information on rainfall seasonality and the degree to which annual precipitation is concentrated in a few months. It is particularly useful for assessing rainfall variability, drought susceptibility, flood potential, soil erosion risk, and climate change impacts on precipitation patterns. The Precipitation Concentration Index (PCI) was employed to assess the temporal concentration of rainfall within a year following Oliver (1980):

$$PCI = \frac{\sum_{i=1}^{12} P_i^2}{\left(\sum_{i=1}^{12} P_i\right)^2} \times 100 \quad \ldots\ldots\ldots\ldots\ldots (10)$$

Where, P_i = precipitation of month (mm) and $\sum P_i$= annual precipitation (mm). PCI values were interpreted according to Oliver (1980) as:

Sl	PCI	Interpretation
i.	<10	Uniform rainfall distribution
ii.	11–15	Moderate concentration
iii.	16–20	Irregular distribution
iv.	>20	Strong irregularity

Higher PCI values indicate rainfall concentrated in fewer months, while lower values indicate a more uniform annual distribution.

2.9 Standardized Precipitation Index (SPI)

Meteorological drought conditions were evaluated using the Standardized Precipitation Index (SPI), originally proposed by Thomas B. McKee and colleagues (McKee et al., 1993). SPI is recommended by the World Meteorological Organization as a standard drought monitoring indicator. Monthly precipitation totals were fitted to a Gamma probability distribution and subsequently transformed into a standard normal distribution:

$$SPI = \frac{X-\mu}{\sigma} \ldots\ldots\ldots\ldots\ldots (11)$$

Where, X is precipitation, μ is mean precipitation, and σ is standard deviation.

SPI values were calculated at three accumulation periods:

- SPI-1, Represents short-term meteorological drought conditions at the monthly scale.
- SPI-3, Represents seasonal drought conditions and short-term water availability.
- SPI-12, Represents long-term hydrological and climatological drought conditions.

2.9.1 SPI Classification

Drought and wetness conditions were classified according to standard SPI categories.

Sl No	SPI Value	Category
i.	≥ 2.0	Extremely Wet
ii.	1.5 to 1.99	Severely Wet
iii.	1.0 to 1.49	Moderately Wet
iv.	-0.99 to 0.99	Near Normal
v.	-1.0 to -1.49	Moderately Dry
vi.	-1.5 to -1.99	Severely Dry
vii.	≤ -2.0	Extremely Dry

2.9.2 SPI Heatmap Analysis

A heatmap of SPI-12 values was generated to visualize the temporal evolution of wet and dry conditions. Positive SPI values indicate wetter-than-normal conditions, whereas negative SPI values indicate drought conditions. The heatmap facilitates identification of prolonged drought episodes and wet periods over the study period.

3. Analysis

3.1 Variability of daily rainfall in Bandarban district

Based on the daily total amounts of rainfall over the district area of Bandarban, rainfall has been categorized as- no rain, light rain, moderate rain, moderately heavy rain, heavy rain, very heavy rain and extreme rain and these are defined for advantage as Cat-I, Cat-II, Cat-III, Cat-IV, Cat-V, Cat-VI and Cat-VII respectively. Analysis reveals that most dominating of about 50% of the total rainfall events are in Cat-I. About 12.5% rain events are heavy category and among these events Cat-V, Cat-VI and Cat-VII events are of 4.0%, 1.1% and 0.1% respectively. The relevant other information is given in Table 1. More detailed rainfall distribution of Bandarban district is given in the Fig. 2.

Table 1: Categorization of daily rainfall in Bandarban district

Category	Rainfall Scale (mm)	Number of rainfall events	Percentage (%)
No rain (Cat-I)	<1	8207	49.9
Light rain (Cat-II)	1-10	4524	27.5
Moderate rain (Cat-III)	11-22	1646	10.0
Moderately Heavy rain (Cat-IV)	23-43	1207	7.3
Heavy rain (Cat-V)	44-88	650	4.0
Very heavy rain (Cat-VI)	89-149	179	1.1
Extreme rain (Cat-VII)	>=150	23	0.1

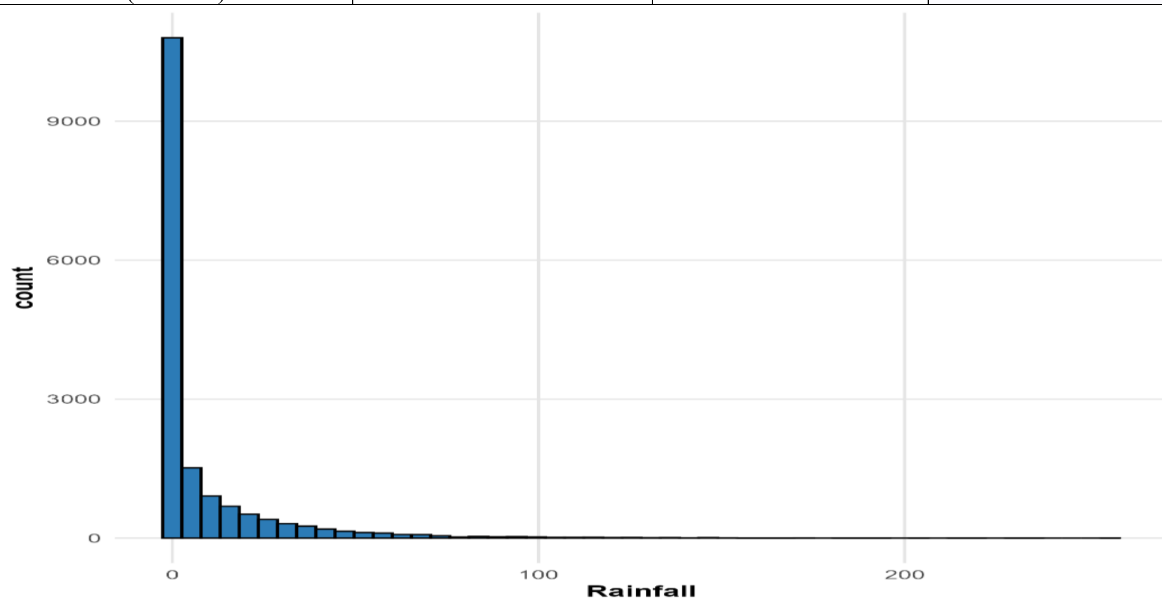

Fig. 2: Histogram of the daily rainfall of Bandarban district during 1981-2025.

3.2 Variability of Monthly rainfall

The amounts of monthly rainfall in Bandarban district are notable from April to October. It is higher in the monsoon months with the highest in July, followed by June and August. Rainfall in other months is lower and is the lowest in January (Fig. 3) As a follow up of this, the standard deviation (SD) is the highest in July, followed by August and June, but lowest in January. The coefficient of variations (CVs) is higher in winter (December, January and February) and pre-monsoon (March, April and May) and post-monsoon (October and November) months, and lower in the monsoon months (June, July, August and September). It is the lowest in June during the observed period of 1981-2025 (Table 2).

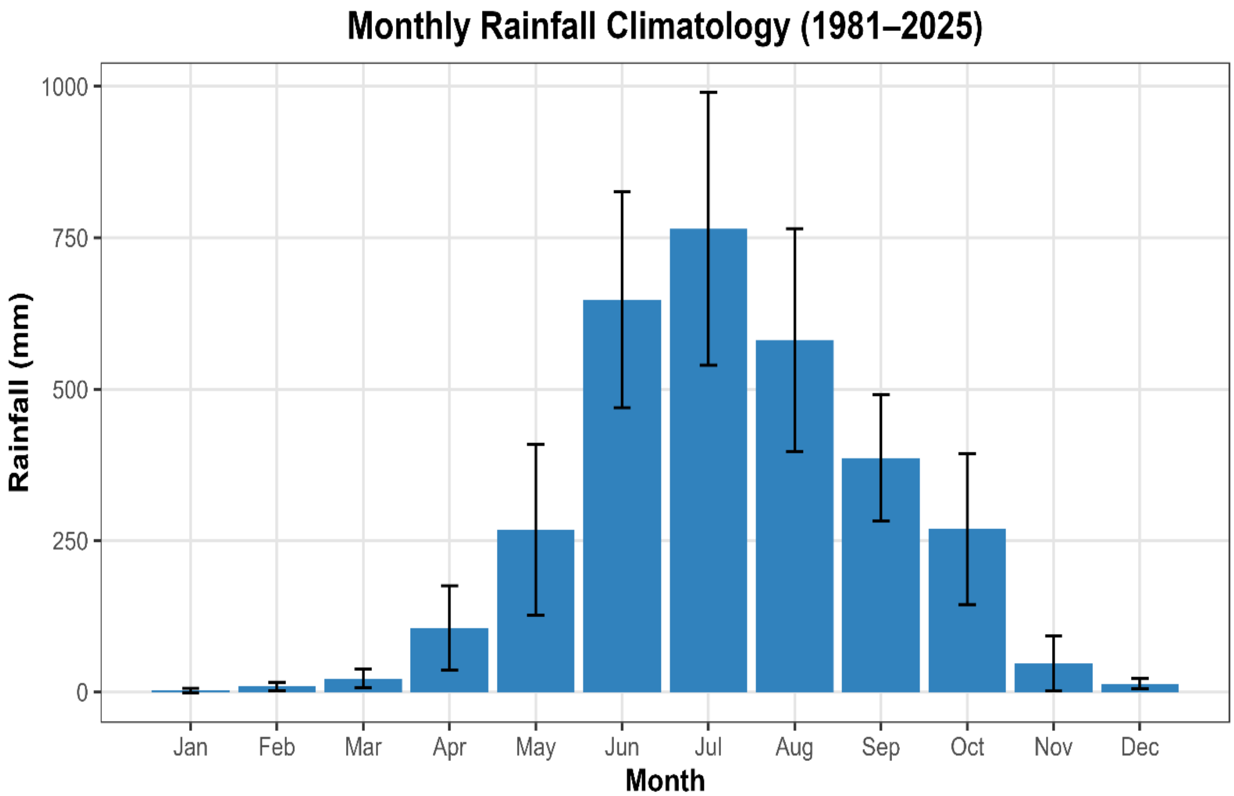

Fig. 3: Monthly distribution of rainfall in Bandarban district during 1981-2025

Table 2: Mean monthly rainfall, SD and CV of Bandarban district

Month	Mean Rainfall (mm)	Standard Deviation (SD) in mm	Coefficient of Variation (CV) mm
January	2.7	3.8	141
February	9.5	7	73.3
March	22.5	15.6	69.1
April	105.9	69.7	65.8
May	268.2	141.1	52.6
June	647.7	178.1	27.5
July	764.9	225.1	29.4
August	581.3	183.9	31.6
September	386.8	104.2	26.9
October	269.1	124.4	46.2
November	47.3	45.5	96.3
December	13.9	8.4	60.6

3.3 Variability of Seasonal rainfall

As an agricultural district seasonal amounts of rainfall, its distribution and variation is very important. Monsoon is the dominating season for rainfall is highly necessary for rice production but rainfall in other seasons is essential for growing vegetables and other crops in the districts. Analysis reveals that the dominating rainfall season is the monsoon, which has been embedded by two seasons with considerable rainfall amounts on pre-monsoon and post monsoon (Fig. 4). Average amounts of rainfall in monsoon, post-monsoon, pre-monsoon and winter seasons during the observed period are 2380.7, 316.4, 396.7 and 25.5 mm respectively (Table 3), which are respectively 76.3%, 10.1%, 12.7% and 0.8% of the annual average rainfall.

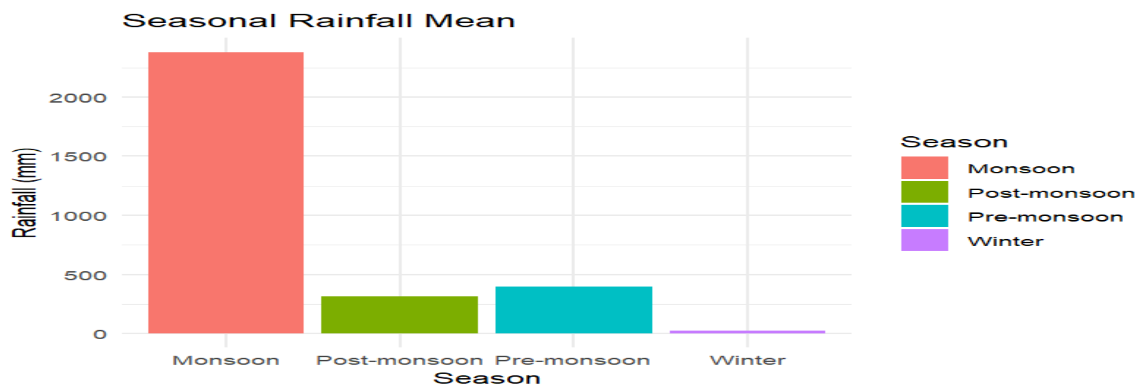

Fig. 4: Seasonal distribution of rainfall in Bandarban district

A rank-based correlation coefficient of Mann–Kendall test values are positive, i.e., increasing trends for both monsoon and post-monsoon seasons but negative for other two seasons (Table 3). P-vales for all of the seasons are greater than 0.05, is the indication of no significant trends in the seasons. Again, the rainfall trends for monsoon and post-monsoon seasons are positive with the magnitudes of 5.66 mm/year and 1.24 mm/year respectively. On the other hand, the trends of pre-monsoon and winter seasons are negative, with the magnitudes of -1.02 mm/year and 0.22 mm/year (Table 3 and Fig. 5).

Table 3: Mean seasonal rainfall, SD and CV, Mann Kendall Trends of Bandarban district

Season	Mean rainfall (mm)	Standard Deviation (SD)	Coefficient of Variation (CV)	Kendall's tau (MK tau)	p-value (MK-p)	Trends (Sen slope)
Monsoon	2380.7	336.7	14.1	0.15	0.14	5.66
Post-monsoon	316.4	138.3	43.7	0.07	0.5	1.24
Pre-monsoon	396.7	146.9	37	-0.04	0.72	-1.02
Winter	25.5	11.5	45.1	-0.17	0.11	-0.22
Annual	3119.8	391.0	12.5	0.15	0.14	7.92

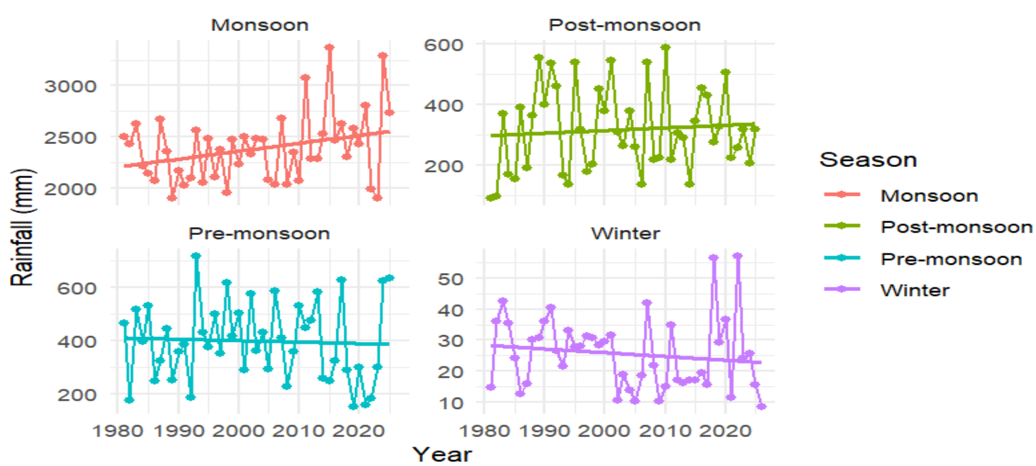

Fig. 5: Trends of rainfall in different seasons in Bandarban district

3.4 Variability of Annual rainfall

Annual amount of rainfall in Bandarban district is highly varying in nature (Fig. 6). The average rainfall in this district during the observed period is about 3120 mm. The STD of annual rainfall in this district is 391.0 mm and the CV is 12.5. Analysis reveals that the Kendall's tau (MK tau) value is positive and trend (Sen's Slope) is 7.92 mm and the p-value is 0.14 (Table 3).

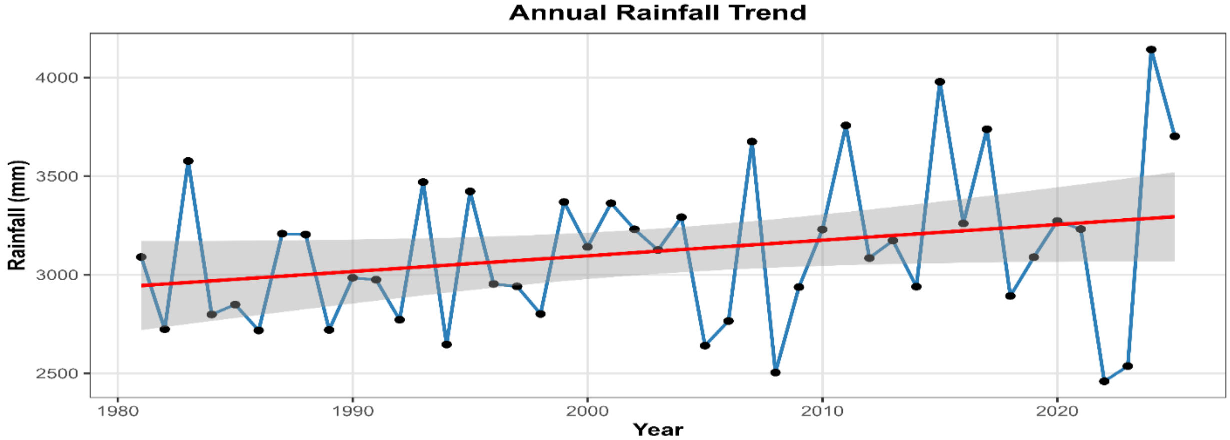

Fig. 6: Temporal variation of annual rainfall in Bandarban district

3.5 Deviation of rainfall in Bandarban district

In monsoon season maximum positive deviation (41.6%) is found in 2015 and minimum negative deviation (-20.3%) is found in 1989. During the observed period 9-seasons have positive deviation, but 31 seasons have negative deviation. Normal rainfalls are found in the remaining 31-seasons. In the recent years of 2024 the notable deviation was 38.3%. On the other hand, in the recent years of 2022 and 2023 the negative deviations of -16.6% and -20.3% were notable. Rainfall amounts were very high during the recent 20 years (Fig. 7).

In post-monsoon season the maximum positive deviation of rainfall (86.0%) is found in 2010 and minimum negative deviation (-71.6%) is found in 1981. During the observed period 17 seasons were with positive deviation and 25 seasons were with negative deviations. In the recent years of 2020 the deviation was 60.1% and in 2024 it was -34.7%. As a whole, rainfall deviations are high in this district (Fig. 8). In pre-monsoon season, the maximum positive deviation of 80.9% in 1993 and minimum deviation of -62.1% in 2019. During the observed period 17 seasons were above positive deviation and 27 seasons were with negative deviation. In the recent years of 2024 and 2025 deviations were 57.1% and 59.6%. On the other hand, the notable negative deviations in 2021 and 2022 were -59.9% and -53.9%. Negative deviations were dominating during the recent years in this district (Fig. 9).

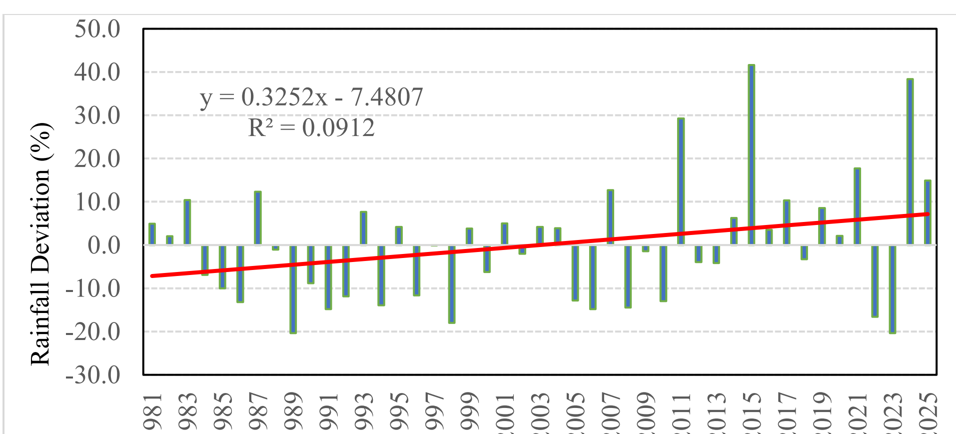

Fig. 7: Deviation of Monsoon Rainfall in Bandarban district during 1981-2025

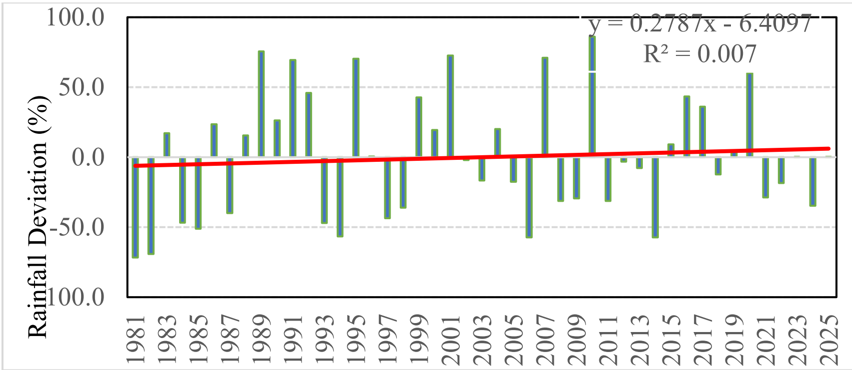

Fig. 8: Deviation of Post-monsoon Rainfall in Bandarban district during 1981-2025

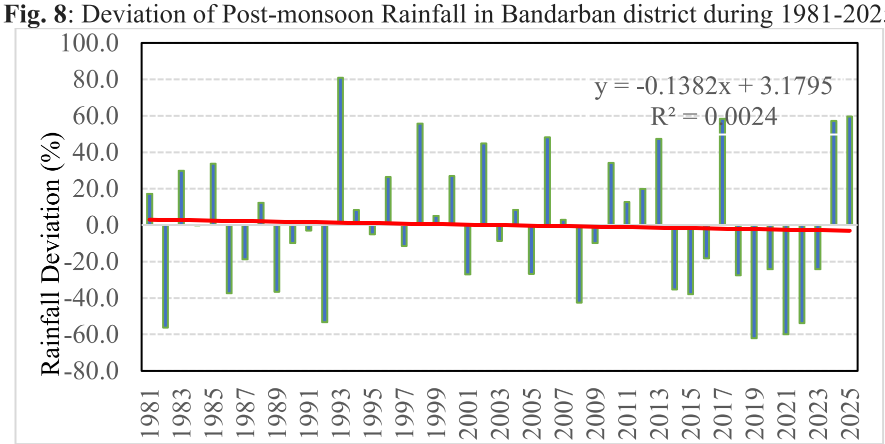

Fig. 9: Deviation of Pre-monsoon Rainfall in Bandarban district during 1981-2025

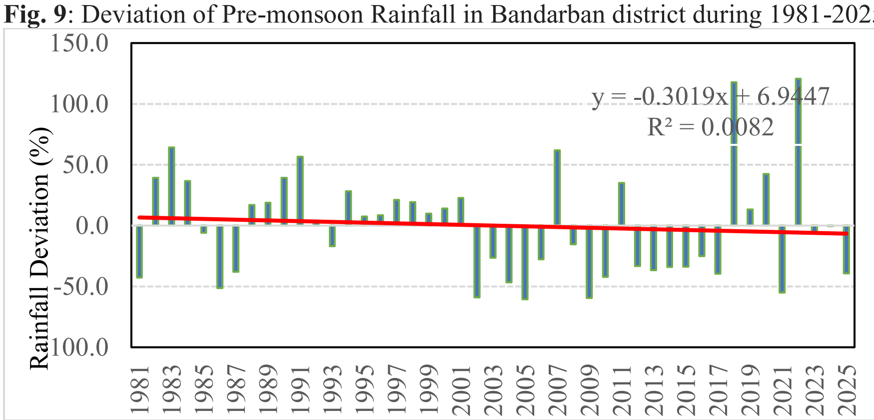

Fig. 10: Deviation of Winter Rainfall in Bandarban district during 1981-2025

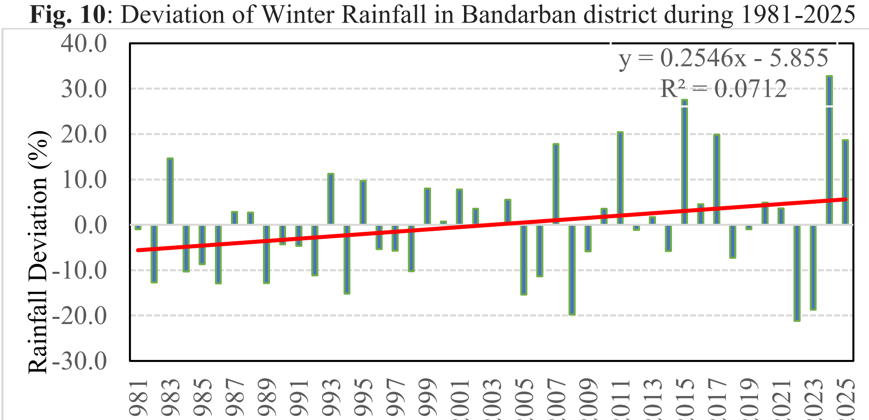

Fig. 11: Deviation of Annual Rainfall in Bandarban district during 1981-2025

In winter season, the maximum positive deviation of 120.6% in 2022 and lowest negative deviation of -60.6%. During the observed period 18 seasons were of positive deviation and 25 seasons were with negative deviation. In the recent years of 2018 the deviation was 117.8% and in 2025 it was of -39.2%. Highly rainfall deviations are quite frequent in the recent years in this district (Fig. 10). Annual rainfall of Bandarban district was highly variable in nature. During the observed period it was deviated as low as -21.2% (in 2022) and as maximum as 32.8% (in 2024). Within the observed period rainfall situation was with positive deviation in 8-years and it was negative deviation in 33 years. Highly frequent annual rainfall deviations are observed during the recent 20 years (Fig. 11), which is closely aligned with the monsoon rainfall pattern in this district.

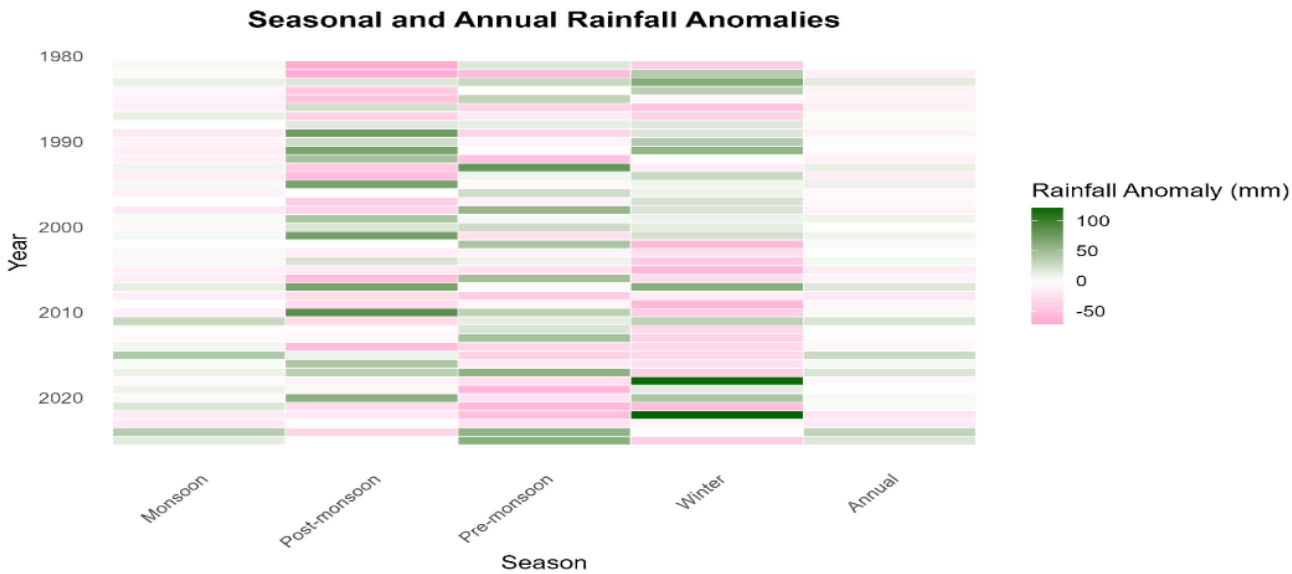

Fig. 12: Heat map displaying the deviation (%) of rainfall in Bandarban district during 1981-2025

A composite analysis of seasonal and annual rainfall deviations is depicted in the Fig. 11 and a brief summary of rainfall deviation is given in the Table 4. The number of excess rainfall instance in the monsoon, post-monsoon, pre-monsoon and winter seasons are 9, 17, 17 and 18 respectively but the number of deficit rainfall instances is 14, 20, 18 and 20. In the case of annual rainfall, the number normal rainfall is dominating, but the number of excess rainfall instances and deficit rainfall instances are in 8 years each.

Table 4: Summary of seasonal and annual rainfall in Bandarban during 1981-2025

Rainfall Status	Monsoon Season	Post-monsoon Season	Pre-monsoon Season	Winter Season	Annual
Maximum Deviation	41.6	86.0	80.9	120.6	32.8
Minimum Deviation	-20.3	-71.6	-62.1	-60.6	-21.2
Number of Excess Rainfall year	9	17	17	18	8
Number of Below Rainfall year	14	20	18	20	12
Number of Normal Rainfall year	22	8	10	7	25

3.6 Precipitation Concentration Index

Analysis of the Precipitation Concentration Index (PCI) on an annual basis reveals that rainfall over the Bandarban district is highly uneven. The distribution primarily falls into the irregular and strongly irregular categories, indicating increased susceptibility to localized floods during wet spells. According to Oliver's widely accepted Precipitation Concentration Index Classification, annual PCI values are divided into uniform (≤ 10), moderate (11–15), irregular (16–20), and strongly irregular (> 20) distributions. Over the observed period in Bandarban, the temporal distribution of rainfall deviates completely from uniform conditions. The magnitude of the annual PCI predominantly ranges between 16 and 20, signifying an irregular precipitation distribution. Historical analysis shows that rainfall is classified as irregularly distributed in 36 individual years during the observed timeframe. In several years, the PCI value exceeded 20, indicating a strongly irregular or high-concentration precipitation distribution.
Years exhibiting strongly irregular rainfall include 1982, 1987, 1997, 2003, 2014, 2016, 2019, and 2021. The clustering of these extreme metrics in recent decades highlights a shift toward more erratic climate patterns in the region. Temporal distribution analysis demonstrates a statistically significant increasing trend in the annual PCI for the Bandarban district (Fig. 13). This upward trajectory suggests that the total annual rainfall is concentrating into fewer, more intense months rather than spreading evenly across the year. The Mann-Kendall test yields a positive Kendall's Tau (τ) value. This confirms a monotonic increasing trend in precipitation concentration over Bandarban district. The computed p-value falls below the standard significance threshold ($\alpha = 0.05$), meaning the null hypothesis of "no trend" is rejected. The observed rise in rainfall irregularity is statistically significant and driven by shifting climate dynamics rather than random natural variability. Sen's Slope estimator shows a positive annual rate of change, quantifying the steady, long-term increase in the index value per year

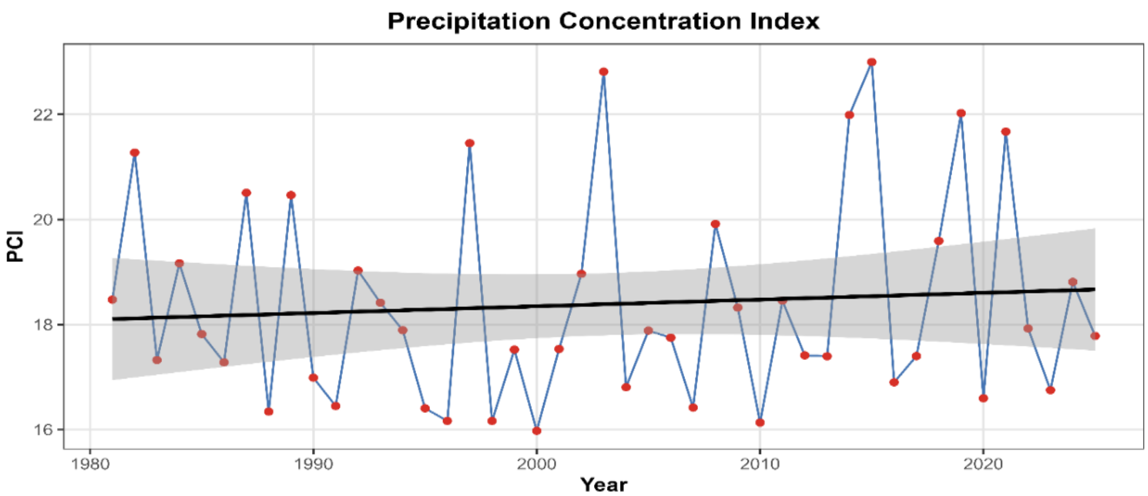

Fig. 13: Temporal variation of PCI over Bandarban district during 1981-2025

3.7 Standardized Precipitation Index

An analysis of the **Standardized Precipitation Index (SPI)** using rainfall data (1981–2025) reveals that conditions in the Bandarban district are predominantly 'Near Normal'. Severe dry and extreme conditions are statistically rare, indicating a very low risk of rainfall-related hazards. Short-term precipitation anomalies analyzed over a 3-month scale are dominated by the 'Near Normal' category, accounting for approximately (70%) of the observed period. Hazardous SPI occurrences are minimal, as follows: (i) **Extreme Wet:** ~ 2.6%, (ii) **Severe Wet:** ~ 2.2%, (iii) **Severe Dry:** ~ 5.2% and (iv) **Extreme Dry: ~1.3%.**
The long-term SPI for the region displays similar stability. The dominant category is also 'Near Normal', covering ~ 72% of the study timeframe. Significant wet and dry situations occur infrequently: (i) **Extreme Wet:** ~ 4.0%, (ii) **Severe Wet: ~ 4**.0%, (iii) **Severe Dry:** ~ 5.6% and (iv) **Extreme Dry:** ~ 0.0%.

The associated SPI heat map (Fig. 15) indicates that extreme or severe rainfall-related risks are negligible across the region. However, a closer temporal evaluation reveals that strictly "wet" situations have become less frequent in the Bandarban district in recent years.

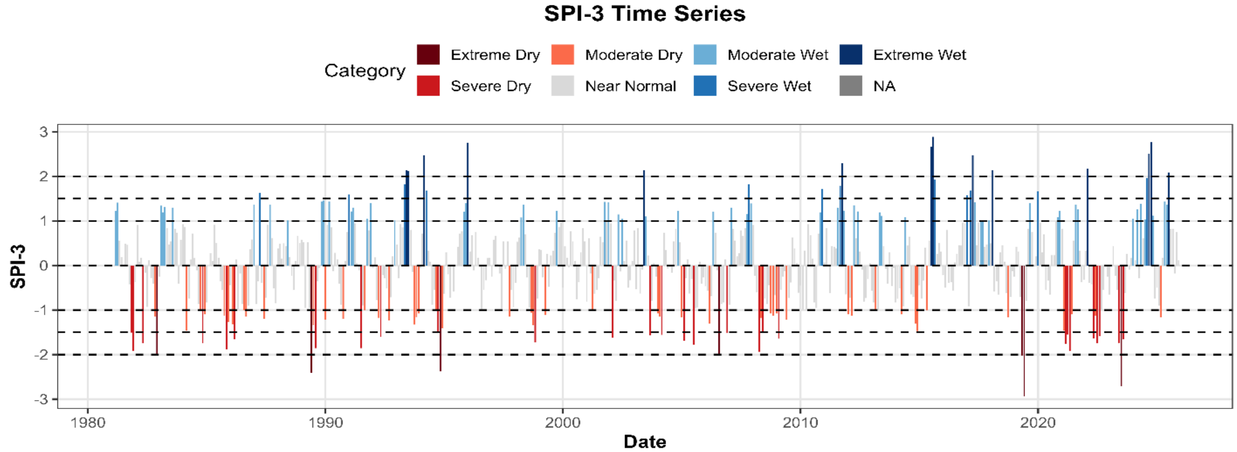

Fig. 14: Temporal variation of 3-month SPI over Bandarban district during 1981-2025

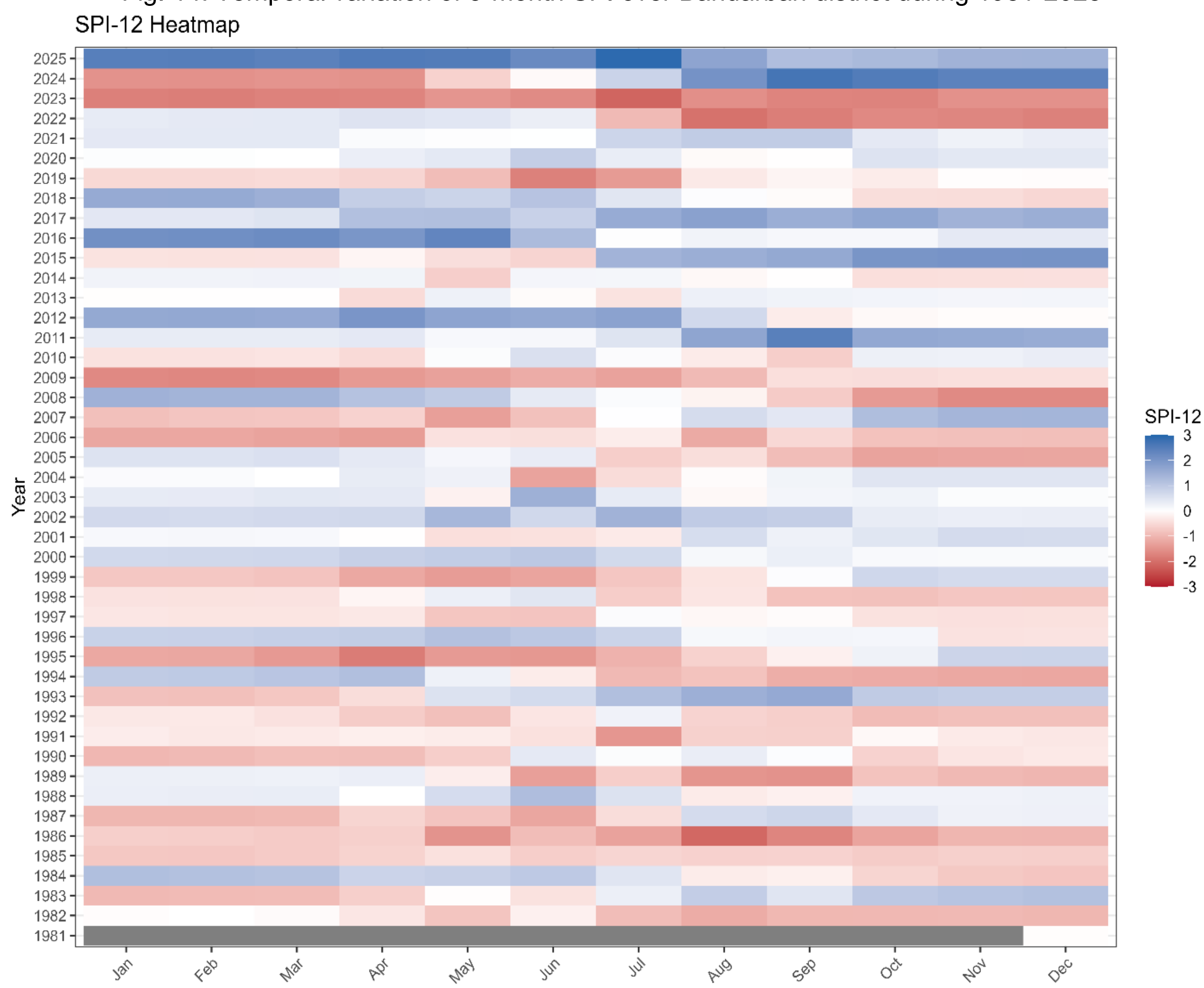

Fig. 15: Temporal variation of 12-month SPI over Bandarban district during 1981-2025

3.8 Changing behviour of rainfall

To assess the impact of climate change on precipitation, we compared rainfall distributions between two distinct periods (1981–2000 and 2001–2025) using box plots (Fig. 15). The analysis reveals that the 25th percentile, median, and 75th percentile of rainfall amounts have increased, alongside a rise in extreme precipitation events. This upward shift confirms a significant alteration in rainfall patterns during the 2001–2025 period compared to the historical 1981–2000 baseline (Table 5)

Table 5: Comparison of daily and annual rainfall conditions in two different climate periods

Conditions	Daily Rainfall (mm)		Annual Rainfall (mm)	
	1981-2000	2001-2025	1981-2000	2001-2025
Maximum	235.8	256.1	3577.1	4142.5
75th percentile	7.3	8.4	3207.4	3519.3
Median	0.0	0.1	2964.2	3229.8
25th Percentile	0.0	0.0	2778.5	2915.0
Minimum	0.0	0.0	2646.5	2459.6

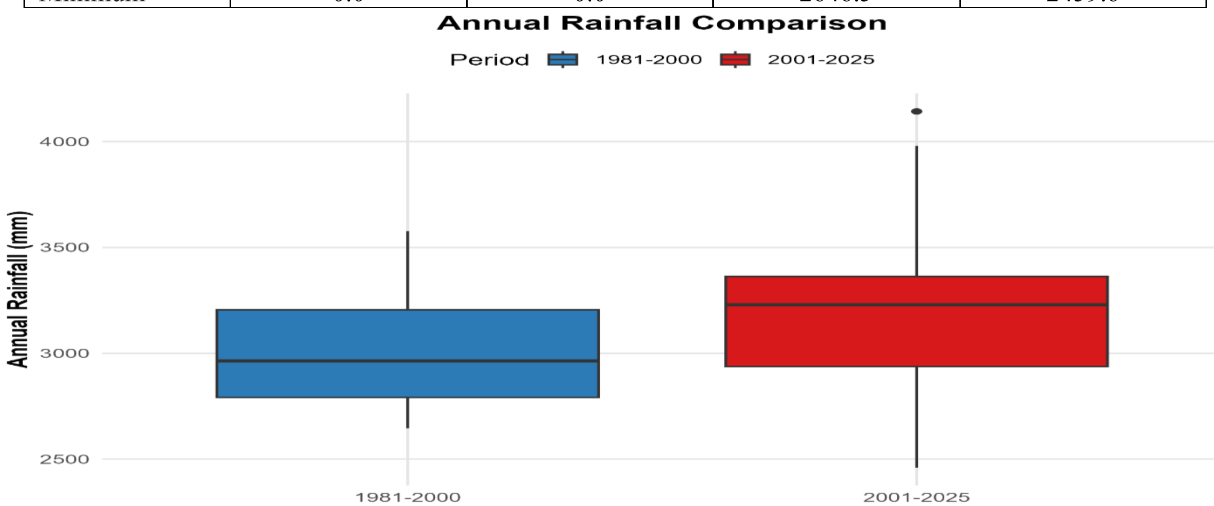

Fig. 16: Box plots of annual rainfall during 1981-2000 and 2001-2025

4. Conclusion

The rainfall in Bandarban exhibits extreme seasonal variation, while light rain (Cat-I) dominates about 50% of events. The district relies on significant monsoon precipitation for its robust agricultural cycles. Rainfall variance (coefficient of variation) is highest during winter and the transitional seasons. Rainfall events with 'Category V' are rare and above make up about 5.2% of total events, which can pose risks of localized flooding or landslides in the hilly district.

Bandarban district experiences a highly variable rainfall climate, with an average annual rainfall of approximately 3,120 mm. The monsoon season dominates the year's precipitation, while the pre-monsoon and post-monsoon periods also provide substantial rainfall. The district receives 76.3% rainfall in monsoon season, 12.7% in pre-monsoon season, 10.1% in post-monsoon season and 0.8% in winter season of annual total.

Both monsoon and pre-monsoon seasons exhibit positive rainfall trends with rate of 5.66 mm/year and 1.24 mm/year respectively. But both pre-monsoon and winter season show decreasing trends by -1.02 mm/year and -0.22 mm/year respectively. Mann–Kendall and p-value tests indicate that these seasonal trends are not statistically significant. Overall, the districts total annual rainfall fluctuates noticeably, with a standard deviation (STD) of 391 mm and a coefficient of variation (CV) of 12.5.

Rainfall in the Bandarban district is becoming increasingly erratic, with total annual rainfall concentrating into fewer, more intense months. Statistical testing confirms a steady upward trajectory in rainfall irregularity, pointing to climate change as the driver rather than natural variability. Based on Oliver's PCI Classification, Bandarban's rainfall distribution primarily falls into the irregular (16-20) to strongly irregular (>20) categories. Over the observed timeframe, 36 years experienced irregularly distributed rainfall. Strongly irregular precipitation was concentrated in recent decades, specifically in 1982, 1987, 1997, 2003, 2014, 2016, 2019, and 2021. The Mann-Kendall test estimates a statistically significant positive trend (α = 0.05), validating that the region is persistently shifting toward higher rainfall concentration.

Based on historical rainfall data (1981–2025), Bandarban district's precipitation conditions are highly stable and predominantly "Near Normal", resulting in a very low risk of rainfall-related hazards. Normal conditions cover approximately 70% of the timeframe, with extreme wet approximately 2.6%, severe wet approximately 2.2%, severe dry approximately 5.2%, and extreme dry approximately 1.3% occurrences remaining minimal. Normal rainfall conditions similarly dominate approximately 72% of the historical period, showing extremely low frequencies of significant dry or wet events. Despite the overall statistical stability, temporal analysis indicates a slight, recent decline in the frequency of strictly wet situations.

Climate change has significantly shifted rainfall patterns. Comparing the 2001–2025 period to the 1981–2000 baseline shows notable increases in average rainfall with the 25th, 50th, and 75th percentiles all rising alongside a surge in extreme precipitation events.

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