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Understanding the Meteorological Conditions Leading to Extreme 24-Hour Rainfall Events Exceeding 300 mm in Bangladesh

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Abstract

Bangladesh experiences frequent extreme rainfall events during the summer monsoon (June-October), making it one of the rainiest places on Earth. Its location under the South Asian Monsoon belt, near the Bay of Bengal, and at the foothills of the Himalayas contributes to this. The Bay of Bengal, with sea surface temperatures above 26°C year-round, further influences weather patterns, including cyclones. In recent years, the frequency and intensity of extreme rainfall in Bangladesh have increased. Since 2017, the country has seen ten events where over 300 mm of rain fell in 24 hours, causing significant loss of life and infrastructure damage. Despite this, the meteorological drivers behind these extreme events remain poorly understood. This study investigates extreme rainfall events in Bangladesh since 2010, focusing on identifying the key factors that lead to such events. Preliminary findings reveal that extreme rainfall occurs when several meteorological conditions combine, each capable of producing heavy rain. These conditions include the blocking of the subtropical Jetstream over the Indian subcontinent, stagnation of the South Asian monsoon circulation, the presence of a monsoon low-pressure system, and strong phases of the Madden-Julian Oscillation (MJO) in Phases 3 and 4. The more these factors align, the greater the likelihood of extreme rainfall. The position of the upper-level jet over the Indian subcontinent plays a significant role in determining the location of these events. These findings offer valuable insights for improving extreme rainfall forecasts in Bangladesh, helping weather forecasters provide more accurate and timely warnings.

Background

South Asian Monsoon provides essential rain for Bangladeshi subsistence farmers, whose livelihoods largely depend on rainfed agriculture; however, extreme rainfall triggers catastrophic flooding almost every year, wreaking havoc on the socioeconomic conditions of Bangladesh.

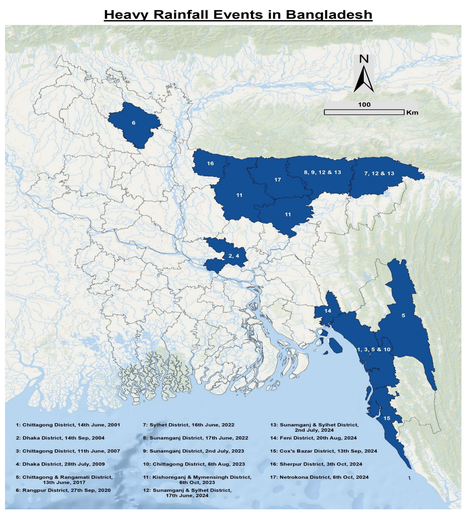


Figure 1: Spatial Distribution of the Extreme Rainfall Events over Bangladesh.

Research Objective

This study aims to conduct a comprehensive analysis of the extreme rainfall events to identify the key meteorological drivers and the physical mechanisms responsible for triggering extreme rainfall over Bangladesh. Further, we aims to identify areas susceptible to extreme rainfall risk and make policy recommendations to minimize socioeconomic vulnerabilities.

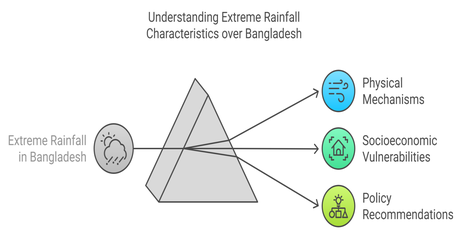


Figure 2: A comprehensive understanding of the extreme rainfall characteristics over Bangladesh.

Data and Methodology

This study analyzed hourly ERA5 re-analysis data for the 17 extreme rainfall events occurred over Bangladesh to understand the regional and large-scale dynamical and thermodynamical meteorological conditions leading to 24-Hour rainfall total exceeding 300 mm. We used Radar data from Bangladesh Airforce Meteorological division and Indian Meteorological Department. We used satellite data from UEMETSAT program. We used daily station rainfall data from Bangladesh Water Res Bangladesh Water Development Board (BWDB)'s Flood Forecasting & Warning Centre. The current study used two high-resolution gridded precipitation datasets: 1) Bangladesh Gridded Rainfall (BDGR) and 2) the Enhancing National Climate Services for Bangladesh Meteorological Department (ENACTS-BMD).

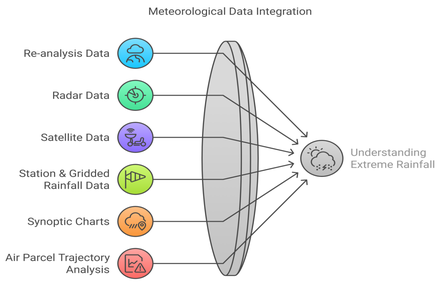


Figure 3: Different types of meteorological data are analyzed to generate a comprehensive understanding of the extreme rainfall events over Bangladesh.

Table 1: Extreme rainfall events studied in this study.

Index	Event Location (District)	Year	Month	Day	Rainfall (mm)
1	Chittagong	2001	June	14	590
2	Dhaka	2004	September	14	341
3	Chittagong	2007	June	11	408
4	Dhaka	2009	July	28	333
5	Chittagong, Rangamati	2017	June	13	343
6	Rangpur	2020	September	27	433
7	Sylhet	2022	June	16	303.8
8	Sunamganj	2022	June	17	304
9	Sunamganj	2023	July	2	322
10	Chittagong	2023	August	7	322
11	Kishoreganj, Mymensingh	2023	October	6	476, 378
12	Sunamganj, Sylhet	2024	June	17	365, 333
13	Sunamganj, Sylhet	2024	July	2	300, 309
14	Feni	2024	August	20	304
15	Cox's Bazar	2024	September	13	501
16	Sherpur	2024	October	3	320
17	Netrokona	2024	October	6	308

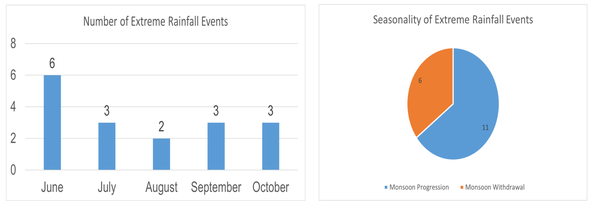


Figure 4: Temporal (left) and season (right) distribution of extreme rainfall events

Results

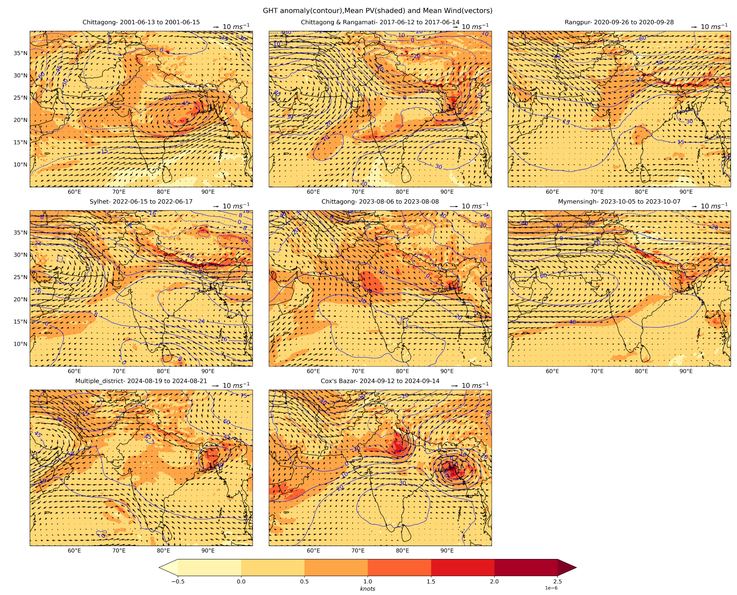


Figure 5: Geopotential Height Anomaly (contour), Mean Potential Vorticity Anomaly (shaded) and Mean Wind (vector). Upper-tropospheric ridge over northwestern India and Pakistan induces mean sea level pressure (MSLP) cyclones or stationary low-pressure systems over Bangladesh and northeastern India. Cyclonic circulation over Bangladesh generates a low-level southwesterly geostrophic upslope flow across Bangladesh.

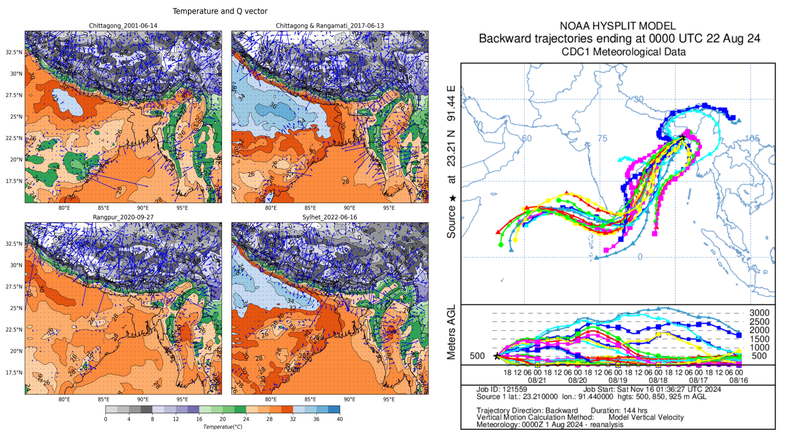


Figure 6: To help diagnose forcing for ascent (e.g., cycloninc vorticity advection, warm air advection), we use the Q-vector form of the inviscid, adiabatic quasigeostrophic (QG) omega equation (left). Three 144-h backward air parcel trajectories from the NOAA HYSPLIT model ending at 500 hPa (right).

Physical Mechanisms for Extreme Rainfall Over Bangladesh

We found that extreme rainfall events in Bangladesh result from the coupling of local, regional, and large-scale meteorological factors. The key drivers include:

Synoptic-Scale Factors:

Stationary Synoptic Patterns: A high-amplitude upper-tropospheric ridge over northwestern India and Pakistan induces mean sea level pressure (MSLP) cyclones or stationary low-pressure systems over Bangladesh and northeastern India. This generates a low-level southwesterly geostrophic upslope flow across Bangladesh.

Local Factors:

Orographic Enhancement:

- The southwesterly upslope flow over the Arakan Mountain and Meghalaya Plateau drives moisture flux convergence in these regions, intensifying rainfall over southeastern and northeastern Bangladesh.
- Orographic lifting forces the ascent of warm, moist air from the Bay of Bengal, saturating the atmosphere and triggering extreme rainfall, particularly in Sylhet and Chattogram regions.
- Coupled with warm air advection, this orographic mechanism prolongs rainfall duration and intensity.

Land-Atmosphere Interaction: High evaporation from local wetlands increases column-integrated water vapor, amplifying rainfall totals.

Meso-Scale Factor:

Madden-Julian Oscillation (MJO): Enhanced convective activity in Phases 2 and 3 of the MJO over the western and central equatorial Indian Ocean leads to heavy rainfall in the Chattogram Division. Trajectory analysis using NOAA's HYSPLIT model (Stein et al. 2015) confirms moisture transport originating from the equatorial Indian Ocean.

South Asian Monsoon Circulation:

The onset and withdrawal phase of the South Asian Monsoon circulation also affect the frequency and intensity of extreme rainfall event over Bangladesh. Almost two thirds of the total extreme rainfall events occurred during the progression phase of the south Asian monsoon circulation.

Conclusion

These findings emphasize the interplay of synoptic patterns, local geography, and mesoscale processes in driving extreme rainfall events in Bangladesh. Our study identified the following meteorological, hydrological and orographic processes for triggering extreme rainfall over Bangladesh.

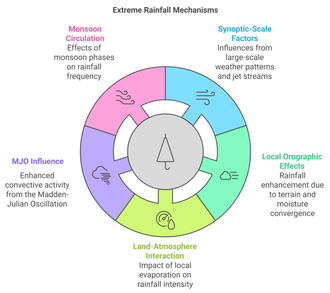


Figure 7: Infographic summarizing the major environmental factors responsible for extreme rainfall in Bangladesh.

References

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