Post-2000 Escalation of Humid Heatwaves and Emerging Cloudburst Risks across the South Asia

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Abstract: The IPCC AR6 (IPCC, 2022) identifies South Asia, particularly India and Bangladesh, as one of the regions most affected by climate change, where extreme weather events are intensified by rising sea levels, melting glaciers, and high social and economic vulnerability. Recent attribution studies confirm that anthropogenic warming has doubled the likelihood of pre-monsoon extreme rainfall events in Bangladesh, such as the 2017 floods that inundated more than 220,000 hectares of cropland. Yet the Northeast India–Bangladesh (NEI–BD) region remains critically underexplored in terms of both thermal and hydrological extremes.

This study assesses the dual vulnerability of the NEI–BD monsoon core, focusing on the post-2000 escalation of humid heatwaves and the emergence of cloudburst hazards. Using ERA5 reanalysis, we derived humidex-based heatwave metrics to quantify human-perceived heat stress. Independently, cloudburst occurrences were identified from GPM-IMERG and tipping-bucket rain-gauge observations established under the Kagawa University–JSPS project (Terao et al., 2023), which recorded 39 extreme hourly rainfall events (≥ 100 mm h^{-1}) across eight stations in NEI–BD.

Results show a nonlinear intensification of humid heat stress after 2000, with total heatwave days tripling and multi-week humidex anomalies exceeding 90th percentile of day of the year, while Northwest India (NWI) shows slower change. Simultaneously, clusters of cloudburst events are concentrated over the Meghalaya Plateau and the Himalayan foothills of Arunachal Pradesh. However, cloudburst documentation across NEI remains severely limited owing to the lack of high-resolution data and restricted accessibility of rainfall records from multiple agencies, leading to large observational gaps.

Although the two extremes are not causally linked, their spatial co-occurrence within the same moist-warm environment highlights a shared climatic driver—a warming, moisture-rich boundary layer that fuels both thermal stress and convective deluges. The NEI–BD corridor is therefore emerging as a dual-exposure hotspot, demanding integrated monitoring and adaptation strategies for compound climate risks.

Keywords: ***Humidex, Heatwave, Cloudburst, South Asian monsoon, Compound vulnerability.***

Introduction

The South Asian Monsoon exerts profound influence on heat and rainfall extremes. Historically, heatwaves have been concentrated in arid NWI, but recent decades reveal a marked shift toward the humid NE-BD, where high moisture (Saha et al., 2023) amplifies discomfort. Meanwhile, short-duration, high-intensity rainfall events, known as cloudbursts, are becoming more frequent, yet remain poorly documented because of data limitations. Studying both extremes together is essential for understanding evolving monsoon-scale thermodynamic instability and regional vulnerability.

Methodology

ERA5 reanalysis (0.25° × 0.25°, 1940–2023) was used to compute daily maximum humidex from hourly 2m air and dew-point temperatures. Humidex heatwave days were defined when values exceeded the 90th percentile of daily climatology for ≥ 3 consecutive days. For hydrological extremes, hourly GPM-IMERG (1998–2023) data were analyzed to detect rainfall events of ≥ 100 mm h^{-1} with at least 8 connected cells/grids. Independent tipping-bucket gauges from the JSPS–Kagawa network provided ground validation, confirming 39 cloudburst cases at eight stations across NEI–BD (Figure 1).

Results

Humidex-based diagnostics reveal a pronounced post-2000 intensification of both the frequency and duration of humid heatwaves across the NEI–BD, with total heatwave days increasing by roughly +10 days dec^{-1} (Figure 2) and the longest spells extending by +1.5 days dec^{-1}. The Hour of Exposure (HOE) metric reveals a steep rise in cumulative moist-heat duration, exceeding 60-70 hours $year^{-1}$ over the eastern monsoon core. Interannual variations show that while Northwest India experiences sporadic increases after the 1990s, NEI–BD displays a sustained, accelerating rise, exceeding 1500 hours season^{-1} in recent decades, reflecting prolonged heat stress and shorter recovery periods between events.

Concurrently, cloudburst clusters are concentrated over the Meghalaya Plateau and Arunachal foothills coinciding with high-HoE zones and regions of elevated moist instability. Yet systematic cloudburst monitoring remains hindered by data scarcity and limited accessibility. Although humid heatwaves and cloudbursts originate from different processes, their spatial coexistence within a warming, moisture-rich boundary layer suggests a shared thermodynamic influence. Enhanced near-surface humidity, weak air circulation, and higher atmospheric instability together magnifies both human heat stress and flash-flood potential across the monsoon-dominated east.

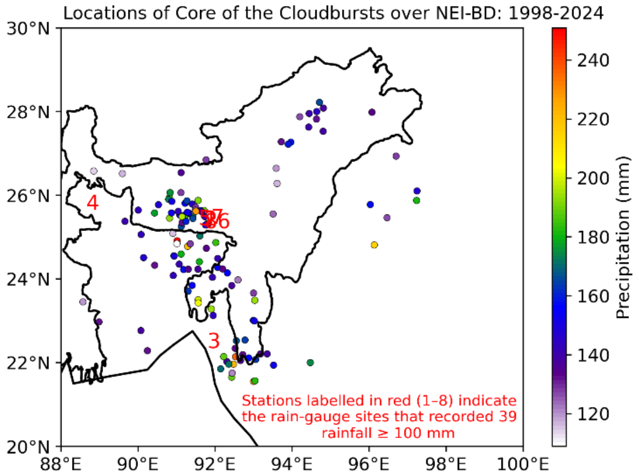

Figure 1, Cloudburst hotspots (≥ 100 mm h $^{-1}$ and 8 connected cells/grids, 1998–2023, GPM-IMERG) over the NE-BD region for season April-September.

Conclusion

The NEI–BD region is rapidly emerging as a compound-extreme hotspot, simultaneously vulnerable to persistent humid heatwaves and intense localized cloudbursts. The sharp rise in HoE underscores prolonged human exposure to extreme humid heat, while recent observations confirm clustered cloudburst activity over orographically active zones such as the Meghalaya Plateau and Arunachal foothills.

These findings emphasize the urgent need to integrate thermal and hydrological diagnostics within a unified modelling framework capable of resolving both processes consistently. Developing high-resolution (kilometer-scale) regional climate projections and physically coupled land–atmosphere models is essential to understand feedbacks among moist-heat buildup, convective instability, and precipitation extremes. Such predictive frameworks will play a pivotal role in advancing early-warning systems, impact forecasting, and climate-resilient planning for the eastern monsoon subcontinent, where climate change is amplifying both heat and hydrological risks.

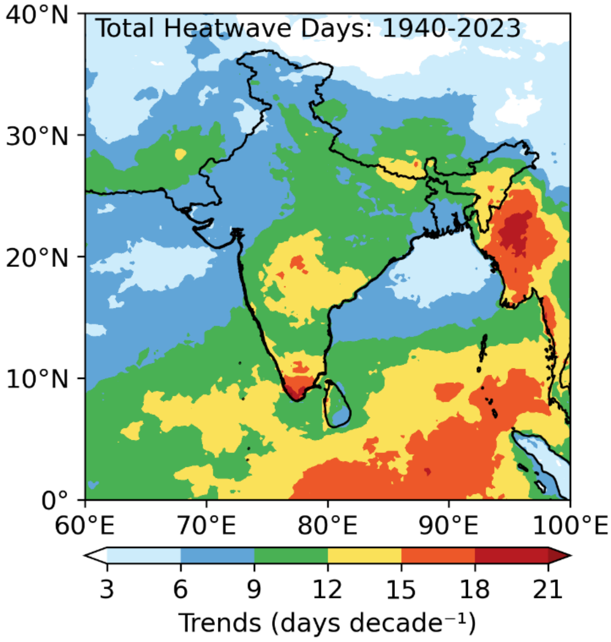

Figure 2, Spatial trend of total heatwave days (1940–2023) based on humidex ≥ 90th percentile. Only significant trends (95 % level) are shown.

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