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A Comprehensive Review of Cloudburst Prediction Techniques Using Modern Computing: An IMD-Based Perspective

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Abstract
Cloudbursts are severe destructive events characterised by extreme rainfall in short duration particularly in hilly and mountainous regions. Cloudbursts pose a significant threat in India, especially during the South-West Monsoon season in the duration from June to September. India has many different climate regions, such as the Himalayas, the Indo-Gangetic Plain, the southern peninsula, and coastal areas, and cloudbursts occur occasionally across these regions. However, only 31 cloudburst events have been officially recorded, most of them in Himachal Pradesh, Uttarakhand, and Jammu & Kashmir. Even with advancement in numerical weather prediction, accurate forecasting of cloudbursts events remains a major challenge due to limited observation strategies. Moreover, mini-cloudbursts which are more frequent but occur over small spatial area in very short duration also go undetected by the existing methods that are designed for cloudburst-scale event. In recent years, modern computing techniques such as Machine Learning (ML), Deep Learning (DL), and big data analytics are being used as promising tools for extreme rainfall prediction. This paper presents a comprehensive review of existing cloudburst prediction techniques while focusing on IMD based meteorological datasets. The critical analysis of Traditional Statistical Methods, ML models, DL architectures, and hybrid method approaches is performed. This paper proposes a conceptual framework for cloudburst prediction using modern computing. This review not only identifies key research gaps but also outlines future directions for developing more reliable, region-specific cloudburst early warning systems.
Keywords: Cloudburst, Mini-cloudburst, Prediction, Extreme Rainfall, IMD, Machine Learning, Deep Learning, LSTM, CNN, Early Warning Systems

Introduction

Extreme rainfall events show increasing variability and intensity over India in recent years, particularly in the duration from month of June to September (southwest monsoon season). Monsoon assessment reports by IMD indicate that while long-term seasonal mean rainfall does not show a uniform increasing trend, short-duration heavy and extremely heavy rainfall events that can be counted as cloudbursts have become more frequent [1]. This shift toward localized and high-intensity precipitation has significantly increased the occurrence of cloudburst related disasters.

The IMD defines a cloudburst as rainfall that exceeds the value of 100 mm in one hour over an area of about 20 km² to 30 km² [1]. Cloudburst events are majorly reported from orographically complex regions, including Uttarakhand, Himachal Pradesh, Jammu & Kashmir, the Western Ghats, and Northeast India, where strong vertical geographic uplift enhances convective activity of the event [1].

Cloudburst development is strongly influenced by thermodynamic instability, moisture availability, and orographic lifting. The most relevant theoretical parameters include Convective Available Potential Energy (CAPE) [6][8], Moisture Flux Convergence (MFC) [7][9] and Orographic Uplift Mechanism [8].

IMD-Based Statistical Evidence

Figure 1 shows the statistics of extreme weather events marked by destructive heavy rainfall. IMD post event analysis and disaster summaries reveal that cloudbursts are commonly associated with flash floods and landslides, often causing extensive damage to infrastructure and loss of human life [1]. Moreover, IMD observational studies highlight that sub daily rainfall extremes which may last for an hour to 3 hours, are increasing in hilly regions. According to this data it is observed that many cloudburst events are identified after occurrence rather than being predicted. The Sparse Rain Gauge Networks limit localized monitoring of these events.

These findings emphasize on the limitations of already existing conventional cloudburst forecasting systems and thus the need for better and advanced prediction approaches.

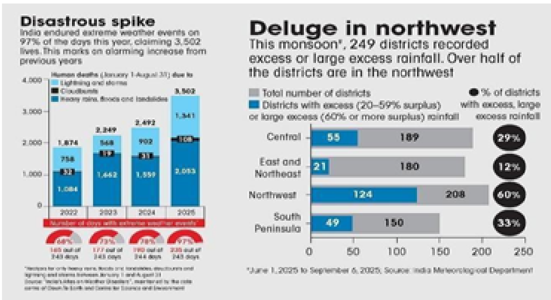


Figure 1 Year 2025 Extreme Event Counts.
Source: Indian Meteorological Department.

Need for the Study

The conventional Numerical Weather Prediction (NWP) models are designed for large scale atmospheric processes. These models often operate in spatial resolution viewing the atmosphere in big blocks thus failing to capture highly localized events like cloudbursts [5]. IMD has acknowledged the cloudbursts as the most difficult to forecast extreme weather events, due to their localized nature, rapid development and sudden occurrence [1].

Recent advancements in Machine Learning and Deep Learning have shown their strong potential for handling nonlinear atmospheric relationships using the historical meteorological datasets [5]. When these models are applied to rainfall and atmospheric data from IMD, they can complement physical forecasting methods and improve accuracy of short-term prediction methods.

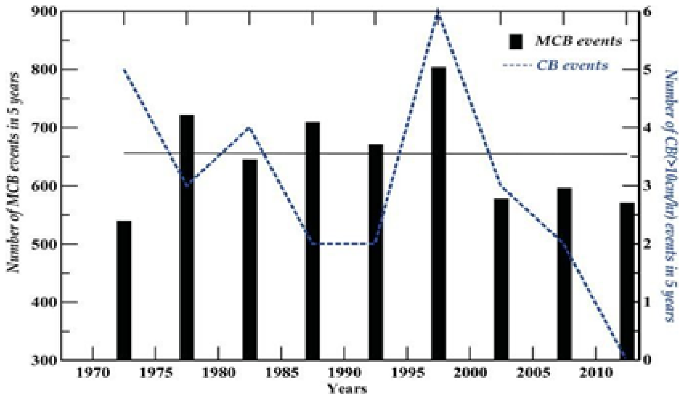


Figure 2 Number of CB and MCB events observed per year during the period 1969–2015 in India.

The temporal variation of cloudburst and mini-cloudburst events that occurred in India during the period 1969 to 2015, is illustrated in Figure 2. While the cloudburst occurrences are rare, mini-cloudburst events are more frequent, with their count exceeding 500 mini-cloudbursts over a period of 5 years. The graph shows a peak in both cloudburst and mini-cloudburst activity in the duration from year 1995 to 2000, thus suggesting increased atmospheric instability resulting in the extreme rainfall conditions. The sustained high frequency of mini-cloudburst events, even during decreased cloudburst occurrences, highlights the limitations of traditional cloudburst-centric approaches. Thus, it emphasizes the need for high resolution and data driven prediction frameworks that can capture mini-cloudburst scale events as well.

This paper provides a review of various cloudburst prediction techniques using modern computing. It focuses exclusively on IMD-based meteorological datasets. The paper compares ML and DL models used in the recent studies. It proposes a conceptual framework for cloudburst prediction and identifies research gaps as well as future scope.

Challenges in Cloudburst Prediction

Cloudbursts are extreme precipitation events characterized by heavy rainfall in short duration and confined to highly localised spatial area [7]. Such events occur when strong thunderstorm clouds grow very large, and their intensity further increases when moist air is forced to rise over hills or mountains. Therefore, hilly and mountainous regions are more prone to cloudbursts [8][1].

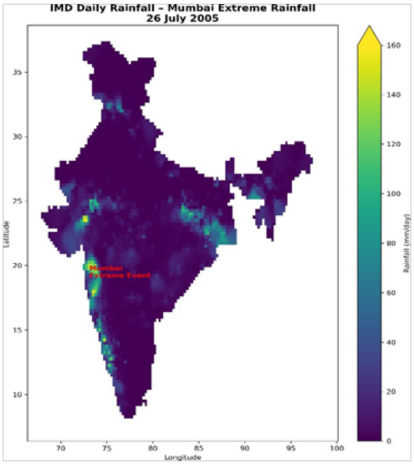
One of the main challenges in accurate prediction of cloudbursts is the lack of sufficient weather observations, especially in complex terrains such as Himalayas and Western Ghats, where monitoring networks are limited. Although the India Meteorological Department maintains rain gauge networks operating for many years, the density of stations in given area is insufficient to detect highly localized extreme rainfall events. Therefore, many cloudburst events go undetected or not documented properly [1][8].

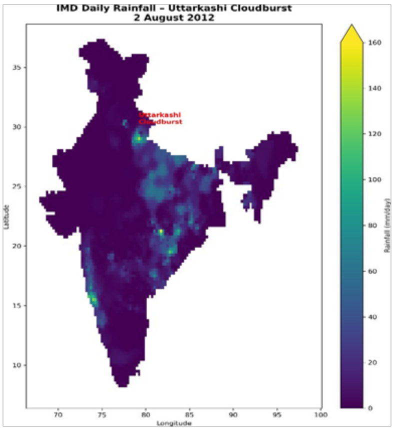
Another major challenge arises since there are multiple atmospheric conditions that may cause cloudburst events. These events occur due to rapid changes in small-scale weather processes, such as moist air suddenly gathering in a small area and then rapidly rising upward. These changes happen too fast, to be captured by standard numerical weather prediction (NWP) models. Thus, such events are difficult to predict accurately. As a result, operational models operating at synoptic scale or mesoscale resolutions often fail to capture localized cloudburst dynamics [11][9].

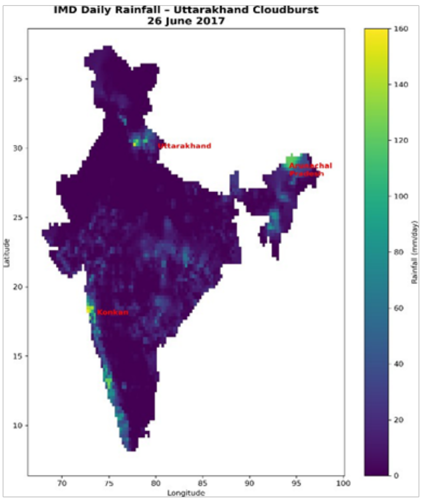
Furthermore, the limited availability of labelled cloudburst events significantly constrains the development of data-driven prediction models. The absence of a universally standardized definition, along with inconsistencies in rainfall thresholds and reporting practices, results in sparse and imbalanced datasets, posing challenges for training robust machine learning and deep learning models [1][9].

These limitations underscore the need for high-resolution observational datasets, improved event classification strategies, and modern computing approaches, including machine learning and artificial intelligence, to enhance cloudburst detection and prediction capabilities.

IMD Datasets for Cloudburst Prediction







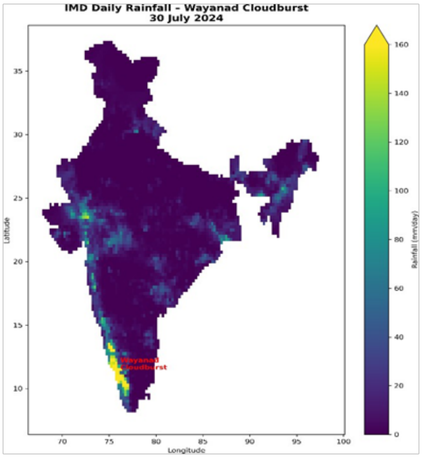


Figure 3 Extreme weather events due to cloudbursts and multiple mini cloudbursts for different years: (a) Mumbai extreme and disastrous rainfall on 26th July 2005; (b) Uttarkashi Cloudburst on 2nd August 2012; (c) Uttarakhand, Arunachal Pradesh, Konkan region extreme events on 26th June 2017; (d) Wayanad Cloudburst on 30th July 2024.
Source: IMD gridded rainfall data.

IMD provides long-term meteorological datasets that includes hourly and daily rainfall. It also includes temperature and humidity, wind speed and wind direction as well as surface pressure. These datasets form the backbone of cloudburst research in India. However, limited spatial density and missing high-frequency observations pose challenges in real-time prediction of the events.

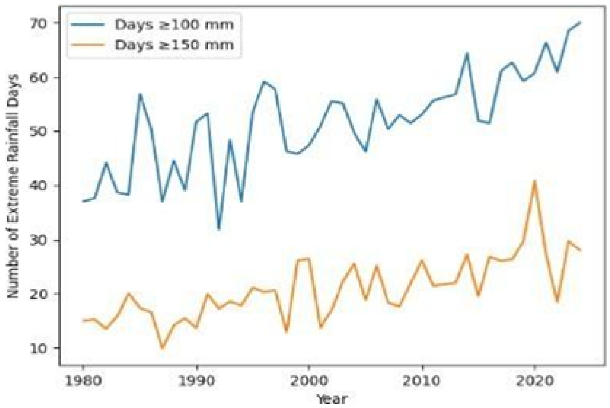


Figure 4 Representative trends derived from IMD-reported extreme rainfall statistics.
Source: IMD [1].

Figure 4 illustrates long-term trend of extreme rainfall days more than 100 to 150 mm over India based on IMD reported rainfall intensity thresholds, highlighting increase of more than 2000 in high-intensity precipitation events.

Literature Review of Cloudburst Prediction Techniques

Extreme rainfall events show increasing variability and intensity over India in recent years, particularly in the duration from month of June to September (southwest monsoon season). Monsoon assessment reports by IMD indicate that while long-term seasonal mean rainfall does not show a uniform increasing trend, short-duration heavy and extremely heavy rainfall events that can be counted as cloudbursts have become more frequent [1]. This shift toward localized and high-intensity precipitation has significantly increased the occurrence of cloudburst related disasters.

Traditional Statistical Approaches

Early cloudburst studies relied on analysis of rainfall threshold, synoptic weather patterns, and post-event assessment of IMD rain-gauge data [1][11]. While these approaches improved physical understanding, they offered limited predictive capability.

Machine Learning Models

Random Forest (RF) models have been applied widely for classification of extreme rainfall events due to their robustness and interpretability [6]. While ML models like Support Vector Machines (SVM) and logistic regression models have also been tested, while demonstrating reasonable classification accuracy but the limited temporal modelling capability at the same time [7].

Deep Learning Models

Long Short-Term Memory (LSTM) networks are effective particularly for rainfall time-series forecasting because of their ability to capture the long-term temporal dependencies [10]. Studies using IMD hourly rainfall data report improved prediction performance compared to traditional ML models. Convolutional Neural Networks (CNN) and hybrid CNN–LSTM models further enhance the accuracy of prediction by integrating spatial and temporal features of the given data [13].

Table 1 Related Work Summary

Prediction Method	Dataset	Key Outcome
Statistical Analysis	IMD raingauge data	Identified cloudburst-prone regions [1]
RF, SVM	IMD rainfall	Improved extreme rainfall classification [2]
ML classifiers	IMD historical data	Accurate binary event prediction [3]
LSTM	IMD hourly data	Improved short-term prediction – hybrid method

Conceptual Framework for Cloudburst Prediction

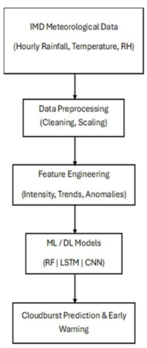


Figure 5 Conceptual framework for cloudburst prediction using modern computing and IMD datasets

Hybrid and Physics-Informed Models combine physical constraints from atmospheric science with data driven learning, improving interpretability and generalization. Such approaches are increasingly recommended for operational early warning systems.

Conclusion

This paper demonstrates a comprehensive review of cloudburst prediction techniques using modern computing, while focusing on IMD based datasets. Machine Learning and Deep Learning approaches particularly LSTM and hybrid models demonstrate strong potential for improving short-term cloudburst forecasting. However, advancements in data availability, model integration, and operational deployment are essential for reliable early warning systems. Future work should focus on integration of high resolution IMD data along with Satellite hyperspectral precipitation image data and hybrid physics informed ML models. It can include real time cloudburst early warning systems and AI models for decision support.

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