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Disambiguation of Cloudbursts: Not All Extreme Short-Term Rainfall Events Constitute Cloudburst

—What Sets Apart Cloudburst from Extreme Heavy Rainfall Events?

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Abstract

Misinformation casts doubt on well-supported theories. Recently, it has become more common to refer to intense, short-duration heavy rainfall events as "cloudbursts" without considering the established and formally defined terms already in use. This may result in ambiguity, as it directly contradicts or overlap with established terminology for the same phenomenon or terms that share similar syntax but refer to entirely different phenomena. Furthermore, "Cloudburst" is an outdated term encompassing predominantly convective down burst of varying scales. The use of the term in similar context of extreme rainfall event indicates an unfamiliarity with contemporary literature on cloudburst. This paper conducts a comprehensive review of existing research and evidence on cloudbursts. It aims to provide a clear explanation of the distinctions between cloudbursts and extreme rainfall events. Various studies on the complex relationships among cloudbursts, precipitation dynamics, thermodynamics, large-scale forcing, orographic forcing, geomorphology, and their resulting impacts have been reviewed. Most studies have suggested that higher-altitude regions, typically ranging from 1000 to 2500 m, experience more frequent cloudbursts. Cloudbursts occur on the plains; however, mountainous regions are more prone to cloudbursts owing to their orography and geographical features. Multiple studies have provided compelling evidence that cloudbursts are convectively triggered and followed by orographically locked systems. Therefore, the absence of any of these interconnected processes hinders the occurrence of cloudbursts. Moreover, cloudbursts are highly localized and are very difficult to predict because of their very small-scale in space and time compared with extreme rainfall events. Therefore, this study concludes that it is not possible to categorize every occurrence of extreme rainfall within a short time period as a cloudburst. Furthermore, there is currently no widely accepted standard threshold for determining the intensity level that distinguishes cloudbursts from instances of extreme rainfall.

Keywords

Climate Change, Cloudbursts, Extreme Rainfall Events, Rainfall Intensity, Geomorphology, Thermodynamics, Orographic Force

1. Introduction

Cloudbursts and extreme heavy rainfall events are often conflated due to their shared nature of intense precipitation. However, it is crucial to distinguish between these phenomena as they have different characteristics and implications. The term "cloudburst" has a long history in meteorological literature, dating back to the 1800s and peaking in use around the 1940s (Harris & Lanfranco, 2017; Lovel, 1893). Initially undefined, it has evolved into a designation for localized downpours associated with thunderstorms. Elmer (1902) suggested that elongated thunderstorm clouds moving along their long axes could directly cause cloudbursts. Bonnett (1904) and Bharti (2015) described scenarios where the frequency and coverage of showers progressively intensified, leading to a fully overcast sky and intense thunderstorms. Macadie (1908) documented a precipitation event with 290 mm of rainfall within one hour. Horton & Todd (1921) highlighted the localized nature of a cloudburst at Taborton, NY, USA, which received 158 mm of rainfall in two hours over an area of only 8 km in diameter. King (1924) reported a cloudburst lasting 3 1/2 hours, resulting in 305 mm of precipitation over an elliptical region measuring 80 km^2. This storm caused significant infrastructure damage, making roads impassable and sweeping away bridges and houses (Dimri et al., 2017; Bhan et al., 2004).

Douglas (1908) reported a cloudburst in California resulting in sudden and intense flooding. A cloudburst on July 2, 1893, in the Cheviot Hills, UK, caused flash floods that eroded up to 2 km^2 of the valley cross-section, destroying bridges and roadways (Clark, 2005). By the mid-20th century, cloudbursts were defined as concentrated rainfall events with a small geographical extent (several km in diameter). Varney (1924) and Miller (1951) documented that lightning and thunder frequently accompany intense downpours. The 2011 Copenhagen cloudburst resulted in over 1 billion USD in total damages, excluding direct municipal repair costs and indirect costs such as decreased earnings, business disruptions, increased insurance premiums, and potential relocation of companies from Copenhagen. Cloudbursts cause significant damage, including flash floods, stream bed erosion, landslides, and mudflows (Asthana & Asthana, 2014; Barros et al., 2004; Dimri et al., 2016). Woolley et al. (1946) provided a formal definition of a cloudburst as "a heavy and localized rainfall characterized by its sporadic nature and high intensity, resembling the sudden bursting and release of an entire cloud." This definition has gained widespread acceptance in English dictionaries. The Merriam-Webster Dictionary defines "cloudburst," originating in 1869, as sudden and abundant rainfall or outpouring.

Recent studies have highlighted the increasing frequency and intensity of extreme rainfall events due to climate change, emphasizing the need for accurate definitions and distinctions between cloudbursts and other extreme rainfall events (Smith et al., 2024). A comprehensive study of atmospheric dynamics associated with cloudburst events in 2022 over the Indian Himalayan Region by Samantray and Gouda (2024) highlighted the role of atmospheric phenomena, such as frontal boundaries and moisture transport in forming convective systems that leading to cloudbursts in the Indian Himalayan Region. Moreover, recent paper by Raghuvanshi & Agarwal (2023), Schmith et al. (2023), Mishra et al. (2022), Vijaykumar et al. (2021), and Samantray & Gouda (2023) offer important new information about the mechanisms underlying cloudburst and extreme rainfall occurrences.

Cloudbursts have also been defined using quantitative measures considering the duration, amount, and intensity of rainfall events. Haritashya et al. (2006) and Rashid et al. (2012) proposed a threshold of 100 mm/hour to differentiate between intense rainfall and cloudbursts. Krishnamurthy (2011) characterized an exceptional rainfall event as having a mean precipitation of 100 mm/day when assessed over 24 hours. According to Izzo (2010), a cloudburst can be distinguished from heavy rainfall by a difference of 30 mm/hour in intensity. Dunlop (2008) stated that heavy showers, with a rainfall rate of 10 - 50 mm/hour, are distinguished from severe showers, with a rainfall rate greater than 50 mm/hour, according to the World Meteorological Organization (WMO) standards. Fry et al. (2011) classified a downpour as having an intensity greater than 15 mm/hour. The American Meteorological Society Glossary of Meteorology supports the threshold of 100 mm/hour (Dimri et al., 2017; Bradley & Smith, 1994; Moore et al., 1995; NOAA, 2004).

2. Meteorology of Cloudbursts

Cloudbursts are marked by their unpredictability and can cause significant damage due to sudden and intense rainfall. **Figure 1** depicts the sequence of physical processes involved in cloudburst events, referencing established literature and generalized assumptions about the hydrological conditions required for heavy precipitation and flooding (Das et al., 2006; Thayyen et al., 2013; Asthana & Asthana, 2014; Dimri et al., 2016; Hendriks, 2010). The mechanisms that contribute to the formation of cloudburst events are not yet fully understood (Carbone et al., 2002; Chappell, 1986). However, these events seem to be linked to the interactions occurring between atmospheric conditions and topographical features, especially involving convection and orography (Thayyen et al., 2013; Kala, 2014; Chaudhuri et al., 2015). During cloudbursts, convection

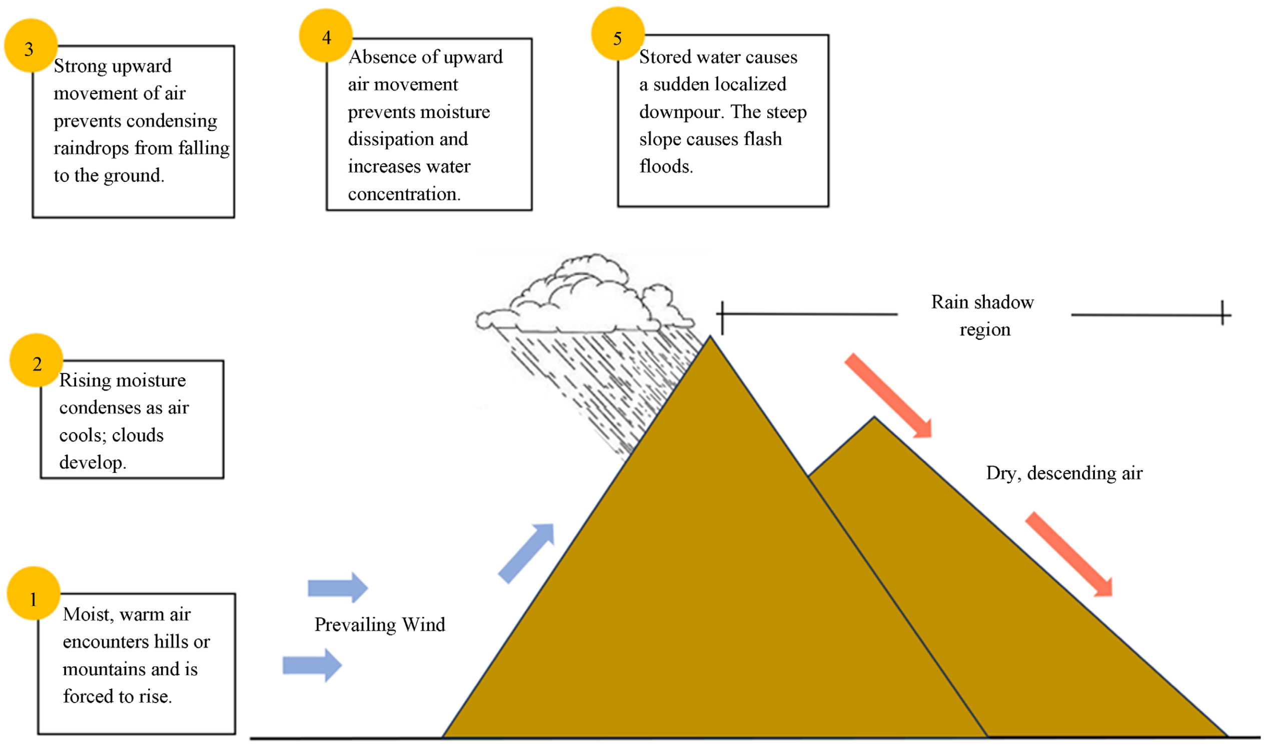

Figure 1. Idealized life cycle for cloudbursts: condensation, precipitation, and rain shadow effect due to orographic lift.

within cumulonimbus clouds can extend to altitudes of approximately 15 kilometers, resulting in atmospheric instability and the generation of intense vertical drafts (Thayyen et al., 2013; Chappell, 1986). According to Barros et al. (2004) and Corfidi (2003) in the Himalayas, convective energy is generated at night by the evaporative cooling of rainfall, the transpiration of plants, and the convergence of air on windward valley slopes. An alternative atmospheric mechanism associated with cloudbursts involves the collision of two cloud systems (Srivastava & Bhardwaj, 2014; Aggarwal et al. 2022; Davis, 2001). Additional evidence concerning the mechanism of cloudburst hydrogeology encompasses their occurrence within the elevation range of 1600 to 2200 meters and their recurrence at identical locations (Asthana & Asthana, 2014; Sharma, 2011). It is assumed that hydrographs of cloudburst events exhibit a flashy nature, attributed to their occurrence over limited spatial extents and brief temporal intervals (Thayyen et al., 2013). In 2010, a step-backwater model incorporating multiple cross-sections, a two-dimensional depth-averaged hydraulic model, and Manning's equation was employed to produce a hydrograph for a cloudburst event. (Heideman & Fritsch, 1988; Glass et al. 2003; Thayyen et al., 2013; Gourley, & Vergara, 2020). Cloudbursts can also feature hail, lightning, and windstorms, complicating the distinction between them and thunderstorms (Das et al., 2006; Srivastava & Bhardwaj, 2014).

Numerous studies have established a distinction between cloudbursts and other flash flood events, despite the potential for overlap in weather occurrences

(Das, 2022; Das et al., 2006; Devi, 2015; Srivastava & Bhardwaj, 2014; Thayyen et al., 2013). These studies contribute significantly to the understanding of hydro-meteorological phenomena in the Himalayas, as indicated by Shrestha et al. (2000), reinforcing the notion that cloudbursts are distinct from thunderstorms and hailstorms. The differentiation is crucial for the scientific comprehension of weather patterns in the Himalayas, as well as for the management and forecasting of significant cloudburst events that may lead to considerable damage and loss of life (Gourley et al., 2012; Heideman & Fritsch, 1988; Herring et al., 2018; Bhan et al., 2015).

3. Mechanism and Locations of Cloudburst Occurrences

Cloudbursts are particularly prevalent in mountainous regions, where orographic lift (air forced to rise over mountains) can increase precipitation. Examples include the Rocky Mountains and the Himalayas (Gourley, & Vergara, 2020; Bhambri et al., 2016; Kane & Chelius, 1986; Bhan et al., 2015). This is likely due to warm air currents from a thunderstorm following the upward elevation of a mountain. The impact of excessive rainfall is particularly pronounced on mountain slopes because descending water accumulates in valleys and gullies. Furthermore, the formation of a low-pressure areas at mountain summits leads to the most frequent observation of cloudbursts in high-altitude regions (Bhan et al., 2004; Bhan et al., 2015; Samantray & Gouda, 2024). Cloudbursts are most prevalent in the interior regions of continental landmasses as well as in arid and mountainous areas. The topographical conditions of mountainous regions, such as precipitous hills, facilitate cloud formation. Furthermore, monsoon cloudbursts are common during the monsoon season in regions with monsoon climates, such as India, because of the elevated moisture content in the atmosphere. Cloudbursts are also possible in tropical and subtropical regions, particularly during the rainy season when thunderstorms are more prevalent (Bhan et al., 2004; Samantray & Gouda, 2024; Schumacher & Johnson, 2005).

A cloudburst is defined as a meteorological phenomenon where moisture-laden air rapidly ascends over elevated landscapes, resulting in the formation of a significant vertical column of "cumulonimbus" clouds (Samantray & Gouda, 2024). These clouds are commonly associated with heavy precipitation, as well as thunder and lightning phenomena. The upward cloud motion is referred to as "orographic lift". The presence of unstable clouds leads to the formation of intense rainstorms localized in specific areas, occurring once these clouds accumulate sufficient weight and become trapped within the ridges and valleys of the surrounding hills (Smith et al., 2001; Smull & Augustine, 1993). The formation of tall cumulonimbus clouds occurs within approximately 30 minutes when moisture ascends rapidly at velocities ranging from 60 to 120 km/h. A single-cell cloud typically has a duration of approximately one hour, during which the majority of precipitation occurs in the final twenty to thirty minutes. Individual single-cell clouds can merge to form multicell storms, which may persist for several hours (Smull &

Augustine, 1993; Bhan et al., 2004). The presence of cumulonimbus convection, driven by significant thermodynamic instability resulting from moisture and rapid dynamic lifting associated with steep orographic features, leads to the occurrence of cloudbursts. As elevation increases, clouds that contain moisture accumulate weight, leading to the occurrence of intense rainstorms at specific intervals. **Figure 1** illustrates the conceptual life cycle of cloudbursts, encompassing the processes of condensation, precipitation, and the rain shadow effect resulting from orographic lift (Asthana & Asthana, 2014; Barros et al., 2004; Dimri et al., 2016; Bhan et al., 2015). The process of orographic lifting involving moist and unstable air results in the release of convective available potential energy, which is essential for the formation of a cloudburst (Das et al., 2006; Dimri et al., 2017; Bhan et al., 2015).

4. Intensity of Cloudbursts

Cloudbursts are sudden, intense rainstorms that release a substantial amount of rainfall in a short duration, often resulting in severe flash floods. These storms are characterized by their rapid onset and extraordinary rainfall intensity. They predominantly occur in hilly or mountainous regions and are triggered by the rapid uplift of air, leading to swift condensation and precipitation. The impacts of cloudbursts are significant, ranging from flooding and landslides to widespread disruption of daily activities. For instance, on November 29, 1911, an automatic rain gauge in Porto Bello, Panama, recorded 63 mm of rainfall within 3 minutes. **Table 1** below Summary of the duration, rainfall depth, & location of some of the worst cloudburst events. Various studies underscore the common geographical features associated with cloudbursts (Gagan & Moore, 2001; Dimri et al., 2017; Moore et al., 1995; Pontrelli et al., 1999).

Table 1. Summary of the duration, rainfall depth, & location of some of the worst cloudburst events.

DURATION	RAINFALL	LOCATION/YEAR
1 hr.	9.84 in. (250 mm)	Leh, Ladakh, India (2010)
1 hr.	5.67 in. (144 mm)	Pune, Maharashtra, India (2010)
1 min	1.5 in. (38.10 mm)	Basse-Terre, Guadeloupe (1970)
1.5 hr.	7.15 in. (182 mm)	Pune, Maharashtra, India (2010)
2 hr.	3.94 in. (100 mm)	Pithoragarh, Uttarakhand, India (2016)
5 hr.	15.35 in. (390 mm)	La Plata, Buenos Aires, Argentina (2013)
5.5 min.	2.43 in. (61.72 mm)	Port Bell, Panama (1911)
10 hr.	57.00 in. (1448 mm)	Mumbai, Maharashtra, India (2005)
13 hr.	45.03 in. (1144 mm)	Foc-Foc, La Réunion (1966)
15 min.	7.8 in. (198.12 mm)	Plumb Point, Jamaica (1916)

Continued

20 hr.	91.69 in. (2329 mm)	Ganges Delta, Bangladesh/India (1966)
20 min.	8.1 in. (205.74 mm)	Curtea de Argeş, Romania (1947)
24 hr.	73.62 in. (1870 mm)	Cilaos, La Réunion (1952)
40 min.	9.25 in. (234.95 mm)	Guinea, Virginia, United States (1906)
30 min.	2.20 in. (50 mm)	Copenhagen area of Denmark (2011)
15 min.	3.94 in. (100 mm)	Kashmir, India (2023)
2.0 hr.	10 in. (254 mm)	Uttarakhand, northern India (2021)
1.5 hr.	11.97 in. (304 mm)	Jammu & Kashmir, Amarnath (2022)
2.0 hr.	10.95 in. (278 mm)	Srinagar, Kashmir (2023)
1.0 hr.	10.47 in. (266 mm)	Leh, Ladakh (2024)
1.5 hr.	11.14 in. (283 mm)	Himachal Pradesh (2025)

5. Extreme/Heavy Rainfall Events

Extreme rainfall events are scientifically defined based on statistical thresholds and meteorological criteria. Extreme rainfall events are typically defined as instances in which the amount of rainfall significantly exceeds the normal range for a specific region over a short period. These events are often characterized by their intensity, duration, and resulting impact on the environment and society (IPCC Special Report on Extremes, 2012; Smith et at., 2001; Intergovernmental Panel on Climate Change (https://www.ipcc.ch).

Scientific Definitions: The intensity refers to the rate of rainfall, usually measured in mm/hour. An extreme rainfall event is defined as rainfall exceeding a certain threshold, such as 50 mm/hour. The duration is the length of time over which rainfall occurs. For example, an event might be considered extreme if it involves continuous heavy rainfall for over 24 hours. The return period is the estimated average time interval between the occurrences of an event of a defined size or intensity. For example, a "100-year storm" is an event that has a 1% chance of occurring in any given year (Herring et al., 2018; Smith et al., 2001). American Meteorological Society (https://www.ametsoc.org/).

World Meteorological Organization: The WMO plays a crucial role in defining and standardizing extreme weather events, including extreme rainfall events. The WMO collaborates with the National Meteorological and Hydrological Services (NMHS) worldwide to ensure consistent and accurate weather observations and forecasts. They provide guidelines and frameworks to help countries define and classify extreme weather events based on local climatological data and historical records World Meteorological Organization (https://wmo.int/).

National Weather Services (NWS): Various countries often adopt NWS and WMO guidelines to suit their specific regional climates and needs (National Weather Service (NWS) https://www.weather.gov/). Several examples are provided below:

United States: The National Oceanic and Atmospheric Administration (NOAA) defines extreme rainfall events based on historical data and statistical thresholds. For example, an event may be classified as extreme if it falls within the top 1% of all recorded rainfall events in a given area.

Europe: The European Environment Agency (EEA) often uses similar statistical methods to define extreme rainfall events that exceed the 95th percentile of the historical rainfall data (https://www.eea.europa.eu/en).

Australia: The Bureau of Meteorology (BOM): defines extreme rainfall events based on both intensity and duration, such as rainfall > 50 mm in an hour or 200 mm in 24 hours (http://www.bom.gov.au/).

World Meteorological Organization (*WMO*): Defines extreme rainfall as events that are statistically rare and have significant impacts on society and the environment (https://wmo.int/).

National Weather Service (*NWS*): Specific thresholds such as rainfall > 50 mm in an hour, are often used to issue warnings (https://www.weather.gov/).

India: The India Meteorological Department (IMD) defines extreme rainfall events as instances where rainfall is >150 mm in 24 hours. They also categorize events based on severity, such as "very heavy rainfall" (115.6 to 204.4 mm) and "extremely heavy rainfall" (>204.4 mm) in 24 hours (https://mausam.imd.gov.in/).

Japan: The Japan Meteorological Agency (JMA) considers rainfall events extreme if they are >50 mm per hour or 200 mm in 24 hours. They also use return periods to classify events, such as a "50-year rainfall event" (https://www.jma.go.jp/).

United Kingdom: The UK Met Office defines extreme rainfall events using statistical thresholds, such as the 99th percentile of historical rainfall data. They also consider the impact on infrastructure and the environment when classifying events (UK Met Office https://www.metoffice.gov.uk).

China: The China Meteorological Administration (CMA) defines extreme rainfall events based on both intensity and duration, such as rainfall >50 mm in an hour or 250 mm in 24 hours (CMA) http://www.cma.gov.cn/).

Brazil: The National Institute of Meteorology (INMET) classifies extreme events as those exceeding 100 mm in 24 h, considering their frequency and impact (Instituto Nacional de Meteorologia https://portal.inmet.gov.br/).

6. Meteorology of Extreme Rainfall

It is important to determine the types of weather systems that are commonly responsible for producing extreme rainfall (IPCC Special Report on Extremes, 2012). Extreme rainfall can be caused by various weather systems, such as mesoscale convective systems, tropical cyclones, atmospheric rivers, frontal systems, orographic lifting, and localized thunderstorms (Herring et al., 2018). Each system produces significant amounts of rainfall over different durations and areas. The most common systems are outlined below. Each of these systems can interact with the local geography and atmospheric conditions to produce extreme rainfall (Herring et al., 2018; NOAA, 2004; Bhan et al., 2015; Schumacher & Johnson, 2005; Smith et al., 2001).

Mesoscale Convective Systems (*MCSs*): These are large, organized groups of thunderstorms that can cover hundreds of km and last for several hours. They are responsible for a significant proportion of extreme rainfall events (Smith et al., 2001; Schumacher & Johnson, 2005).

Tropical Cyclones: These systems, including hurricanes and typhoons, can produce intense rainfall over a wide area because of their large size and the vast amount of moisture they carry from the ocean (Bhan et al., 2015; Schumacher & Johnson, 2005).

Atmospheric Rivers: These are narrow corridors of concentrated moisture in the atmosphere that often originate in the tropics. When they make landfall, they release large amounts of rainfall, especially when they encounter mountainous terrain (Herring et al., 2018; NOAA, 2004).

Frontal Systems: Cold, warm, and occluded fronts can lead to heavy rainfall. The lifting of warm and moist air over a front can result in prolonged and intense precipitation (Bhan et al., 2015; Schumacher & Johnson, 2005; Smith et al., 2001).

Orographic Lifting: When moist air is forced to ascend over mountains, it cools and condenses, leading to heavy rainfall on the windward side of the mountain range (Bhan et al., 2015; Schumacher & Johnson, 2005).

Localized Thunderstorms: These produce extreme rainfall over a small area in a short period, often leading to flash flooding (Smith et al., 2001; Schumacher & Johnson, 2005).

These weather systems can vary in intensity and duration, but all have the potential to produce extreme rainfall events that can significantly impact regions.

7. Discussion and Conclusion

Most studies suggest that higher-altitude regions, typically ranging from 1000 to 2500 m, experience more frequent cloudburst events. Cloudbursts occur on plains; however, mountainous regions are more prone to cloudbursts owing to their orography and geographical features. In addition, multiple studies have provided compelling evidence that cloudbursts are convectively triggered and followed by orographically locked systems. The absence of any of these interconnected processes hinders the occurrence of cloudbursts. Moreover, cloudbursts are highly localized events and are very difficult to predict because of their very small scale in space and time compared with extremely heavy rainfall. Thus, this study concludes that all instances of intense rainfall in a short time period cannot be classified as cloudbursts. Furthermore, there is currently no universally agreed intensity threshold that differentiates cloudbursts from other instances of high-intensity rainfall. **Table 2** summarizes the key differences between cloudbursts and extreme rainfall events.

Table 2. Summary of the key differences between cloudbursts and extreme rainfall events, with all references included in the journal's main text.

[redacted]	CHARACTERISTICS	IMPACT
[redacted]	*Intensity*: Cloudbursts are characterized by extremely high rainfall rates. Typically exceeding 100 millimeters (about 4 inches) per hour. *Short Duration*: They occur over a very short period, usually less than an hour. *Geographical area*: Cloudbursts are highly localized, affecting areas less than 20 - 30 square kilometers. Cloudbursts are challenging to predict owing to their localized nature and the complex atmospheric conditions involved in their creation.	*Flash floods*: Sudden and intense rainfall can lead to rapid flooding, especially in urban areas with poor drainage. *Landslides*: In mountainous regions, heavy rainfall can trigger landslides. *Infrastructure damage*: Sudden influx of water can overwhelm drainage systems, leading to significant damage to infrastructure.
[redacted]	*High Intensity*: Extremely high rainfall rates compared to the average precipitation levels for a particular region. *Prolonged Duration*: These events can last from several hours to multiple days, significantly increasing the total amount of rainfall. *Frequency and Magnitude*: The frequency and intensity of these events are often influenced by climate change, leading to more frequent and severe occurrences. *Geographical Area*: Can cover large regions, sometimes spanning hundreds of kilometers.	*Widespread flooding*: Prolonged rainfall can lead to river flooding and inundation of large areas. *Soil saturation*: Extended periods of rain can saturate the soil, increasing the risk of landslides. *Agricultural damage*: Prolonged wet conditions can damage crops and affect agricultural productivity.
[redacted]	**FORMATION MECHANISM**	**OTHER**
[redacted]	Cloudbursts often result from rapid condensation owing to orographic lifting or convective activity. By contrast, other extreme rainfall events are associated with larger-scale weather systems.	Extreme rainfall events are often defined as daily precipitation exceeding the 95th percentile of the historical distribution. No universally agreed-upon threshold of intensity that differentiates cloudbursts from other instances of high-intensity rainfall.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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