



Localized analysis of Cloudburst dynamics over Indian Himalayan Region during 2022

P. SAMANTRAY ^{1,2} and K. C. GOUDA ^{1,3}

¹ CSIR National Institute of Data Science & AI (Formerly Fourth Paradigm Institute),

Wind Tunnel Road, Bangalore, India

² Visvesvaraya Technological University, Belagavi, Karnataka, India

³ Academy of Scientific and Innovative Research (AcSIR), Ghaziabad, UP, India

(Received 10 June 2025, Accepted 1 December 2025)

*Corresponding author's email: kcgouda.4pi@csir.res.in

सार – इस शोध में भारतीय हिमालयी क्षेत्र (Indian Himalayan Region–IHR) में स्थानीयकृत बादल फटने (Cloudburst) की घटनाओं का अध्ययन किया गया है। वर्ष 2022 में इस क्षेत्र में बादल फटने की कुल 66 घटनाएँ देखी गईं, जो हाल के समय में चरम वर्षण घटनाओं (Extreme Rainfall Events–EREs) की बढ़ती तीव्रता का संकेत देती हैं। सीमित जानकारी एवं जागरूकता के कारण पर्वतीय आपदाएँ प्रायः ध्यान में नहीं आ पाती हैं। स्थलाकृतिक विशेषताओं में व्यापक विविधता तथा क्षेत्रीय अपसरण के कारण EREs की तीव्रता, अवधि और आवृत्ति में भी परिवर्तनशीलता पाई जाती है। इसलिए इन घटनाओं के दौरान वायुमंडल की गतिशीलता का अध्ययन करना महत्वपूर्ण है, ताकि शोधकर्ताओं की समझ में वृद्धि हो तथा भविष्य में अत्यधिक तीव्र स्थानीयकृत घटनाओं का बेहतर अनुकरण किया जा सके। व्यवस्थित विश्लेषण के लिए इस अध्ययन में IHR को देशांतर के आधार पर 10×10 के बॉक्सों में विभाजित किया गया। इसके अतिरिक्त, विभिन्न बॉक्सों में बादल फटने की घटनाओं के दौरान प्रेक्षित वर्षा के संदर्भ में वायुमंडलीय गतिशीलता का सांख्यिकीय एवं प्रेक्षणात्मक विश्लेषण किया गया। घटनाओं से दो दिन पूर्व से प्रारंभ होने वाली अवधि को ध्यान में रखते हुए कालिक विश्लेषण किया गया। विभिन्न बॉक्सों में प्रमुख भौतिक एवं ऊष्मागतिकीय वायुमंडलीय मापदंडों तथा वर्षा के बीच संबंध को समझा और विश्लेषित किया गया। भविष्य के सटीक पूर्वानुमान के लिए वायुमंडल और भूमि की सतह के बीच जटिल अंतःक्रियाओं को समझना अत्यंत महत्वपूर्ण है। इन जटिल अंतःक्रियाओं के विस्तृत अध्ययन से ऐसे महत्वपूर्ण निष्कर्ष प्राप्त किए जा सकते हैं, जो पूर्वानुमान मॉडलों में सुधार तथा पृथ्वी की प्रणालियों की बेहतर समझ में सहायक होंगे।

ABSTRACT. In this research, the focus is on examining the occurrence of localized Cloudburst events in the Indian Himalayan region (IHR). Specifically, in the year 2022, a total of 66 cloudburst cases were observed in the region, indicating a rise in the severity of extreme rainfall events (ERE) in recent times. Due to limited information and awareness, the mountainous hazards often go unnoticed. As the topographical feature has wider variation and because of the regional divergence there is also a variability in the intensity, duration and frequency of the EREs. Therefore, it is crucial to study the dynamics of the atmosphere during these events in order to enhance the understanding of researchers and facilitate the simulation of highly intense localized events in the future. Longitude-wise box ($1^\circ \times 1^\circ$) was classified over the IHR in this research for a systematic analysis of the ERE dynamics. Furthermore, our study emphasized the statistical observational analysis of atmospheric dynamics in relation to observed rainfall across various boxes during the occurrence of the Cloudburst events. The temporal analysis is carried out by considering the atmospheric studies for the period starting 2 days before the event at the region. The relationship between major physical and thermodynamical atmospheric parameters and rainfall in different boxes has been comprehended and analysed. Understanding the intricate relationships between the atmosphere and land surface is crucial for making accurate predictions about the future. By delving into these complex interactions, researchers can gain valuable insights that can help improve forecasting models and enhance our understanding of the Earth's systems.

Key words – IHR, Box-wise analysis, Atmospheric dynamics, Correlation.

1. Introduction

The meteorological conditions in the Indian subcontinent and Central Asian highlands are significantly impacted by the presence of the Himalayas. Acting as a barrier, the Great Himalaya Range prevents the intrusion of cold continental air from the north into India during the winter season. Additionally, it compels the south-westerly monsoon winds to shed a substantial amount of their moisture before traversing the range in a northward direction. As a consequence, this leads to abundant rainfall on the Indian side of the Himalayas, while creating arid conditions in Tibet. The north-western regions and eastern states of the Himalayan range encounter a significant amount of rainfall during the monsoon season. This precipitation is known for its intensity and frequency, making it a common occurrence in these particular areas. An analysis of localized extreme rainfall events in the Indian mountain region, particularly the Himalayas, has provided valuable insights into precipitation patterns. It has been observed that as one moves from the southern foothills of the Himalayas towards the higher elevations in the north, there is a decrease in rainfall patterns. Notably, mean summer precipitation has shown an increase over the foothills in the Western Himalayas, while experiencing a decline at higher elevations. On the other hand, winter precipitation has witnessed a region-wide increase, except for certain specific areas. These findings shed light on the complex dynamics of rainfall distribution in the Indian mountain region and contribute to our understanding of the changing climate patterns in this ecologically significant area (Banerjee *et al.*, 2020). Summer precipitation in the Western Himalayas has shown an upward trend in the foothills, indicating an increase in rainfall in these lower-lying areas. Conversely, higher elevations have experienced a decrease in summer precipitation, suggesting a shift in weather patterns that favour more rainfall at lower altitudes. This spatial variation in summer precipitation highlights the complex nature of climate change impacts in the region (Saini *et al.*, 2023). The study examines the characteristics of precipitation patterns at different altitudes within the subregions of the Indian Himalayan Region (IHR), specifically focusing on Shivalik's IHR (SH), Lesser IHR (LH), and Higher IHR (HH). Furthermore, the research delves into the longitudinal variations across the western IHR (WH), central IHR (CH), and eastern IHR (EH). To analyze trends in precipitation, the study employs a non-parametric Mann-Kendall method, while change point detection is conducted using the Pettitt test. This comprehensive analysis provides valuable insights into the precipitation patterns and trends within the different subregions of the Indian Himalayan Region, contributing to a better understanding of the complex dynamics of precipitation distribution in this geographically diverse area (Yadav *et al.*, 2024). The ISM is responsible for providing

a considerable amount of moisture to the region, thereby playing a significant role in the occurrence of extreme rainfall events (Singh *et al.*, 1997 ; Chaudhuri *et al.*, 2015). The distribution of solar radiation and moisture movement, which in turn impacts precipitation distribution, is influenced by factors such as vegetation cover, soil moisture content, and surface roughness. These elements play a crucial role in determining how much solar radiation is absorbed or reflected, as well as how moisture is retained or evaporated from the soil surface (Banerjee *et al.*, 2020). The geographical features of the IHR create a conducive environment for the occurrence of cloudbursts, resulting in frequent flash floods and landslides that claim the lives of numerous individuals annually. Despite ongoing research, there remains uncertainty surrounding the precise mechanisms that drive cloudbursts, including orographic lifting, the distribution of precipitation, the thresholds for precipitation, and the source or origin of these phenomena (Kumar *et al.*, 2018). The moisture supply for cloudburst incidents in regions like Leh can exhibit variability, as certain occurrences might experience moisture intrusion from the Arabian Sea rather than the Bay of Bengal. Cloudbursts, which are characterized as meso-gamma scale events, can exert significant socio-economic impacts, particularly in remote hilly areas where the occurrence of flash floods and landslides is more likely (Dimri *et al.*, 2017). The Himalayan orography is not uniform across states; while Himachal Pradesh and Jammu & Kashmir exhibit a one-step barrier-like structure, Uttarakhand is characterized by a two-step orography, where moist air undergoes successive lifting over the Lesser Himalaya and the Greater Himalaya, leading to complex rainfall distribution (Singh and Kumar, 1997; Banerjee *et al.*, 2019; Dimri *et al.*, 2017). The atmospheric dynamics play a significant role in understanding the mechanisms behind such occurrences. Empirical investigations have consistently demonstrated a significant link between CAPE and the occurrence of extreme precipitation events, including cloudbursts. Notably, when comparing different data-driven methodologies, it has been consistently observed that CAPE exhibits the highest degree of correlation with extreme precipitation events among various meteorological variables (Antoniadou *et al.*, 2023 ; Vijaykumar *et al.*, 2021; Rybka *et al.*, 2021). The Convective Inhibition (CIN) serves as a crucial mechanism that inhibits the initiation of convective energy until a specific threshold is surpassed. Once this threshold is exceeded, convective storms have the potential to form quickly, which may result in the occurrence of intense precipitation events such as cloudbursts. The existence of extremely low CIN values ($< 0 \text{ J kg}^{-1}$) points towards conducive environments for storm generation, indicating limited convective inhibition and the possibility of intense rainfall events like cloudbursts (Ganjir *et al.*, 2022; Chevuturi *et al.*, 2015). The relationship between relative

humidity and cloudburst events is significant, as it influences the atmospheric conditions conducive to intense precipitation. The occurrence of cloudbursts is closely associated with the convergence of warm and cold air masses, as well as the interaction between saturated and unsaturated air. This unique combination of atmospheric conditions, commonly found within a temperature and humidity front, provides the necessary environment for the development of powerful and concentrated precipitation events, such as cloudbursts. The presence of high relative humidity, especially in conjunction with other atmospheric factors like temperature gradients, influences cloud dynamics and the potential for heavy precipitation events such as cloudbursts (Chaudhuri *et al.*, 2015). The interplay between wind shear and orographic lift has the potential to magnify the influence of these two mechanisms, culminating in the swift emergence of powerful precipitation events like cloudbursts. This synergy between the variation in wind velocity and direction across different altitudes and the upward displacement of air due to the presence of mountains or hills has been seen the impact of both forces, ultimately resulting in the rapid intensification of precipitation events (Kumar *et al.*, 2018). The presence of low cloud cover in India has a direct correlation with the incidence of cloudburst events, which can be attributed to specific atmospheric conditions. These cloudbursts are characterized by their short duration but high intensity, and they occur when the relative humidity and cloud cover are at their maximum levels, accompanied by low temperatures and slow winds. Localized extreme rainfall events, such as cloudbursts, are influenced by various factors including temperature gradients, humidity levels, topography, and monsoonal influences. These factors collectively shape the conditions that give rise to such intense precipitation. Temperature gradients refer to the differences in temperature across a given area, which can create instability in the atmosphere and contribute to the formation of cloudbursts. Humidity levels play a crucial role as well, as high levels of moisture in the air provide the necessary fuel for intense rainfall. Additionally, the topography of an area can impact the movement and concentration of moisture-laden air masses, further enhancing the likelihood of cloudbursts. Lastly, monsoonal influences, such as seasonal wind patterns, can bring about significant changes in weather patterns, leading to localized extreme rainfall events.

2. Data and methodology

2.1. Data

The India Meteorological Department (IMD) maintains a comprehensive archive of rainfall observation data for India, spanning over 125 years. It offers detailed daily gridded rainfall datasets for India with a high level of spatial resolution. These datasets span a significant

timeframe from 1901 to 2024 and can be accessed in two distinct resolutions: $1^\circ \times 1^\circ$ & $0.25^\circ \times 0.25^\circ$. The dataset is organized in a grid format, where each point represents a specific location. In the case of the $1^\circ \times 1^\circ$ dataset, the first data record begins at 6.5°N latitude & 66.5°E longitude, & it extends to 38.5°N latitude & 100.5°E longitude. On the other hand, for the $0.25^\circ \times 0.25^\circ$ dataset, the starting point remains the same at 6.5°N latitude & 66.5°E longitude, but it concludes at 38.5°N latitude & 100°E longitude (Rajeevan *et al.*, 2008). We have used $0.25^\circ \times 0.25^\circ$ rainfall data for our study analysis. The datasets hold significant importance in the examination of climate trends, anticipation of weather occurrences, & interpretation of the fluctuations in rainfall dispersion across diverse regions in India.

ERA5, a cutting-edge climate reanalysis, has been developed by the European Centre for Medium-Range Weather Forecasts (ECMWF) to provide a comprehensive understanding of the Earth's climate system. This state-of-the-art dataset offers a wealth of information, including hourly data on multiple atmospheric, land-surface, and ocean-state parameters. The atmospheric parameters are available at a high spatial resolution of $0.25^\circ \times 0.25^\circ$ across 37 pressure levels, enabling detailed analysis of the atmosphere. Furthermore, ERA5-Land surface variables are provided at a resolution of 9 km, allowing for a thorough examination of land-surface processes. With daily updates released five days after real time, ERA5 ensures that researchers and forecasters have access to the most recent and reliable climate data for their analyses and predictions (Hersbach *et al.*, 2020). It includes information about uncertainties for all variables at reduced spatial and temporal resolutions. The ERA5 reanalysis data was employed to gather information on various meteorological variables including CAPE, CINE, relative humidity, temperature, wind, and cloud cover. These variables were carefully selected to provide a comprehensive understanding of the atmospheric conditions during the study period. By utilizing this dataset, we were able to analyze and interpret the interplay between these factors and their impact on the observed phenomena. The data on cloudburst events is sourced from the South Asia Network on Dams, Rivers, and People (<https://sandrp.in/>) which is mainly based on media reports.

2.2. Methodology

Box-wise rainfall analysis in the Himalayan region focuses on examining the spatial variations of rainfall across different geographical divisions, topographical features, and altitudinal zones. While the provided search results do not contain direct box-wise rainfall analysis for the entire Himalayan region, they do provide relevant information regarding rainfall analysis in the region. The extent of each box are presented in Fig.1 and Table 1.

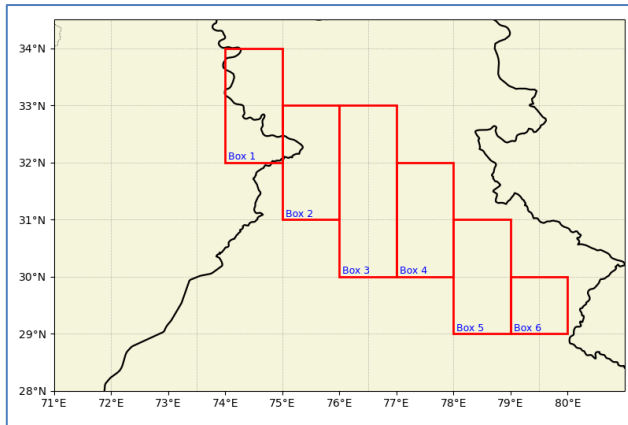


Fig. 1. Spatial map of study area highlighting the six boxes

TABLE 1

The classification of six regions (boxes) based on their longitudinal orientation

Region	Longitude extent (°E)	Latitude extent (°N)
Box 1	74-75	32-34
Box 2	75-76	31-33
Box 3	76-77	30-33
Box 4	77-78	30-32
Box 5	78-79	29-31
Box 6	79-80	29-30

This study aims to explore how the aforementioned atmospheric parameters interact and potentially influence the onset of cloudbursts. By analysing the correlations between observed rainfall and the different atmospheric (physical and thermodynamical) variables, the study seeks to gain insights into the complex dynamics that contribute to the occurrence of these intense precipitation events. This research focuses on examining the relationship between recorded rainfall and various atmospheric factors such as relative humidity, CAPE, CINE, temperature, wind, cloud coverage among others, in the context of cloudburst occurrences. The analysis specifically looks at the conditions prevailing on the day preceding the cloudburst event as well as two days prior to the event. In 2022, there were a total of 66 Cloudburst events (<https://sandrp.in/>) recorded across different states of IHR, as shown in table 2.

Here the localized and non-localized cloudbursts are clustered and the counts as well as analysis are done accordingly. Cloudburst events that are localized pertain to instances of heavy rainfall that are restricted to a small area. These occurrences are characterized by their high intensity and can result in substantial precipitation over a confined region, frequently resulting in sudden floods and

landslides. The prediction of localized cloudbursts poses a challenge due to their limited geographical scope and the swift formation of intense rainfall within a particular locality. On the contrary, non-localized cloudburst events are not constrained to a specific region but can have an impact on larger areas. These incidents may encompass a wider geographical expanse when compared to localized cloudbursts, leading to intense and abrupt rainfall affecting multiple locations simultaneously. While localized cloudbursts are more contained and focused, non-localized cloudbursts have the potential to affect a broader range, resulting in widespread flooding and other associated risks.

The Fig. 2, provides a visual breakdown of the distribution of events within the IHR framework, distinguishing between those that are localized and those that are non-localized. This categorization offers valuable insights into the nature and scope of events reported over the IHR. We used Pearson's correlation coefficient (cc) to quantify linear association between rainfall and atmospheric variables (CAPE, CIN, RH, etc.) at daily resolution. This method quantifies the linear association between two variables, ranging from -1 (perfect negative relationship) to $+1$ (perfect positive relationship). In this study, daily rainfall values were correlated with thermodynamic and dynamic parameters such as CAPE, CIN, relative humidity, temperature, wind shear, and cloud cover. Correlations were computed separately for each of the six spatial boxes and for three temporal windows: two days before the event, one day before the event, and on the event day. The advantage of using correlation analysis is that it provides a quantitative measure to evaluate how atmospheric instabilities and moisture conditions interact with observed rainfall across varying orographic settings in the IHR. By performing box-wise correlations, we were able to capture the spatial heterogeneity of these relationships and highlight differences between the one-step orography of Himachal Pradesh and Jammu & Kashmir, and the two-step orography of Uttarakhand. Figure 2. represents the spatial map highlighting location of Boxes (1-6) therein.

3. Results and discussion

Elevation and rainfall frequency are closely linked in affecting how precipitation is spread out in the Himalayan area. In 2022, the most rainfall and the highest number of cloudburst events happened at around ~ 2434 m, according to NCAR satellite data (Samantray and Gouda, 2024). This finding matches earlier research that shows precipitation patterns in the Indian Himalayan Region (IHR) depend a lot on elevation, with mid-elevations usually getting the heaviest rainfall because of better orographic uplift and moisture gathering (Singh and Kumar 1997; Banerjee and Dimri, 2019 ; Yadav *et al.*, 2024).

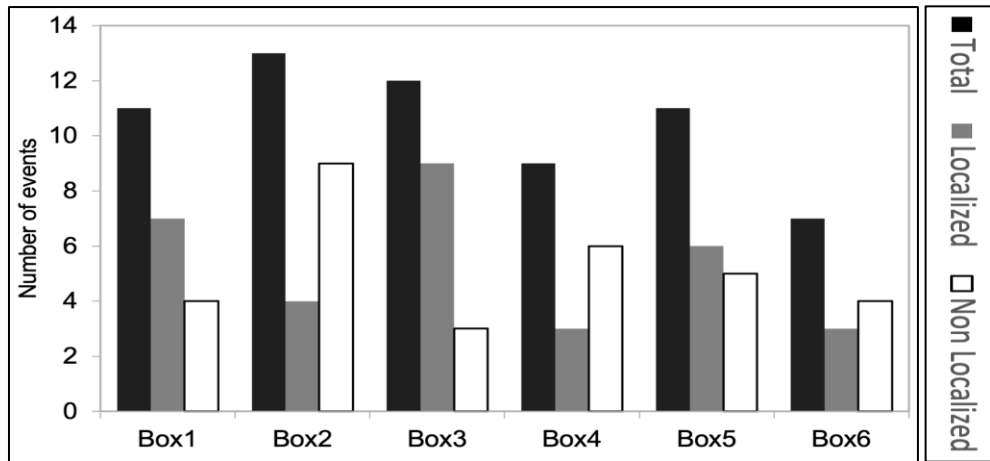
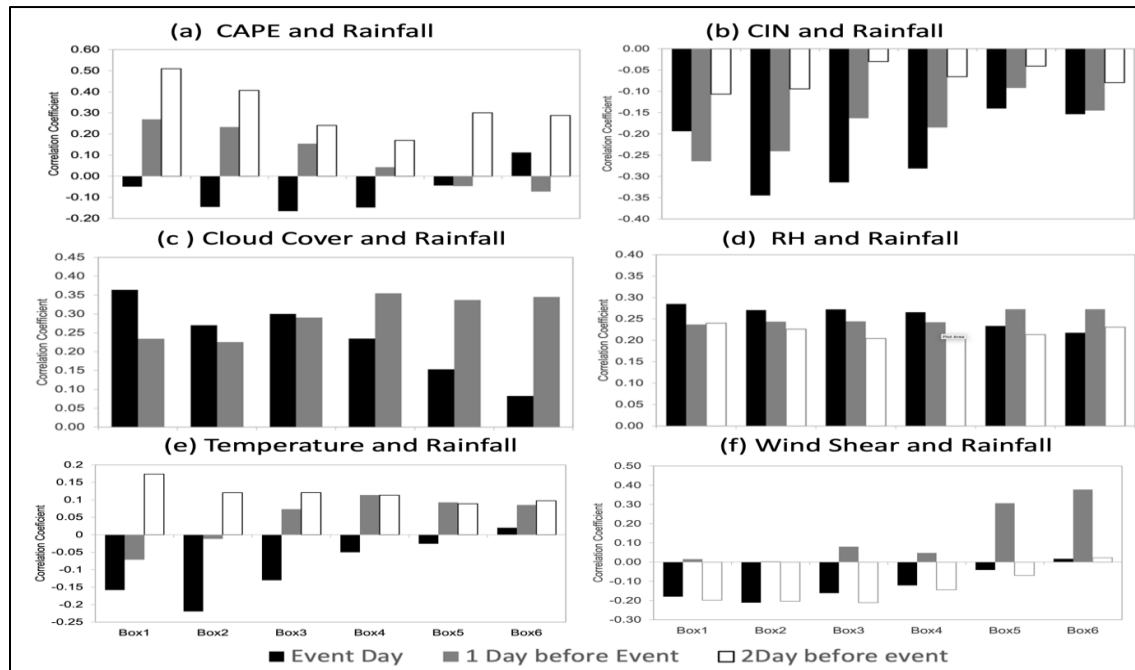


Fig. 2. Box-wise classification of localized and non-localised Cloudburst events

TABLE 2

The distribution of locations of Cloudburst events in 2022 over IHR

S.no.	Date in 2022	Lon(°E)	Lat (°N)	Location	S.no.	Date in 2022	Lon (°E)	Lat (°N)	Location
1	19-June	74.09	33.77	J&K	34	27-July	76.66	32.72	HP
2	24-July	74.09	33.77	J&K	35	2-July	76.67	32.72	HP
3	17-July	74.25	34.52	J&K	36	7-July	76.68	31.34	HP
4	20-July	74.35	34.20	J&K	37	15-June	77.11	31.96	HP
5	16-June	74.46	34.24	J&K	38	6-July	77.11	31.96	HP
6	9-May	74.64	33.93	J&K	39	9-July	77.11	31.96	HP
7	21-June	74.64	33.93	J&K	40	25-July	77.11	31.96	HP
8	26-July	74.69	34.51	J&K	41	28-July	77.11	31.96	HP
9	5-July	74.77	34.22	J&K	42	11-August	77.11	31.96	HP
10	20-August	74.84	33.08	J&K	43	16-July	77.17	31.10	HP
11	28-July	74.86	32.73	J&K	44	19-July	77.38	32.62	HP
12	30-May	75.12	32.57	J&K	45	25-September	77.47	30.56	HP
13	14-August	75.14	32.92	J&K	46	14-July	78.03	30.31	UK
14	8-July	75.15	33.73	J&K	47	25-September	78.03	30.31	UK
15	26-August	75.15	33.73	J&K	48	11-August	78.03	30.32	UK
16	11-August	75.19	33.24	J&K	49	24-August	78.43	30.37	UK
17	17-August	75.19	33.24	J&K	50	5-July	78.44	30.73	UK
18	17-July	75.51	32.38	J&K	51	11-August	78.44	30.73	UK
19	9-July	75.52	32.39	J&K	52	2-July	78.48	31.65	HP
20	9-July	75.55	33.15	J&K	53	18-July	78.48	31.65	HP
21	20-July	75.55	33.15	J&K	54	15-August	78.59	31.76	HP
22	28-July	75.77	33.31	J&K	55	1-August	78.77	30.15	UK
23	10-May	75.77	33.31	J&K	56	9-August	78.98	30.29	UK
24	6-July	75.77	33.31	J&K	57	9-July	79.45	29.39	UK
25	10-July	76.12	32.55	HP	58	7-May	79.45	29.39	UK
26	11-July	76.12	32.55	HP	59	20-July	79.56	30.29	UK
27	21-September	76.12	32.55	HP	60	10-August	79.56	30.29	UK
28	25-September	76.12	32.55	HP	61	10-May	79.77	29.84	UK
29	3-May	76.13	32.55	HP	62	8-July	79.77	29.84	UK
30	15-June	76.13	32.55	HP	63	8-July	80.22	29.58	UK
31	8-August	76.13	32.55	HP	64	10-September	80.22	29.58	UK
32	19-August	76.13	32.55	HP	65	30-July	80.22	29.58	UK
33	2-September	76.32	32.22	HP	66	27-June	79.45	29.39	UK



Figs.3(a-f). The correlation between Rainfall and (a) CAPE (b) CIN (c) Cloud cover (d) RH (e) temperature (f) wind shear for each box on the event day, one day prior, two days prior to the event

Specifically, the two-step orography means two successive mountain barriers that cause staged uplift of moist air, leading to complex rainfall timing and distribution. The rapid lifting also due to the combination of convection and orography resulting convectively triggered cell and thereafter formation of cloud and sudden cloudburst (Dimri *et al.*, 2017). This That's why Uttarakhand (Boxes 5–6) boosts lifting at mid-slopes, which helps explain the unique rainfall–CAPE relationships we found in our study, unlike the one-step terrain of Himachal and Jammu & Kashmir (Boxes 1–4). This shows how important topography is in influencing the frequency and strength of cloudburst events in the area.

The correlation between Convective Available Potential Energy (CAPE) and rainfall can vary depending on the specific weather patterns and atmospheric conditions. While a stronger correlation with rainfall two days before an event compared to one day before the event and the event days with respect to rainfall. The relationship between Convective Available Potential Energy (CAPE) and rainfall is characterized by a positive correlation, implying that higher CAPE values are often accompanied by an elevated probability of precipitation. CAPE represents the potential energy available for convective processes within the atmosphere. When CAPE values are elevated, it signifies a greater amount of energy that can be released through convection, thereby promoting the formation of rain. Consequently, it can be deduced that an upsurge in CAPE values generally corresponds to a high chance of rainfall.

The positive correlation coefficient (cc) is observed in the Fig. 3 (a), two days prior to the events in each box. Interestingly, in the Uttarakhand area (Boxes 5–6), the relationship between CAPE and rainfall becomes negative one day before the cloudburst event. This indicates that high CAPE values in these boxes do not necessarily lead to increased rainfall, probably because of Uttarakhand's complex two-step orography, which affects moisture convergence and can postpone convective release. Previous reports have noted such orographic influence, where elevation changes and step-like terrain greatly impact rainfall intensity and distribution (Singh and Kumar, 1997; Banerjee *et al.*, 2019). This implies that for further study, we can utilize the CAPE values two days prior to the event for forecasting purposes.

CIN is a measure of the amount of energy required to lift an air parcel to above the level of free convection, and it can prevent, delay, or inhibit the formation of storms. CIN and CAPE are correlated inversely, meaning that they exhibit opposite behaviour in terms of atmospheric stability and the promotion of convective precipitation events. The Fig. 3 (b), shows -ve cc of rainfall and CIN for each boxes on the event day, one day before the events and two days prior to the event. This inverse relationship indicates that when the atmosphere has sufficient energy for convection (high CAPE), the presence of CIN becomes less likely, thus promoting the development of convective storms. The larger and denser the clouds, the more moisture they can hold. When these clouds reach their saturation point, the water droplets coalesce and precipitate as rain, snow, or

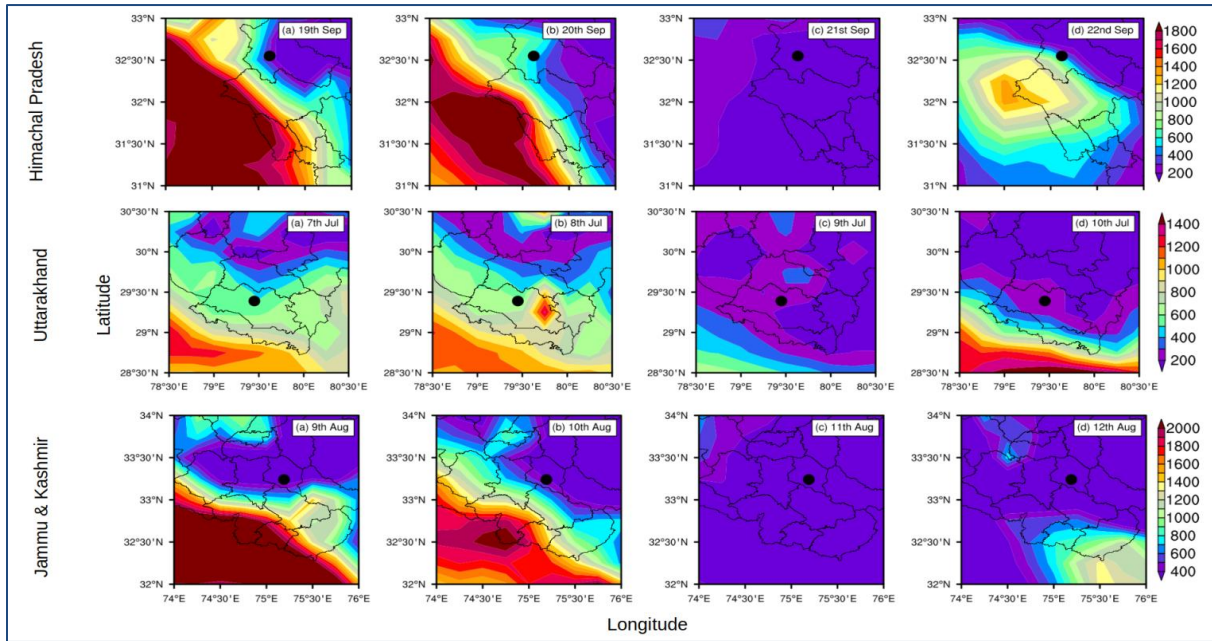


Fig.4. Spatial distribution of CAPE (J/kg) on the event day, one day prior, two days prior to the event and next day of the event in Himachal Pradesh, Uttarakhand and Jammu & Kashmir (2022)

hail. There's a complex relationship between cloud cover and precipitation, with a positive correlation acting as a general trend (Fig. 3(c)). The correlation of rainfall and low cloud cover represents a +ve cc in every box, which implies the indication of high convection during the event and one day prior to the event. Cloud cover and precipitation exhibit a positive correlation, indicating that there is a prevailing inclination for greater cloud cover to coincide with heightened probabilities of precipitation. The relationship between relative humidity (RH) and rainfall is indirect and not always a strong correlation. While higher RH generally indicates a higher potential for rain. RH denotes the moisture capacity of the air at a specific temperature. A higher RH indicates that the air is nearing its saturation point, which can result in condensation and the possibility of precipitation. Here the box-wise RH correlation shows a +ve cc with rainfall (Fig. 3 (d)). Elevated RH levels often accompany ascending air masses. The Fig. 3 (e), demonstrates an inverse relationship with precipitation on the days of the event across all boxes, with the exception of box 6. Conversely, temperature exhibits a positive correlation with rainfall on days preceding the event in the remaining boxes. In this study the vertical wind shear is characterized by a difference in wind speed and/or direction at 1000hpa and 850hpa in the atmosphere. The relationship between wind shear and precipitation in cloudburst events is complex and depends on various factors. While wind shear can impact the development of cloudbursts, it is not the sole factor determining their occurrence. The effects of wind shear can range from positive to negative, or even insignificant, depending on the specific conditions involved. Enhanced cloudburst development may occur

due to the influence of strong vertical wind shear, which can stretch and tilt rising air parcels. This stretching process can result in adiabatic cooling, thereby encouraging condensation and cloud growth within the atmosphere. Additionally, the presence of strong vertical wind shear can help organize the structure of a storm by segregating the updrafts and downdrafts. This organization has the potential to concentrate and intensify precipitation within the affected area, leading to more focused and intense rainfall. On the event day the cc between wind shear and rainfall showing -ve, except in box 6. In other hand the cc shows +ve on the one day prior to the event. (Fig. 3(f)). In certain cases the presence of powerful vertical wind shear has the potential to diminish the intensity of cloudbursts by causing a tilting effect on the updraft, diverting it away from the source of moisture. Consequently, this tilting action restricts the quantity of moisture accessible for the processes of condensation and precipitation. As a result, the vertical structure of the storm becomes disrupted, ultimately leading to a reduction in intensity and a more extensive distribution of rainfall.

To analyze the spatial distribution of extreme precipitation events, we selected one representative event from each state based on rainfall intensity. Three distinct events were examined in order of decreasing intensity: the most severe event occurred on July 9, 2022, in Uttarakhand with an observed rainfall intensity of 225 mm/hr, followed by the September 21, 2022 event in Himachal Pradesh recording 177 mm/hr, and the August 11, 2022 event in Jammu & Kashmir with an intensity of 96 mm/hr.

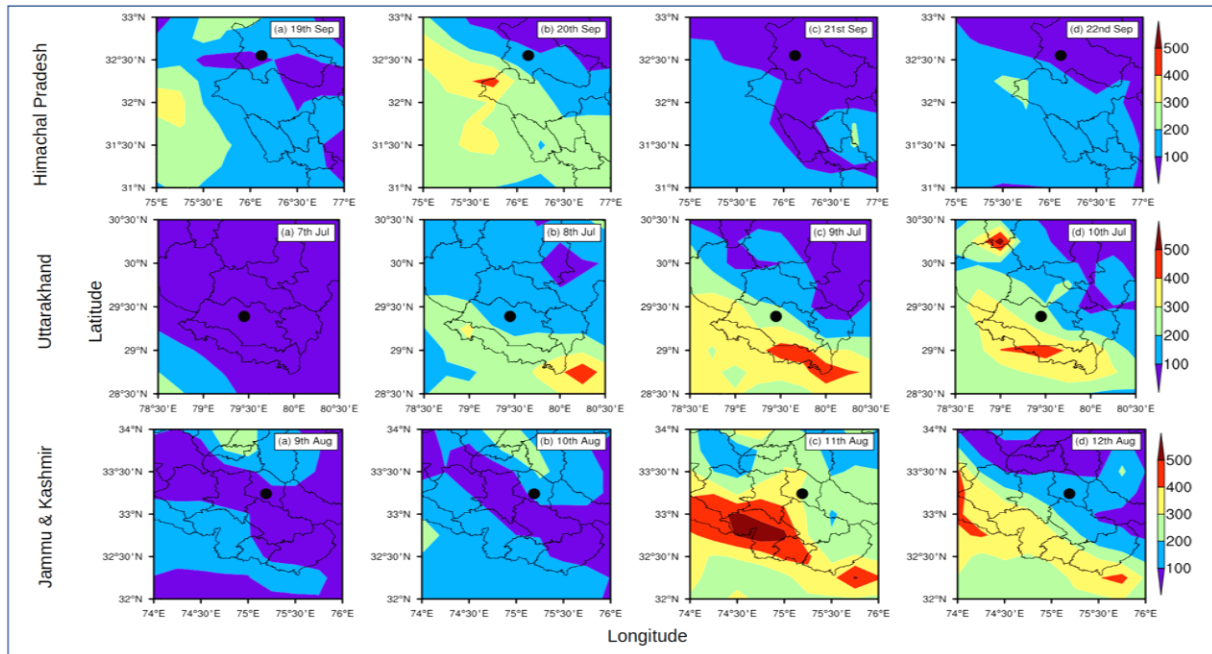


Fig.5. Spatial distribution of CIN on the event day, one day prior, two days prior to the event and next day of the event in Himachal Pradesh Uttarakhand and Jammu & Kashmir in 2022

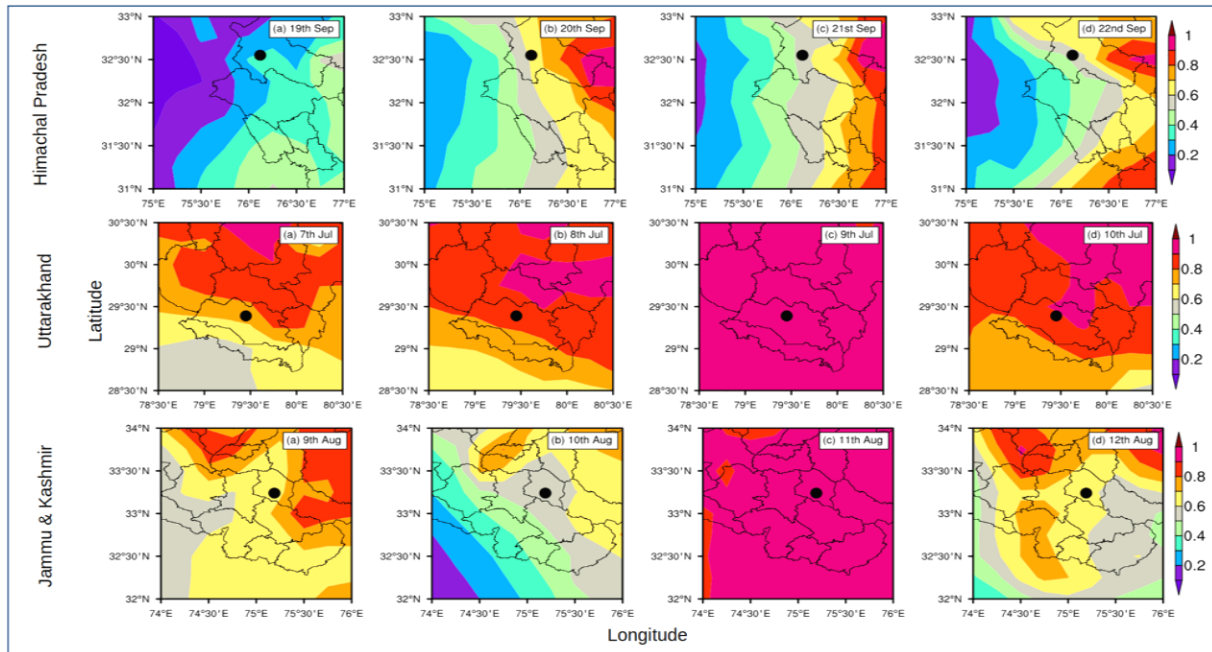


Fig.6. Spatial distribution of Cloud cover on the event day, one day prior, two days prior to the event and next day of the event in Himachal Pradesh, Uttarakhand and Jammu & Kashmir in 2022

The spatial distribution of Convective Available Potential Energy (CAPE) over Himachal Pradesh, Uttarakhand, and Jammu & Kashmir during selected cloudburst events and their surrounding days reveals a consistent pattern of atmospheric instability. Two days prior to each event, CAPE values remain moderate, indicating the onset of convective conditions. A sharp rise

in CAPE is observed one day before the event, with values exceeding 1200–2000 J/kg in several regions, highlighting the buildup of strong atmospheric instability favorable for deep convection, as shown in Fig. 4. On the day of the cloudburst, CAPE values decline compared to the preceding day. This reduction suggests that the accumulated convective energy was released through

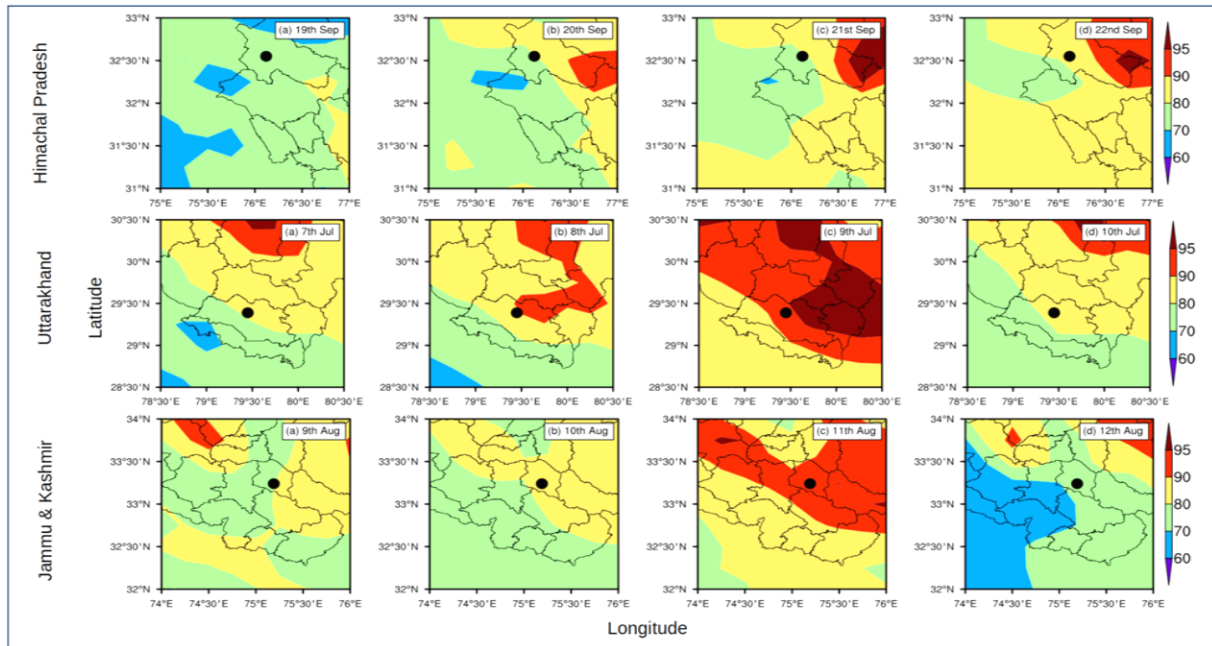


Fig.7. Spatial distribution of Relative Humidity on the event day, one day prior, two days prior to the event and next day of the event in Himachal Pradesh, Uttarakhand and Jammu & Kashmir in 2022

intense convection, leading to the cloudburst event. One day after the event, CAPE values further decrease to relatively low levels, reflecting stabilization of the atmosphere following the energy discharge.

CIN values, which are initially high two days before, gradually weaken by one day prior, lowering the barrier for parcel ascent. On the cloudburst day, CIN becomes very weak, which is 100–200 J/kg, allowing the accumulated CAPE to be explosively released as deep convection and extreme rainfall. After the events, CAPE drops while CIN increases again, reflecting stabilization of the atmosphere. (Fig. 5)

The evolution of total cloud cover over Himachal Pradesh, Uttarakhand, and Jammu & Kashmir during the days surrounding cloudburst events is shown in Fig. 6. In all three regions, cloud cover gradually increases from two days before the events, with moderate coverage (shades of blue–green, ~ 0.4 – 0.6) visible one day prior. On the day of the events, extensive and dense cloud cover (red to dark red shades, ~ 0.9 – 1.0) dominates the affected regions, reflecting the strong convective activity and moisture accumulation necessary for intense rainfall. Following the events, cloud cover decreases substantially in most cases (returning to blue–green shades), indicating dissipation of deep convection after the rainfall outburst. This temporal progression clearly highlights the pre-conditioning of the atmosphere with increasing cloudiness, peaking on the event day, and subsequent reduction as the systems weakened post-cloudburst.

The analysis also shows the Relative Humidity (RH) distribution (%) (Fig. 7) over Himachal Pradesh, Uttarakhand, and Jammu & Kashmir during cloudburst events, similar to the CAPE (Fig. 4) and CIN analyses (Fig. 5). The analysis of Relative Humidity (RH) during cloudburst events over Himachal Pradesh, Uttarakhand, and Jammu & Kashmir shows a clear pattern of moisture buildup and release. Two days before the events, RH values remain moderate (65–80%), indicating the presence of some moisture but not fully saturated conditions. A sharp increase in RH is observed one day prior to the events, with values often rising above 80–90%, reflecting strong moisture convergence into the region. On the day of the cloudburst, RH reaches its peak, frequently exceeding 90–95%, creating a nearly saturated atmosphere highly favorable for deep cloud development and extreme rainfall. Following the events, RH values decline again to moderate levels, highlighting the drying and stabilization of the atmosphere after the convective release. These results demonstrate that high RH, provides the necessary moisture supply and saturation required for the occurrence of cloudbursts in the Himalayan region.

The Fig. 8 shows spatial temperature variations over Himachal Pradesh, Uttarakhand, and Jammu & Kashmir during the days surrounding cloudburst events. In all three regions, a consistent warming trend is observed in the two days leading up to the events, with widespread high temperatures (~ 304 – 307 K). On the day of the events, cooler temperature pockets (~ 298 – 302 K) appear prominently, especially over elevated regions, indicating localized cooling due to strong convection and cloud

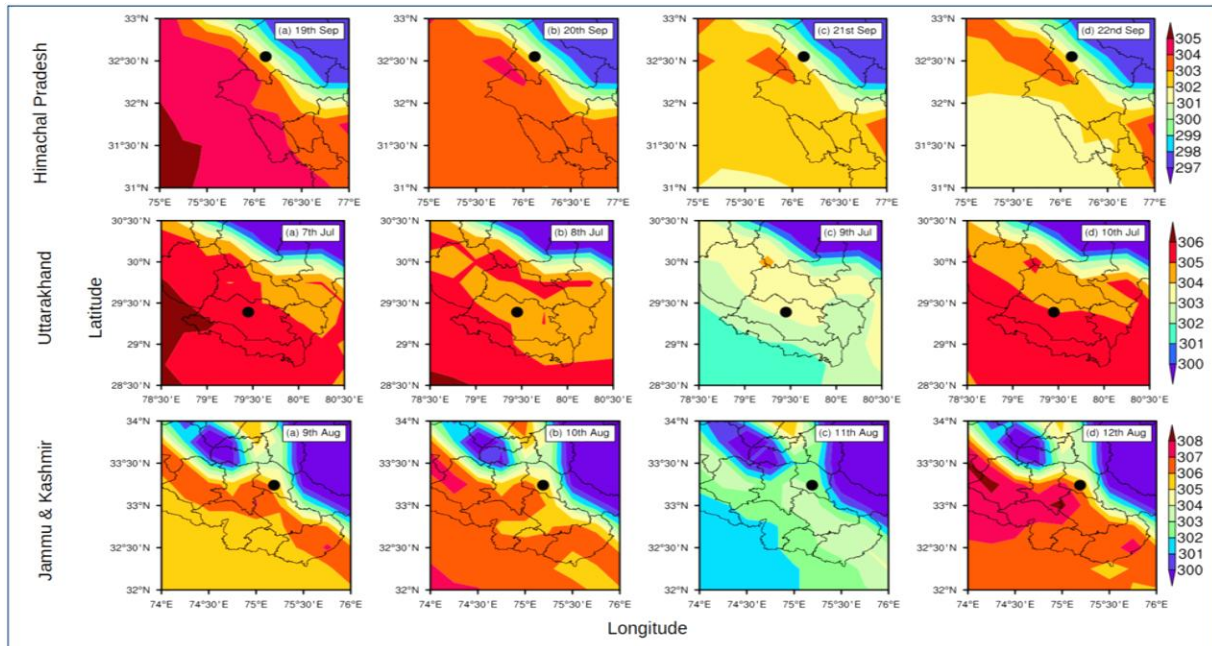


Fig.8. Spatial distribution of temperature on the event day, one day prior, two days prior to the event and next day of the event in Himachal Pradesh, Uttarakhand and Jammu & Kashmir in 2022

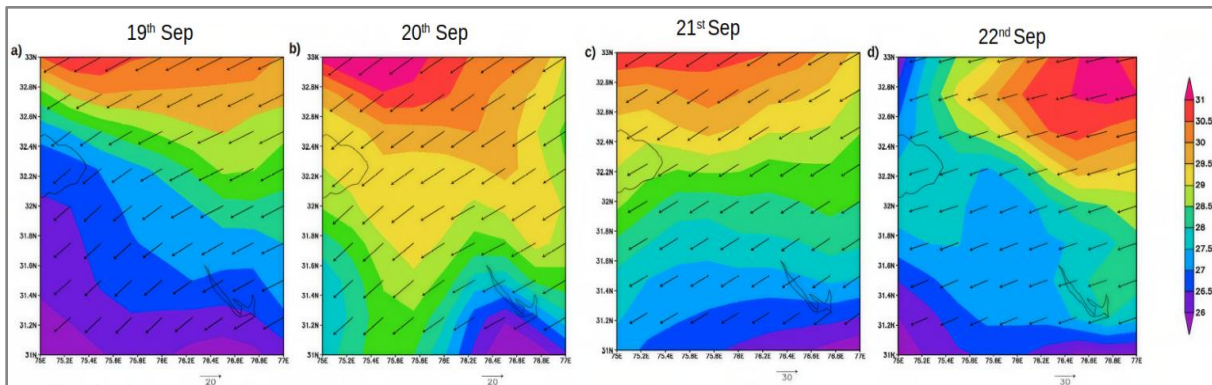


Fig. 9. Spatial distribution of wind shear on the event day, one day prior, two days prior to the event and next day of the event in Himachal Pradesh in 2022

development. This sharp contrast between pre-event warming and event-day cooling highlights the destabilization of the atmosphere, where accumulated heat and moisture rapidly lifted to higher altitudes, resulting in condensation and intense rainfall. The post-event maps show partial warming again, suggesting a return to background conditions after the release of latent heat during the cloudburst. Overall, the sequence reflects the crucial role of pre-event heating followed by sudden localized cooling in triggering cloudbursts across the Indian Himalayan region.

Fig. 9 shows vertical wind shear over Himachal Pradesh during 19-22 September 2022. Shear values increased from 26-29 m/s on 19 September to 30-31 m/s by 20-21 September, with winds shifting from northeast-

southwest alignment. The strongest shear coincided with the cloudburst event on 21 September, creating optimal conditions for sustained convection through enhanced upper-level divergence and moisture transport. Post-event conditions on 22 September showed weakened shear (<29 m/s) and reduced wind alignment, indicating atmospheric relaxation.

A Strong, persistent vertical wind shear with organized northwesterly-westerly flow characterized the four-day period, with peak intensity on 8 July (Fig. 10) The Uttarakhand cloudburst (7-10 July 2022) was characterized by strong, persistent northwesterly-westerly flow with peak intensity on 8 July, creating optimal conditions for sustained convection through enhanced moisture advection and orographic lifting along the Himalayan foothills.

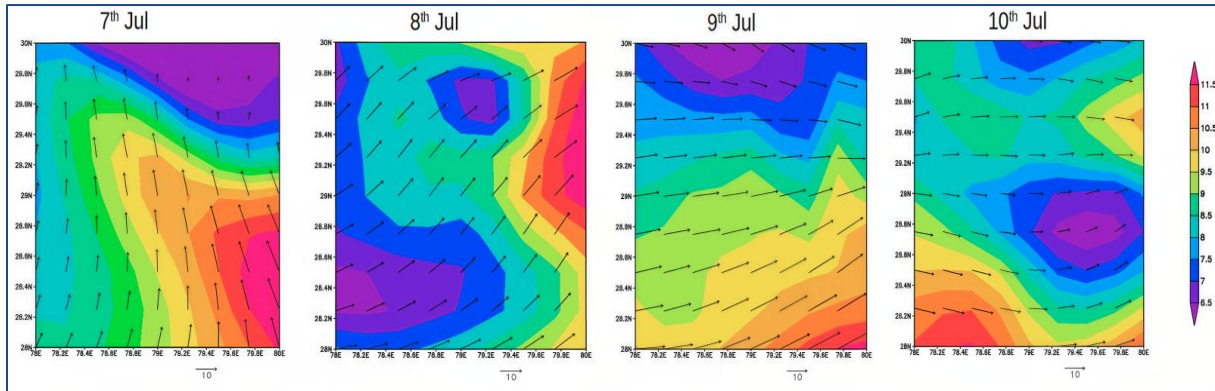


Fig. 10. Spatial distribution of wind shear on the event day, one day prior, two days prior to the event and next day of the event in Uttarakhand in 2022

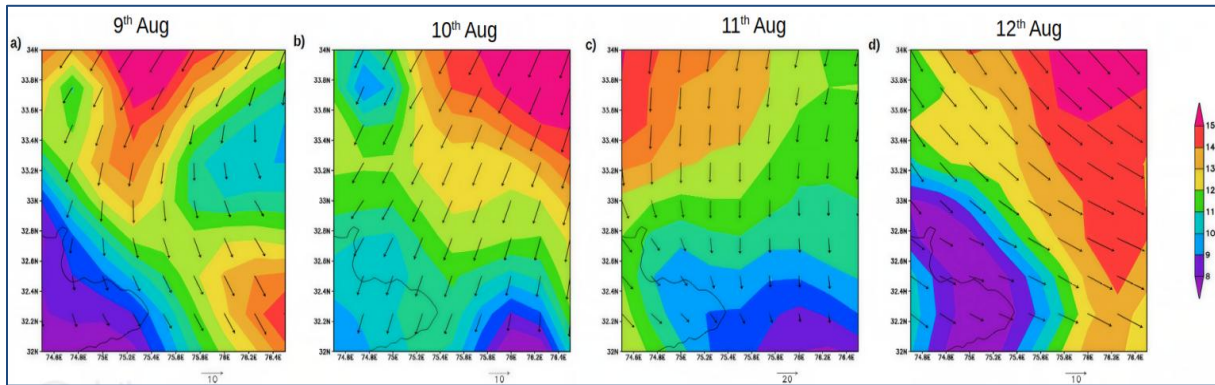


Fig. 11. Spatial distribution of wind shear on the event day, one day prior, two days prior to the event and next day of the event in Jammu & Kashmir in 2022

The Fig. 11 shows wind shear variability over Jammu & Kashmir during 9–12 August 2022. In the days leading up to the cloudburst on 11th August 2022 in Jammu & Kashmir, the wind shear patterns show how the atmosphere evolved to favor the event on 9th and 10th August, winds blowing mainly from the northwest to southeast transported large amounts of moist air into the region, with noticeable shear and convergence helping accumulate instability on the event day, 11th August. Winds show a clear north-to-south and northwest-to-southeast orientation, converging in the central and southern regions during the event. Wind shear is relatively weaker compared to previous days, meaning winds are more aligned vertically. This reduction in shear and presence of strong convergence leads to vertical uplift of moist air, triggering deep convection. The uplift releases latent heat, resulting in Cloudburst event.

4. Conclusions

This study emphasizes the localized analysis of Cloudburst events and the impact of atmospheric dynamics during the events is more important for future prediction. we have mentioned the cloudburst event cycle as two days prior to the event, one day before the event, and the event day. This research emphasizes the important spatial and

topographic effects on cloudburst dynamics in the IHR. We observed a steady positive link between CAPE and rainfall two days before the events in all six boxes, indicating its potential as an early warning sign. However, in Uttarakhand (Boxes 5–6), a negative correlation was noted one day before the event, showing that high CAPE does not always lead to rainfall due to two-step orography and delayed moisture release. In contrast, Himachal Pradesh and J&K (Boxes 1–4) with one-step topography showed a stronger direct relationship between CAPE and rainfall. Other thermodynamic factors like CIN (negative), RH (positive), cloud cover (positive), and wind shear (negative) also displayed consistent patterns across the boxes. These results highlight the need to integrate atmospheric predictors with orographic context to enhance the forecasting of cloudburst events in the IHR. These events are projected to become more frequent and intense due to rising temperatures and changes in atmospheric circulation patterns. By understanding the dynamics of cloudbursts, scientists can better assess the potential impacts of climate change and develop adaptation strategies. Combining information about cloud cover, moisture content, atmospheric stability, and other relevant factors provides a more accurate understanding of the likelihood and type of precipitation.

Acknowledgements

This work is supported by the projects funded by the National Mission on Himalayan Studies (NMHS) of Ministry of Environment, Forest and Climate Change (MoEFCC), Govt. of India, for the project funding support (grant no: GBPNI/NMHS-2019–20/MG/315), CSIR Mission Mode Project (MMP055202) and the project funded by the WOS of DST, Govt. of India. The authors also acknowledge the Director, CSIR NIDSA for his encouragement and support. We kindly acknowledge the use of the CSIR NIDSA high-performance computing (HPC) facility for computational work.

Data Availability

IMD gridded Data and ERA-5 is used for the analysis.

Funding

This work is supported by the projects funded by the WOS of DST, NMHS of MOEFCC, Govt. of India and CSIR Mission Mode Project (MMP055202).

Authors' contributions

P. Samantray: Conceptualization, analysis, investigation, and original and final draft preparation ([email: payoshnisamantray@gmail.com](mailto:payoshnisamantray@gmail.com))

K.C. Gouda: Conceptualization, investigation, original and final draft preparation, Supervision.

Disclaimer: The contents and views expressed in this research article are the views of the authors and do not necessarily reflect the views of the organizations they belong to.

References

- Antoniadou, N., Sørup, H.J.D., Pedersen, J.W., Gregersen, I.B., Schmith, T. and Arnbjerg-Nielsen, K., 2023, "Comparison of data-driven methods for linking extreme precipitation events to local and large-scale meteorological variables", *Stoch. Environ. Res. Risk Assess.*, 37, 11. 4337-4357, <https://doi.org/10.1007/s00477-023-02511-3>.
- Banerjee, A. and Dimri, A.P., 2019, "Comparative analysis of two rainfall retrieval algorithms during extreme rainfall event: A case study on cloudburst, 2010 over Ladakh (Leh), Jammu and Kashmir", *Nat. Hazards*, 97, 3. 1357-1374, <https://doi.org/10.1007/s11069-019-03714-0>.
- Banerjee, A., Dimri, A.P. and Kumar, K., 2020, "Rainfall over the Himalayan foot-hill region: Present and future", *J. Earth Syst. Sci.*, 129, 11. 1-16, <https://doi.org/10.1007/s12040-019-1295-2>.
- Chaudhuri, C., Tripathi, S., Srivastava, R. and Misra, A., 2015, "Observation- and numerical-analysis-based dynamics of the Uttarkashi cloudburst", *Ann. Geophys.*, 33, 6. 671-686, <https://doi.org/10.5194/angeo-33-671-2015>.
- Chevuturi, A., Dimri, A.P., Das, S., Kumar, A. and Niyogi, D., 2015, "Numerical simulation of an intense precipitation event over Rudraprayag in the central Himalayas during 13-14 September 2012", *J. Earth Syst. Sci.*, 124, 7. 1545-1561, <https://doi.org/10.1007/s12040-015-0622-5>.
- Dimri, A.P., Chevuturi, A., Niyogi, D., Thayyen, R.J., Ray, K., Tripathi, S.N., Pandey, A.K. and Mohanty, U.C., 2017, "Cloudbursts in Indian Himalayas: A review", *Earth-Sci. Rev.*, 168, 1-23, <https://doi.org/10.1016/j.earscirev.2017.03.006>.
- Ganjir, G., Pattnaik, S. and Trivedi, D., 2022, "Characteristics of dynamical and thermo-dynamical variables during heavy rainfall events over the Indian region", *Dyn. Atmos. Oceans*, 99, 101315, <https://doi.org/10.1016/j.dynatmoce.2022.101315>.
- Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., Nicolas, J., Peubey, C., Radu, R., Schepers, D. and Simmons, A., 2020, "The ERA5 global reanalysis", *Quart. J. Roy. Meteorol. Soc.*, 146, 730. 1999-2049, <https://doi.org/10.1002/qj.3803>.
- Kumar, A., Gupta, A.K., Bhambri, R., Verma, A., Tiwari, S.K. and Asthana, A.K.L., 2018, "Assessment and review of hydrometeorological aspects for cloudburst and flash flood events in the third pole region (Indian Himalaya)", *Polar Sci.*, 18, 5-20, <https://doi.org/10.1016/j.polar.2018.08.004>.
- Prathipati, V.K., Viswanadhapalli, Y., Chennu, V.N. and Dasari, H.P., 2022, "Evaluation of Weather Research and Forecasting model downscaled rainfall and its variability over India", *Int. J. Climatol.*, 42, 3. 1418-1444, <https://doi.org/10.1002/joc.7311>.
- Rajeevan, M., Bhate, J. and Jaswal, A.K., 2008, "Analysis of variability and trends of extreme rainfall events over India using 104 years of gridded daily rainfall data", *Geophys. Res. Lett.*, 35, 18. L18707, <https://doi.org/10.1029/2008GL035143>.
- Rybka, H., Burkhardt, U., Köhler, M., Arka, I., Bugliaro, L., Görsdorf, U., Horváth, Á., Meyer, C.I., Reichardt, J., Seifert, A. and Strandgren, J., 2021, "The behavior of high-CAPE (convective available potential energy) summer convection in large-domain large-eddy simulations with ICON", *Atmos. Chem. Phys.*, 21, 6. 4285-4318, <https://doi.org/10.5194/acp-21-4285-2021>.
- Saini, R., Sharma, N. and Attada, R., 2023, "Delving into recent changes in precipitation patterns in the Western Himalayas under global warming", in *Global Warming — A Concerning Component of Climate Change*, IntechOpen, <https://doi.org/10.5772/intechopen.1002028>.
- Samantray, P. and Gouda, K.C., 2024, "A comprehensive study of atmospheric dynamics associated with cloudburst events in 2022 over Indian Himalayan Region", *J. Earth Syst. Sci.*, 133, 3. 151, <https://doi.org/10.1007/s12040-024-02370-8>.
- Singh, P. and Kumar, N., 1997, "Effect of orography on precipitation in the western Himalayan region", *J. Hydrol.*, 199, 1-2. 183-206, [https://doi.org/10.1016/S0022-1694\(96\)03222-2](https://doi.org/10.1016/S0022-1694(96)03222-2).
- Vijaykumar, P., Abhilash, S., Sreenath, A.V., Athira, U.N., Mohanakumar, K., Mapes, B.E., Chakrapani, B., Sahai, A.K., Niyas, T.N. and Sreejith, O.P., 2021, "Kerala floods in consecutive years – Its association with mesoscale cloudburst and structural changes in monsoon clouds over the west coast of India", *Weather Clim. Extremes*, 33, 100339, <https://doi.org/10.1016/j.wace.2021.100339>.
- Yadav, M., Dimri, A.P., Mal, S. and Maharana, P., 2024, "Elevation-dependent precipitation in the Indian Himalayan Region", *Theor. Appl. Climatol.*, 155, 2. 815-828, <https://doi.org/10.1007/s00704-023-04661-4>.