



Assessment of wet spell over Northwest India during the first week of March 2024

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सार – पश्चिमी हिमालयी क्षेत्र (WHR) और उत्तर-पश्चिम भारत (NWI) के मैदानी इलाकों में शीतकालीन वर्षण (सर्दियों की बारिश) एक उल्लेखनीय मौसम घटना है जो दिसंबर और मार्च की शुरुआत के बीच होती है। सर्दियों के महीने WHR और NWI में महत्वपूर्ण वर्षण लाते हैं, जो कृषि और जल संसाधनों को प्रभावित करते हैं। यह शोध पत्र मार्च के पहले सप्ताह के दौरान एक महत्वपूर्ण आर्द्र अवधि (Wet spell) की जांच करता है, जो दोनों क्षेत्रों में भारी वर्षा, तीव्र गरज और ओलावृष्टि द्वारा अभिलक्षित थी। 1-3 मार्च, 2024 के दौरान की यह आर्द्र अवधि मुख्य रूप से एक पश्चिमी विक्षोभ (Western Disturbance - WD) से प्रभावित थी, जिसके कारण प्रेरित चक्रवाती परिसंचरण (Induced cyclonic circulation) और प्रेरित कम दबाव प्रणालियों का निर्माण हुआ। इन वायुमंडलीय स्थितियों ने भारी वर्षण की घटना के लिए एक अनुकूल वातावरण तैयार किया। इसके अतिरिक्त, अरब सागर से नमी की निरंतर आपूर्ति ने इस घटना में महत्वपूर्ण योगदान दिया। नमी के इस प्रवाह ने वर्षा की तीव्रता को बढ़ाया और गंभीर गरज के साथ ओले गिरने की प्रक्रिया को सुगम बनाया।

इस अध्ययन से पश्चिमी विक्षोभ और नमी की आपूर्ति के बीच जटिल संबंध का पता चलता है, जो पश्चिमी गोलार्ध (इन्डो-एशिया) और उत्तर पश्चिमी गोलार्ध (एनडो-एशियाई) में शीतकालीन वर्षा की घटनाओं को उत्पन्न करने में महत्वपूर्ण भूमिका निभाते हैं। मौसम प्रणालियों, विशेष रूप से पश्चिमी विक्षोभ, की इन परस्पर क्रियाओं को समझना क्षेत्र में मौसम पूर्वानुमान में सुधार और चरम मौसम के प्रभावों के प्रबंधन के लिए अत्यंत आवश्यक है। इस दौरान, जम्मू, नाहन और मनाली जैसे कुछ स्टेशनों पर रिकॉर्ड तोड़ वर्षा हुई और ये जलवायु संबंधी अभिलेखों में शीर्ष 5 श्रेणियों में शामिल हुए। भारी वर्षा के आंकड़ों से पता चला कि 3 मार्च को जम्मू-कश्मीर और उत्तराखंड के उपखंडों में सबसे अधिक वर्षा दर्ज की गई, कुछ स्टेशनों पर 12 सेमी तक, जबकि हरियाणा में 10 सेमी वर्षा हुई। स्टेशनवार आंकड़ों से पता चलता है कि 2 मार्च को हिमाचल प्रदेश उपखंड में सबसे अधिक स्टेशनों पर भारी वर्षा हुई, उसके बाद जम्मू-कश्मीर का स्थान रहा। हालांकि, 3 मार्च को जम्मू-कश्मीर में भारी से बहुत भारी वर्षा हुई, उसके बाद हिमाचल प्रदेश, हरियाणा और उत्तराखंड का स्थान रहा। भविष्य के शोध में जलवायु परिवर्तन के संदर्भ में इन मौसम पैटर्न के दीर्घकालिक प्रभावों का पता लगाया जाना चाहिए।

ABSTRACT. Winter precipitation in the Western Himalayan Region (WHR) and the plains of Northwest India (NWI) is a notable weather phenomenon that occurs between December and early March. The winter months bring critical precipitation to the WHR and NWI, impacting agriculture and water resources. This paper investigates a significant wet spell during the first week of March, characterized by heavy rainfall, intense thunderstorms, and hailstorms across both regions. The wet spell during 1st-3rd March, 2024 was primarily influenced by a Western Disturbance (WD), which led to the formation of induced cyclonic circulation and induced low-pressure systems. These atmospheric conditions created a conducive environment for the occurrence of heavy precipitation. Additionally, a steady supply of moisture from the Arabian Sea significantly contributed to the event. This influx of moisture enhanced rainfall intensity and facilitated the development of severe thunderstorms and hail.

This investigation highlights the intricate relationship between Western Disturbances and moisture supply in generating winter precipitation events in the WHR and NWI. Understanding these interactions of weather systems mainly WD is vital for improving weather forecasting and managing the effects of extreme weather in the region. During this episode some of the stations like Karta, Jammu, Nahan and Manali received record breaking rainfall and placed in top 5 categories in climatological records. The heavy rainfall data revealed that on 3rd March, the subdivisions of Jammu &

Kashmir and Uttarakhand recorded the highest rainfall, with some stations receiving 12 cm, followed by Haryana at 10cm. Station-wise data indicates that on 2nd March, the highest number of stations in the Himachal Pradesh subdivision reported heavy rainfall, followed by Jammu & Kashmir. On 3rd March, however, stations experienced heavy to very heavy rainfall in Jammu & Kashmir, followed by Himachal Pradesh, Haryana, and Uttarakhand. Future research should explore the long-term implications of these weather patterns in the context of climate change.

Key words– Western Disturbance (WD), Northwest India, Heavy precipitation, Hailstorm.

1. Introduction

Winter precipitation over the Western Himalayan Region (WHR) and plains of the Northwest India (NWI) is a significant weather event that typically encompasses the months of December through February, extending into early March. This period is characterized by various weather patterns and impacts due to the region's unique geographical and climatic features. During these winter months, essential rainfall is brought to the WHR and NWI, influencing agriculture and water availability.

Winter precipitation in NWI is characterized by several critical aspects, affecting both the WHR and the adjoining plains, including Punjab, Haryana, Chandigarh, Rajasthan, Uttar Pradesh (UP), and even extending into North Madhya Pradesh (MP). The precipitation over the region manifests primarily as snowfall in the higher reaches of the WHR, leading to the accumulation of snow that impacts tourism, local travel, and Infrastructure and heightens avalanche risk. In contrast, the plains adjoining WHR receive rainfall, crucial in dam management, agriculture, and water resources. However, it may also cause waterlogging and localized flooding mainly in the region's urban areas. The basic drivers of winter precipitation over this region of study are the WDs, which originate in the Mediterranean and bring moisture-laden air into the region, often intensified by embedded induced cyclonic circulations. These weather systems significantly influence regional climate patterns and socio-economic activities. Local Infrastructure often suffers due to heavy and persistent snowfall, which hampers local transportation and disrupts daily and routine utilities. The impact on agriculture is twofold: it provides essential moisture for *Rabi* crops but poses risks like frost or hail damage. Moreover, snowmelt from these winter events contributes substantially to the region's water supply, sustaining rivers and reservoirs critical for downstream needs in the ensuing dry months.

Winter precipitation in NWI is crucial in shaping the region's climate, influencing water resources, agriculture, and daily life. Understanding these patterns helps in preparing for and mitigating the impacts of severe weather events.

Research on Western Disturbances (WDs) is actively progressing, with numerous studies examining various

aspects such as observation, monitoring, impacts, climate change, and their association with other weather systems. A review book by Dimri and Chevuturi (2016) is a significant resource for understanding WDs from an Indian perspective. Recently, Hunt *et al.* (2024) have contributed a comprehensive review that further expands on this topic.

In a detailed analysis, Hasan and Pattanaik (2024) studied ten WDs and their associated cyclonic circulations from 2018 to 2022. Dimri *et al.* (2023) compared WD and non-WD days in relation to winter precipitation from 1987 to 2020. Additionally, Dar (2023) explored trends in winter precipitation extremes over the WHR linked to WDs. Hunt *et al.* (2024) investigated the influence of climate change on the water cycle in the WHR during winter. The evolution, seasonality, and impacts of WDs were examined by Hunt *et al.* (2018a), while extreme daily rainfall mechanisms in northern India were detailed in Hunt *et al.* (2018b). Furthermore, Hunt *et al.* (2019) analyzed the declining trend of WDs. Mirza and Pattnaik (2024) studied 10 WD events during the winter season that caused extreme precipitation over the WHR with emphasize on associative mechanisms leading to the Induced Circulations.

Kumar *et al.* (2015) documented the winter frequency of WDs over Himachal Pradesh, and in a subsequent study, Kumar *et al.* (2017) focused on heavy rainfall events in March 2015 across parts of India.

Building on this foundation, the current paper investigates a case study of heavy precipitation, thunderstorms, and hailstorm activities occurring from 1st-4th March, 2024, over NWI.

2. Data and methodology

In this paper, a case study of heavy precipitation, thunderstorms, and hailstorm activities that occurred from 1st-4th March, 2024, over NWI have been studied. According to the India Meteorological Department (IMD), NWI comprises 9 meteorological subdivisions: Jammu-Kashmir – Ladakh – Gilgit – Baltistan-Muzaffarabad, Himachal Pradesh, Punjab, Uttarakhand, West Rajasthan, East Rajasthan, Haryana–Chandigarh-Delhi, West UP, and East UP. These meteorological divisions of NWI are shown in green in Fig. 1.

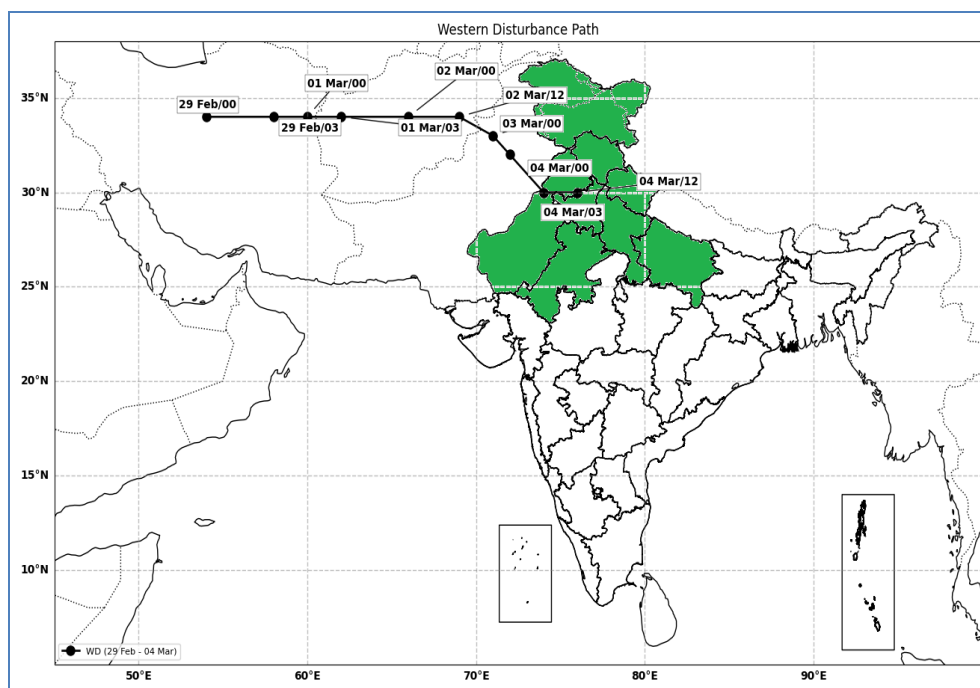


Fig. 1. Study Area (shown by green colour) and track of WD during 29th February-4th March 2024

Data on observed weather, climatology, synoptic conditions, plotted upper-air charts, forecasts, and warnings were collected from the IMD. Satellite imagery was collected from IMD New Delhi. Model products were collected from the Numerical Weather Prediction (NWP) division of IMD. The wind products from the Cooperative Institute for Meteorological Satellite Studies (CIMSS) were also used in this study.

The observed rainfall data has been diagnosed synoptically and dynamically using IMD upper air charts and CIMSS's dynamical products. Hailstorm occurred during the event has also been studied with respect to district wise climatological hailstorm and thunderstorm days. District wise heavy rainfall events have also been ranked with respect to climatological records.

Performance of the IMD GFS model has also been assessed with respect to the event along with assessment of the operational rainfall forecast and rainfall/thunderstorm/hailstorm warning.

3. Results and discussion

The result and discussion have been sub-divided into observational aspects, weather/synoptic systems, Detection of the weather event through INSAT-3D products, assessment of operational and NWP weather forecast & warning.

3.1. Observational Aspects

Maximum temperatures were below normal by 5-8 °C over plains of North India from 29th December 2023 till 29th Feb. 2024 with a very brief respite during 29th January-1st Feb. and 3rd-5th Feb. due to influence of moderate WDs. Also, the minimum temperatures were below 4 °C at many stations over NWI during 12th-17th January 2024.

Very dense fog conditions also persisted over the plains of NWI since 25th December which was maximum in intensity & duration on 14th January when zero visibility observed over entire north Indian plains from Amritsar to Dibrugarh across Haryana, Delhi, UP and Bihar. This severe weather owes mainly to 3 reasons: (i) Lack of any Active WD over NWI, (ii) Prevailing El-Nino conditions, (iii) Strong Jet Stream.

(i) Lack of any Active WD over NWI: This severe weather over north India does primarily owe to lack of any active WD over Northwest India during December and January. Generally, 5-7 WDs impact NWI from December to January. But this winter, no such WD had been received. 2 WDs affected the country, one in December and another in January but their impact was mainly confined to Gujarat, north Maharashtra, East Rajasthan and MP. As a result, WHR has received significantly less precipitation (rain/snow) during

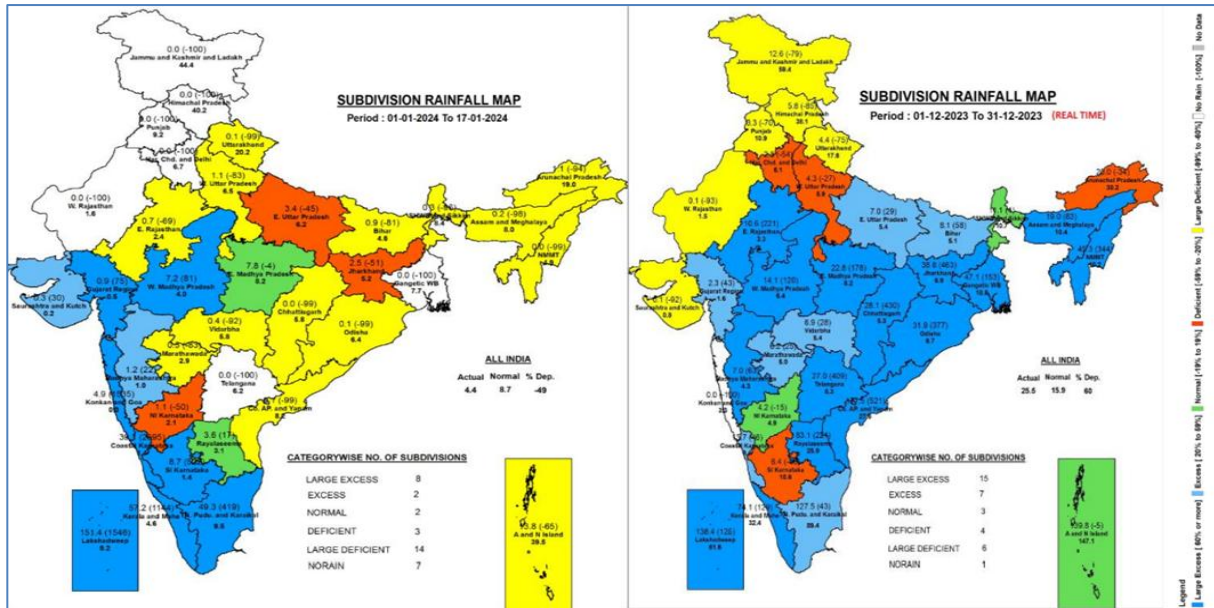


Fig. 2. Subdivisional rainfall during December 2023 (Right Panel) and January 2024 (Left Panel) (Source: IMD)

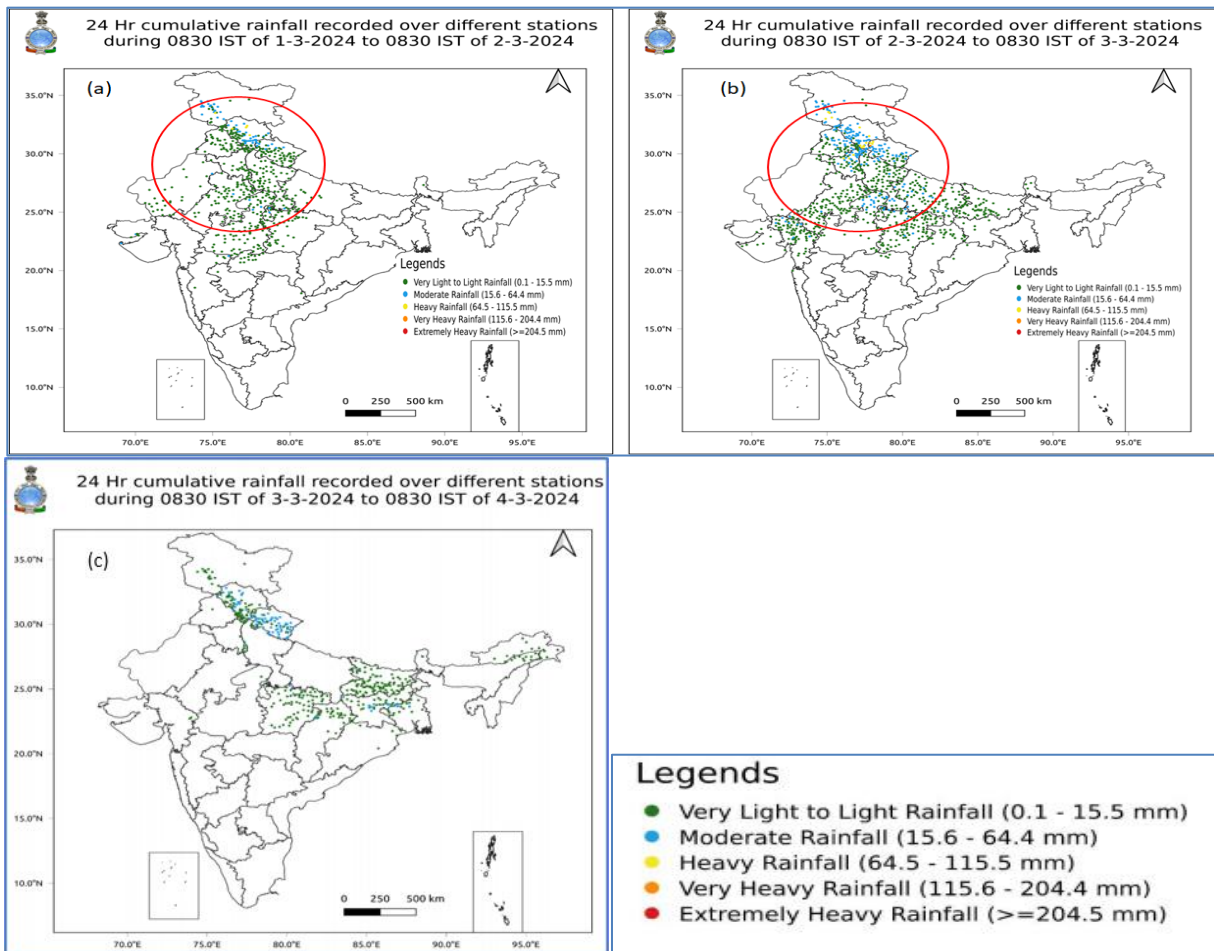


Fig. 3. 24 Hours cumulative rainfall recorded over NWI (encircled region) (a) during 0830 IST of 1st March to 0830 IST of 2nd March (b) during 0830 IST of 2nd March to 0830 IST of 03rd March (c) during 0830 IST of 3rd March to 0830 IST of 4th March (Source: IMD)

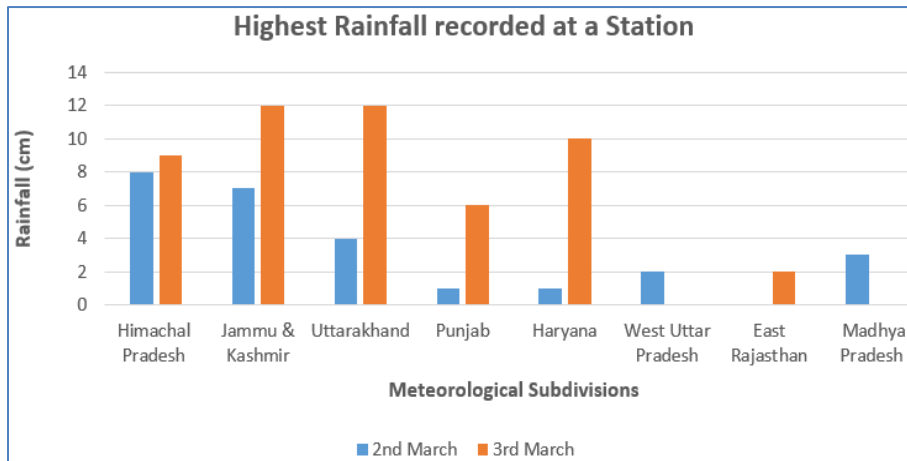


Fig. 4. Subdivision-wise, the highest rainfall (cm) occurred on 2nd and 3rd March, 2024 (Source: IMD)

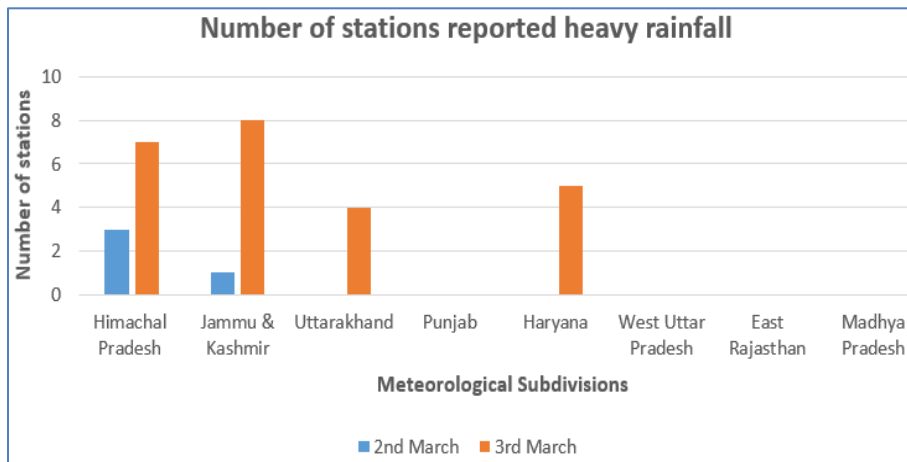


Fig. 5. Subdivision-wise, the number of stations reported HR and VHR on 2nd and 3rd March, 2024 (Source: IMD)

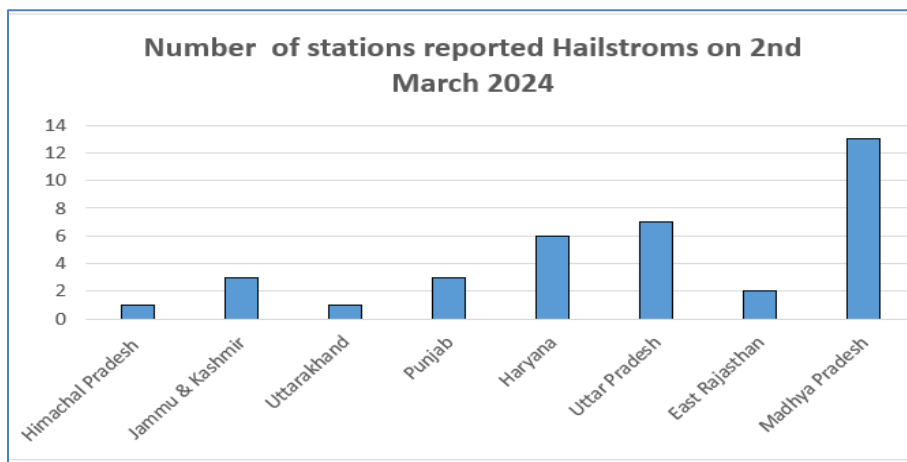


Fig. 6. Subdivision wise the number of stations of hailstorms occurred on 2nd March, 2024 (Source: IMD)

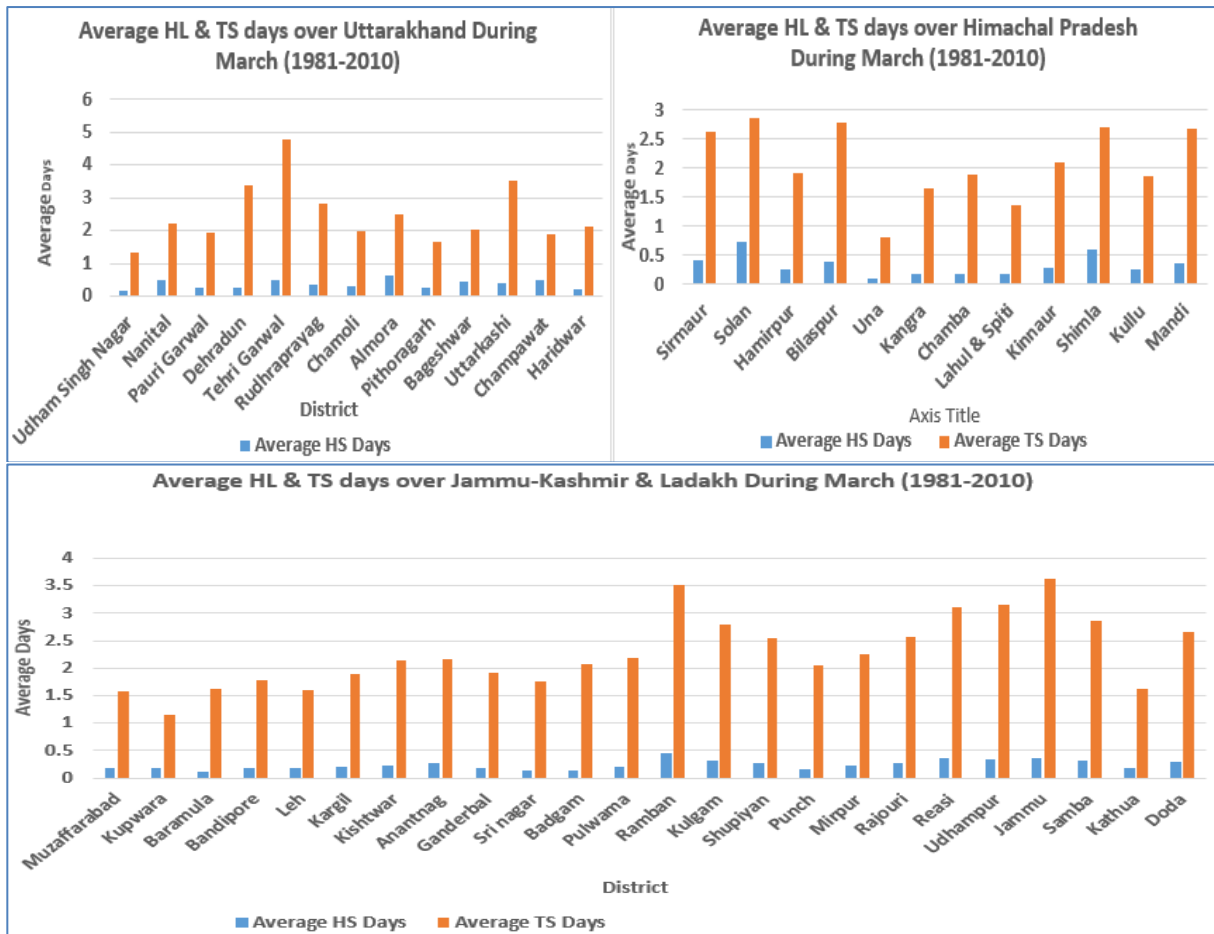


Fig. 7. Average Hailstorm (HL or HS) & Thunderstorm (TS) days during March (1981) over Western Himalayan Region: Uttarakhand in top left panel, Himachal Pradesh in top right panel & over J&K & Ladakh meteorological subdivision in bottom panel (Source: IMD Pune, <https://imd pune.gov.in/hazardatlas/index.html>)

December which is roughly about -80% departure from normal over the region (Fig. 2). Similarly, in January till 17th January there was almost no precipitation over the region.

(ii) The lack of active WDs can also attributed to El-Nino conditions over the Equatorial Pacific Ocean. During El-Nino (La-Nino) years the Cold Wave days over North India happen to be less than normal which is visible in terms of fewer Cold Wave Days during December and January.

(iii) Strong Jet stream winds of the order 250-320 Kmph at about 12 Km above mean sea level had been prevailing over North India during the period. It leads to the subsidence of cold air and enhancing cold wave/cold day conditions over North India which could result into persistence of Cold Conditions over North India.

In the first week of Feb., 2 WDs of light to moderate intensity affected NWI. The only active WD after a 2 month long Cold Day and Dense Fog spell over North India during January & Feb. was the WD which affected NWI during 1st-2nd March 2024 which caused heavy rainfall/snowfall over the WHR& hailstorm activity over the plains of NWI(Fig. 3).

On 1st& 2nd March, 2024, an active WD triggered widespread rainfall and snowfall in the WHR and plains of NWI (refer to last column of Tables 1 & 2). The peak of the weather activity occurred on 2nd& 3rd March, when heavy to very heavy rainfall and snowfall were reported, particularly in the WHR and Haryana. Additionally, intense thunderstorms with lightning, gusty winds, and hailstorms impacted several regions, including Punjab, Haryana, Chandigarh, Rajasthan, Delhi- NCR, UP, and north MP mainly on 2nd March and the rain belt shifted towards WHR on 3rd March 2024.

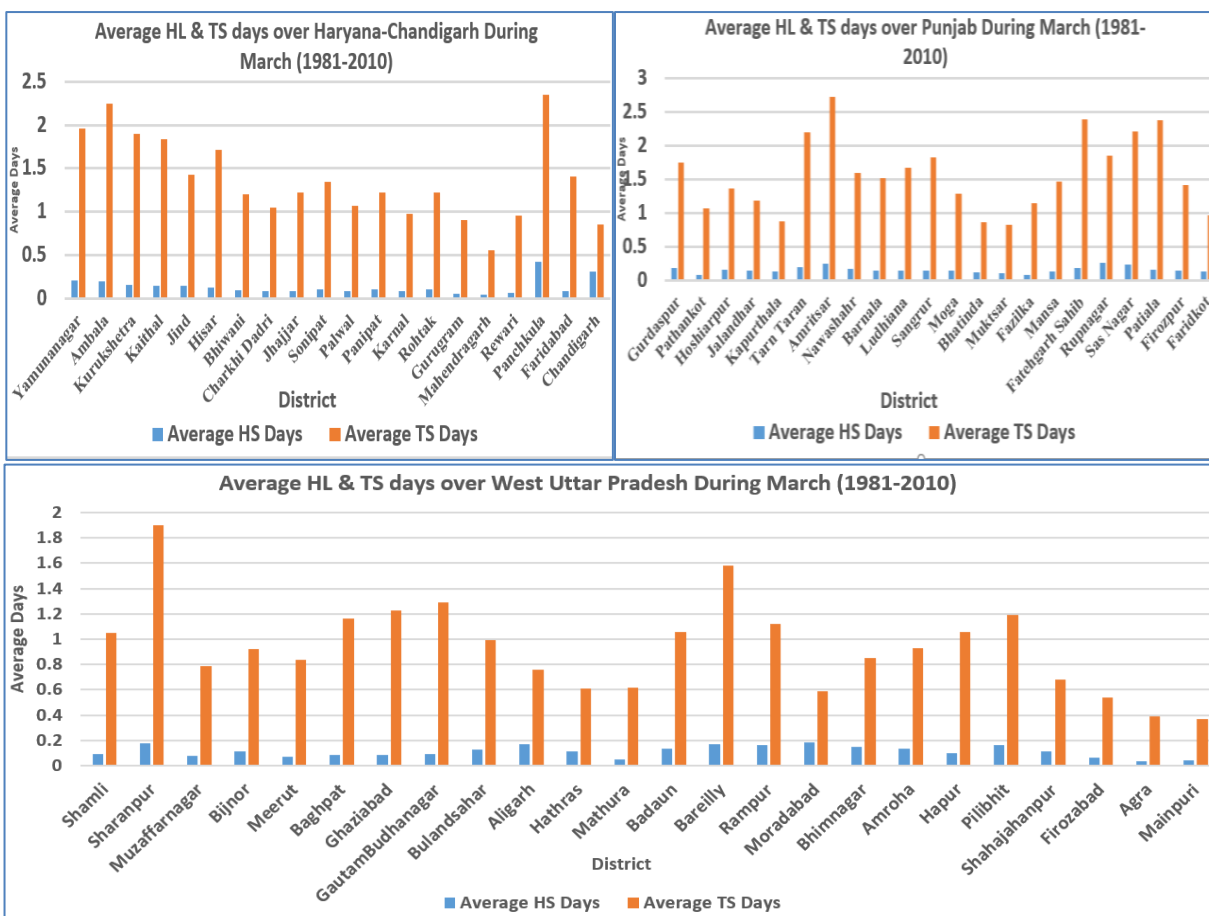


Fig. 8. Average Hailstorm (HL or HS) & Thunderstorm (TS) days during March (1981) over adjoining plains of NWI to Western Himalayan Region: Haryana & Chandigarh in top left panel, Punjab in top right panel and over West Uttar Pradesh meteorological subdivisions in bottom panel (Source <https://imdpune.gov.in/hazardatlas/index.html>)

The heavy rainfall data revealed that on 3rd March, the subdivisions of J & K and Uttarakhand recorded the highest rainfall, with some stations receiving 12 cm, followed by Haryana at 10 cm. Station-wise data indicates that on 2nd March, the highest number of stations in the Himachal Pradesh subdivision reported heavy rainfall, followed by J & K. On 3rd March, however, most stations experienced heavy to very heavy rainfall in J & K, followed by Himachal Pradesh, Haryana, and Uttarakhand (Ref. Fig. 4 & 5).

The thunderstorms persisted for two days, affecting MP, UP, and Uttarakhand (Tables 1 & 2). Impacts from this weather event included, Snow Accumulation, Avalanches and Crop Damage and considerable disruptions and damage across the affected regions, impacting infrastructure, transportation, and agriculture.

The hailstorms activity was the severe weather during this episode. On during 1st to 3rd March, several

districts and stations across the northern and central regions of India experienced significant hailstorm activity (Table 1-2, Fig. 6). Maximum number of hailstorm stations was in MP followed by UP and Haryana. In J & K, the affected areas included Batote, Bhaderwah and Jammu. Himachal Pradesh saw hailstorms in Palampur, while Uttarakhand experienced similar weather conditions in Dehradun, particularly in the Chakarta and Mussoorie regions. In Punjab, districts such as Tarn Taran, Faridkot, and Bathinda were impacted, while Haryana faced hailstorms in Hisar, Rohtak, Karnal, Sonapat, Kaithal, and Jind. UP witnessed hailstorms in Muzaffarnagar, Meerut, Saharanpur, Baghpat, Jalaun, Kasganj, and Farrukhabad. Rajasthan's Hanumangarh and Sikar districts were also affected, as were several districts in MP, including Ashoknagar, Guna, Shivpuri, Morena, Datia, Gwalior, Sheopur Kalan, Raisen, Chhatarpur, Tikamgarh, Nivari, and Panna. On 3rd March the isolated hail storm activity was reported over Uttarakhand, MP and UP. These widespread hailstorms caused localized disruptions and damage to crops, infrastructure, and property.

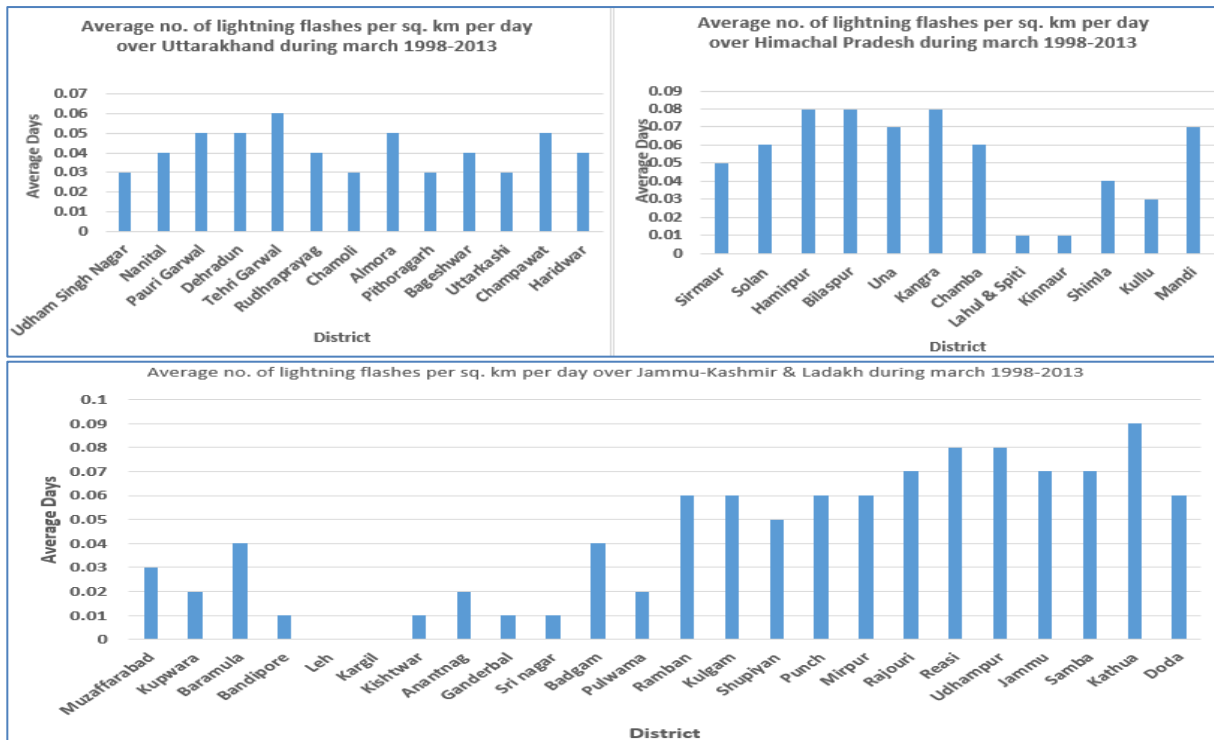


Fig. 9. Average number of lightning flashes (per Square km) during March (1998-2013) over Western Himalayan Region: Uttarakhand in top left panel, Himachal Pradesh in top right panel and over J & K & Ladakh meteorological subdivision in bottom panel (Source <https://imd pune.gov.in/hazardatlas/index.html>)

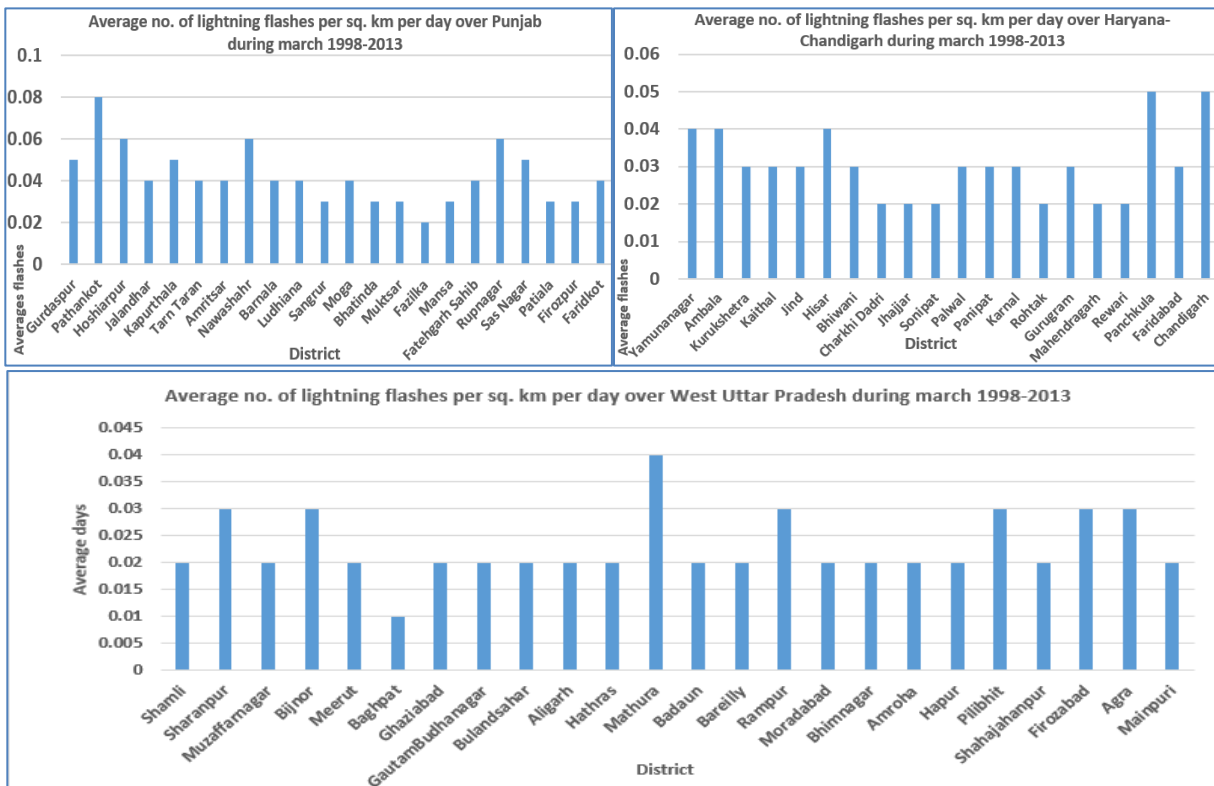


Fig. 10. Average number of lightning flashes (per square km) during March (1981) over adjoining plains of NWI to Western Himalayan Region: Haryana & Chandigarh in top right panel, Punjab in top left panel and over West Uttar Pradesh meteorological subdivisions in bottom panel (Source <https://imd pune.gov.in/hazardatlas/index.html>)

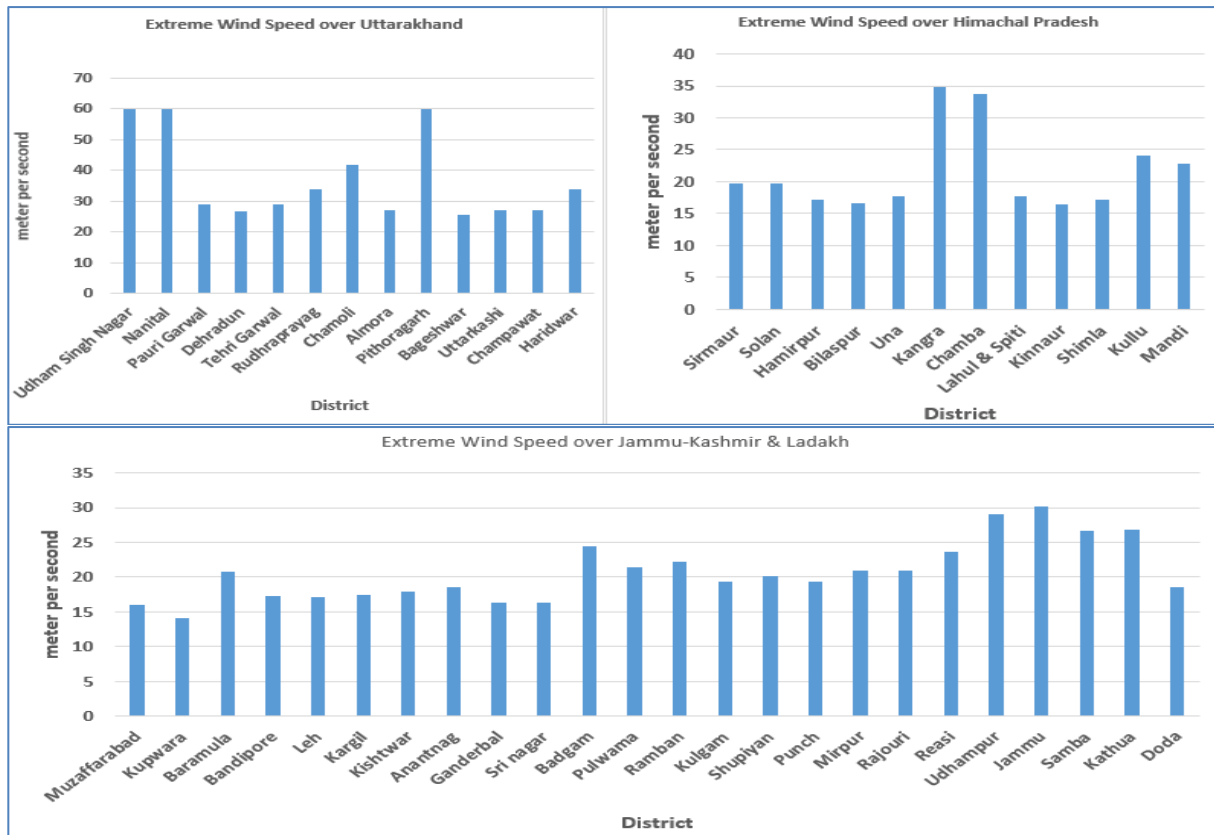


Fig. 11. Climatology of extreme wind speed over Western Himalayan Region: Uttarakhand in top left panel, Himachal Pradesh in top right panel and over J & K and Ladakh meteorological subdivision in bottom panel (Source <https://imd pune.gov.in/hazardatlas/index.html>)

The climatological information for March in terms of significant hazards, like hailstorms (HL or HS), thunderstorms (TS), lightning, and extreme wind is collected for WHR and adjoining plains, namely Punjab, Haryana & Chandigarh and West UP from IMD Pune through web page <https://imd pune.gov.in/hazardatlas/index.html> and the same is represented district wise in Fig. 7-12. Climatology suggests average TS days in Uttarakhand for March are less than 5 days and for Himanchal Pradesh it is less than 3 days and for J&K is less than 3.5 days (Fig. 7). The average hailstorms days during March over WHR are less in number (refer to Fig. 7). If we see the climatology for the plains, average TS days are less than 2 days (Fig. 8). For better understanding the frequency and average picture of other associated hazards during premonsoon month of March, the climatological information for lightning and extreme winds is highlighted in Fig. 9-12. We skip the details, with the one-line summary that thunder-related hazards have more frequency over WHR during March than in the states of the Plains of NWI.

The scrutiny of climatological rainfall collected from IMD Pune through webpage <https://dsp.imdpune.gov.in/>

home_extremes.php#showed that Nahan in Himachal Pradesh recorded 83.3 mm rainfall on 3rd March, 2024, which was the 2nd highest in March during 1953-2024 (refer Fig. 13d). The climatological records of Jammu showed that it was 5th in order on 03rd March 2024 with 58.3 mm rainfall (refer Fig. 13b). Similarly, Manali in Himachal Pradesh also received record-breaking rainfall consecutively on 02nd and 03rd March, with 90mm on 02nd and 89.8 mm on 03rd March, which were 2nd and 4th in rank (refer Fig. 13 c). For similar climatological records refer to Fig. 13 a. Other stations like Kathua in J & K subdivision recorded moderate rainfall, 30.2 mm on 3rd March 2024, which ranked 8th in order in March (1905-2024).

During this wet spell, many areas of NWI experienced isolated intense thunderstorm activities accompanied by lightning, gusty winds, and hailstorms. On 2nd March, these conditions affected Punjab, Haryana, Chandigarh, Rajasthan, NCR-Delhi, UP, and northern MP. In MP, UP, and Uttarakhand, the intense weather continued for two consecutive days, on 2nd and 3rd March.

Media reports indicated several notable effects. Heavy snow accumulation has been observed in various

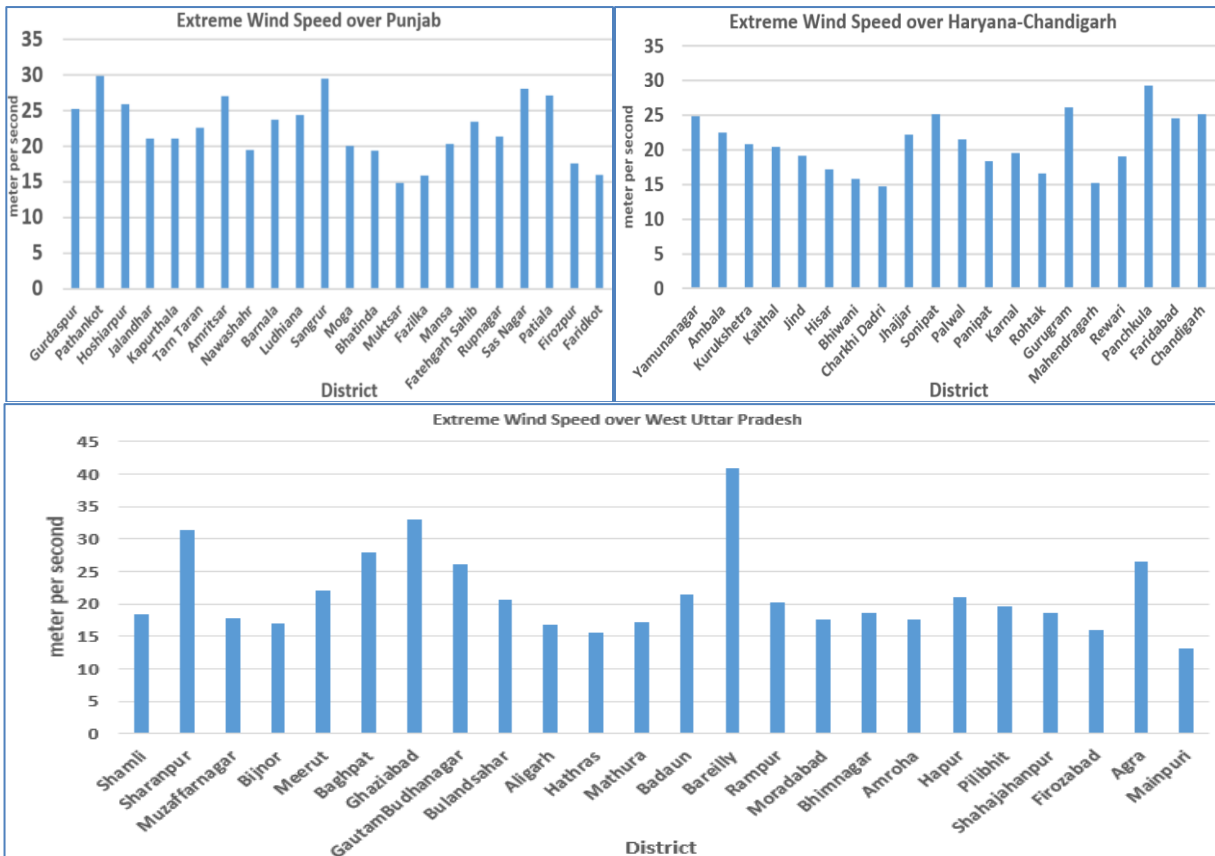


Fig. 12. Climatology of extreme wind speed over adjoining plains of NWI to Western Himalayan Region: Haryana & Chandigarh in top left panel, Punjab in top right panel and over West Uttar Pradesh meteorological subdivisions in bottom panel (Source <https://imd pune.gov.in/hazardatlas/index.html>)

locations along highways and roads in the WHR, with some avalanches also reported in hilly areas. Additionally, the hailstorms and strong winds associated with the thunderstorms have caused significant damage to crops, mainly vegetable and horticultural crops, in the plains of northwest and central India.

3.2. The weather systems

The wet spell from 1st to 4th March was attributed to an active WD that moved slowly as an intense cyclonic circulation from northwest Afghanistan and neighbouring areas into north Pakistan. This system was accompanied by a north-south trough extending southward to the North Arabian Sea in the lower and middle tropospheric levels. Throughout this period, the WD intensified due to increasing upper-level divergence and lower-level convergence, reaching peak values on 2nd March. Under its influence, an induced low-pressure area formed over northwest Rajasthan and adjacent Pakistan on 2nd March. These systems remained largely stationary over the same regions from 1st to 3rd March, with continuous moisture feeding from the Arabian Sea into NWI, resulting in the

intense wet spell and associated thunderstorm & hailstorm hazards.

3.2.1. Day-to-Day characteristics of the WD and associated synoptic systems

The track of WD is illustrated in Fig. 1. The system moved eastward over the Afghanistan region until 12 UTC on 2nd March. It then shifted southeast toward northern Rajasthan by 03 UTC on 04th March, continuing eastward across south Punjab and into Haryana until it weakened.

February 29: The WD was first identified in weather charts as a cyclonic circulation over northeast Iran, extending from lower to upper tropospheric levels (Fig. 14).

March 1: By morning, the WD had slowly moved to a position over northwest Afghanistan and extended to upper tropospheric levels. A trough reached from this cyclonic circulation to the Northwest Arabian Sea in lower and middle tropospheric levels. An induced cyclonic circulation also formed over southwest Rajasthan

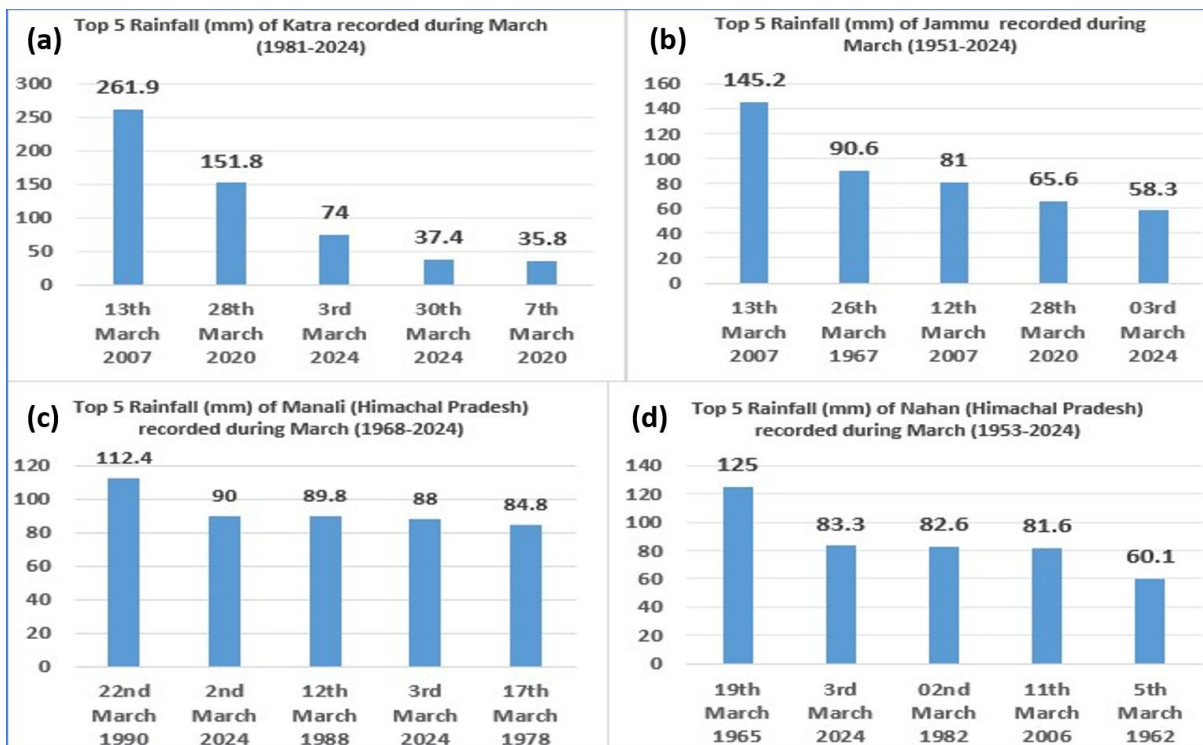


Fig. 13 (a-d).Climatological rainfall records of March for the stations of(a)Katra (b) Jammu (c) Manali and (d) Nahani

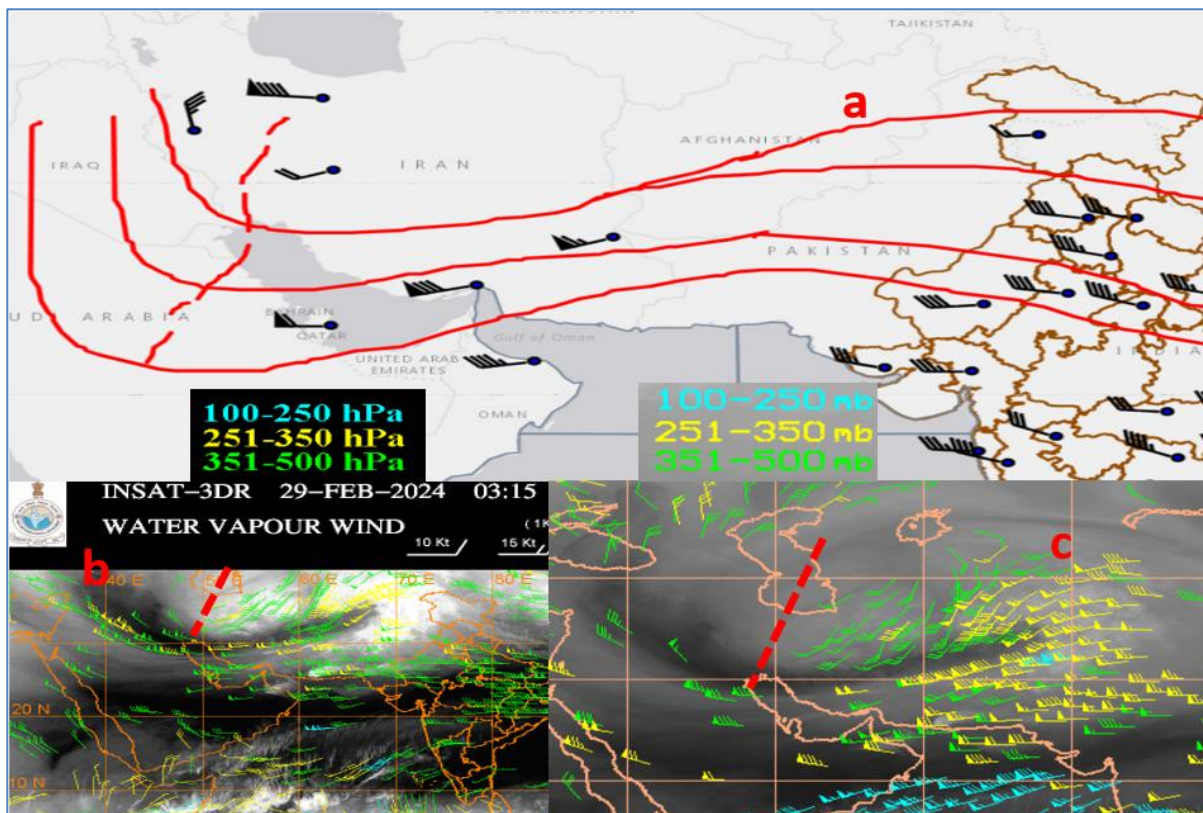


Fig. 14(a-c). (a) 500 hPa wind synoptic chart (b) INSAT 3DR Water Vapour wind (c) CIMSS Upper-Level winds based on 0300 UTC of 29.02.2024

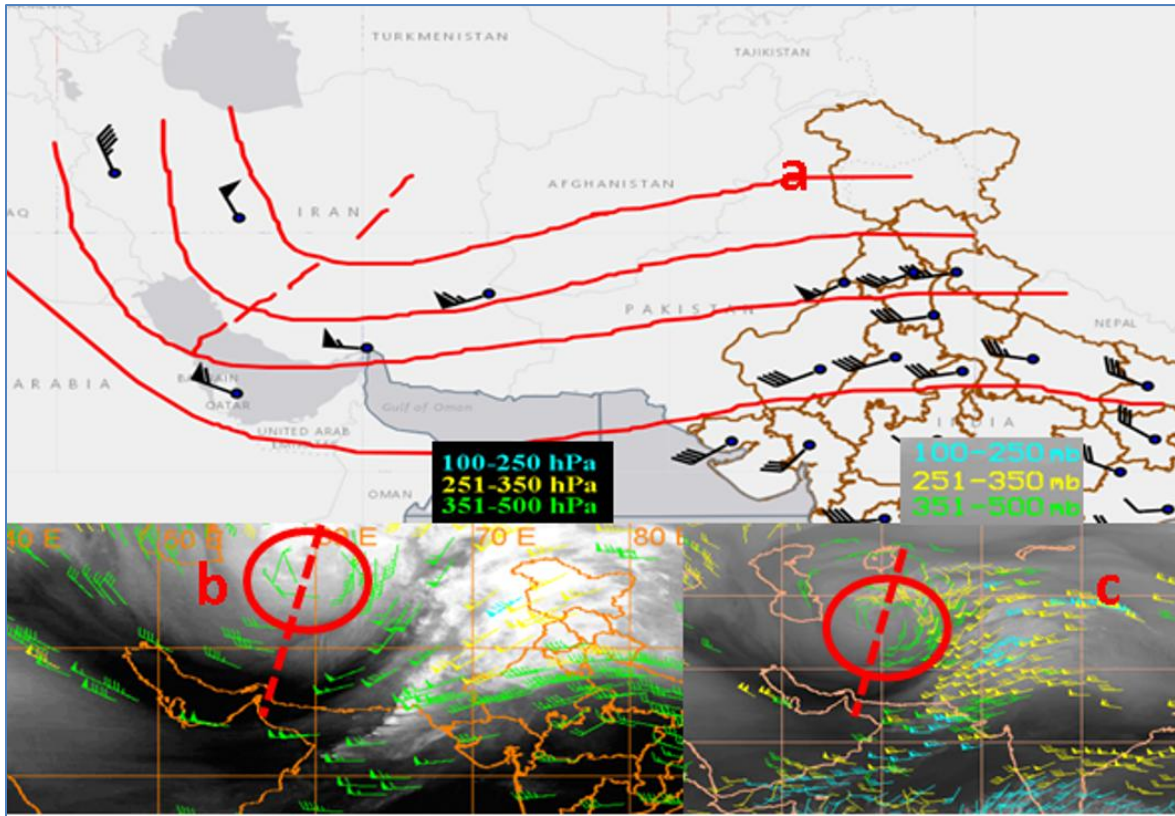


Fig. 15(a-c). (a) 500 hPa wind synoptic chart (b) INSAT 3DR Water Vapour wind (c) CIMSS Upper-Level Winds based on 0300 UTC of 01.03.2024

and adjoining Pakistan. High moisture influx from the Arabian Sea to NWI the WHR was observed (Fig. 15).

March 2: The WD continued its slow movement, positioned as a CC over central Afghanistan and its trough extending southward to the North Arabian Sea. The WD intensified further due to increasing upper-level divergence and lower-level convergence. An induced low-pressure area developed over northwest Rajasthan and adjacent Pakistan, with high moisture feeding from the Arabian Sea (Fig. 16).

March 3: The WD moved very slowly westward, maintaining its cyclonic nature over north Pakistan and the surrounding region in middle and upper tropospheric levels, while the induced low-pressure area lingered over west Punjab and neighbouring areas.

March 4: The WD significantly weakened & rapidly shifted northeast, reaching the extreme northern parts of India. It was then observed as a trough in the middle tropospheric westerlies, with its axis at approximately 5.8 km above mean sea level, running roughly along longitude

74°E to the north of latitude 30°N. The induced low-pressure area became less marked, while the cyclonic circulation was noted over northwest UP and its vicinity, extending up to 3.1 km above mean sea level. From the evening of 4th March onwards, the WD ceased to impact significant weather in the region.

3.3. Detection of the weather event through INSAT-3D products

As per INSAT 3D water vapour winds, WD trough can be seen roughly along 45°E/30°N at 0315 UTC of 28th, 52°E/28°N on 29th, 58°E/26°N on 01st March; 65°E/26°N on 02nd March. As is evident from the 0015-0042 UTC INSAT-3D CTBT imageries (Fig. 17a-f), intense to very intense clouds were detected over north Pakistan adjoining western most parts of Kashmir on 29th Feb.; over J&K and Punjab on 01st March and over entire WHR and adjoining plains on 2nd March. Maximum convection was visible in the 2nd March CTBT imagery followed by 1st March which is in coherence with the maximum rainfall activity occurred on 2nd & 3rd although the hailstorm activity had its peak realized on 1st & 2nd March 2024.

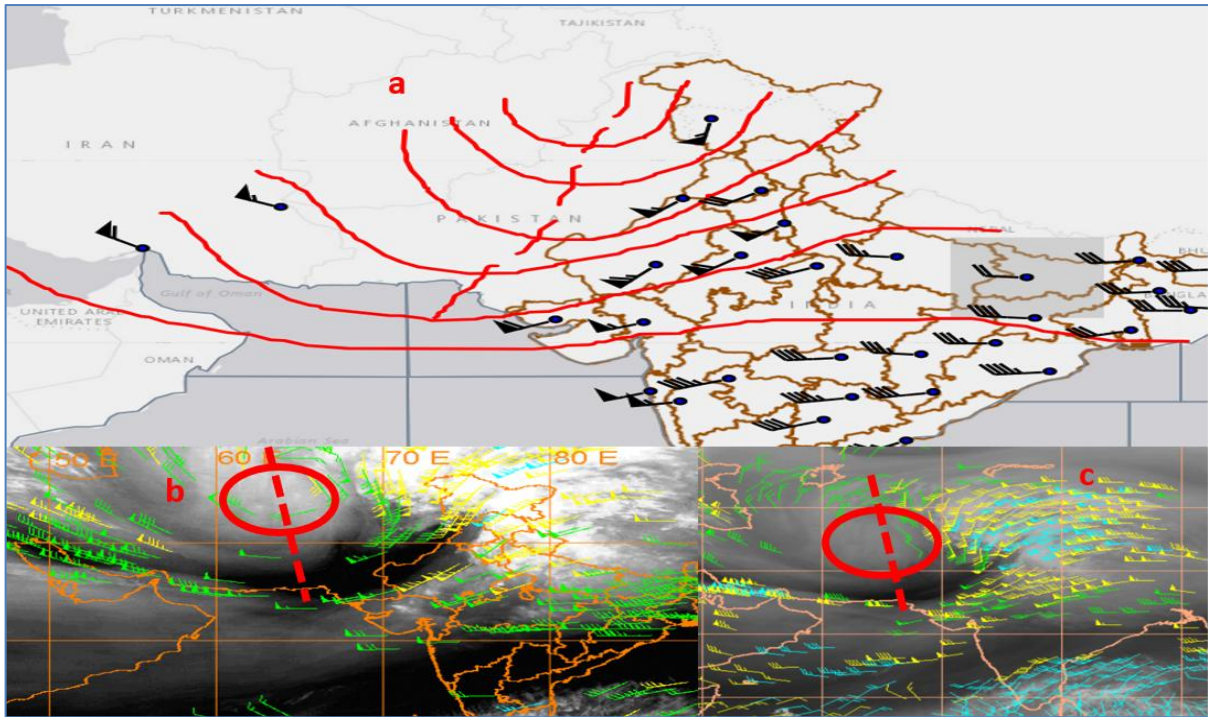


Fig. 16(a-c). (a) 500 hPa wind synoptic chart (b) INSAT 3DR Water Vapour wind (c) CIMSS Upper-Level Winds based on 0300 UTC of 02.03.2024

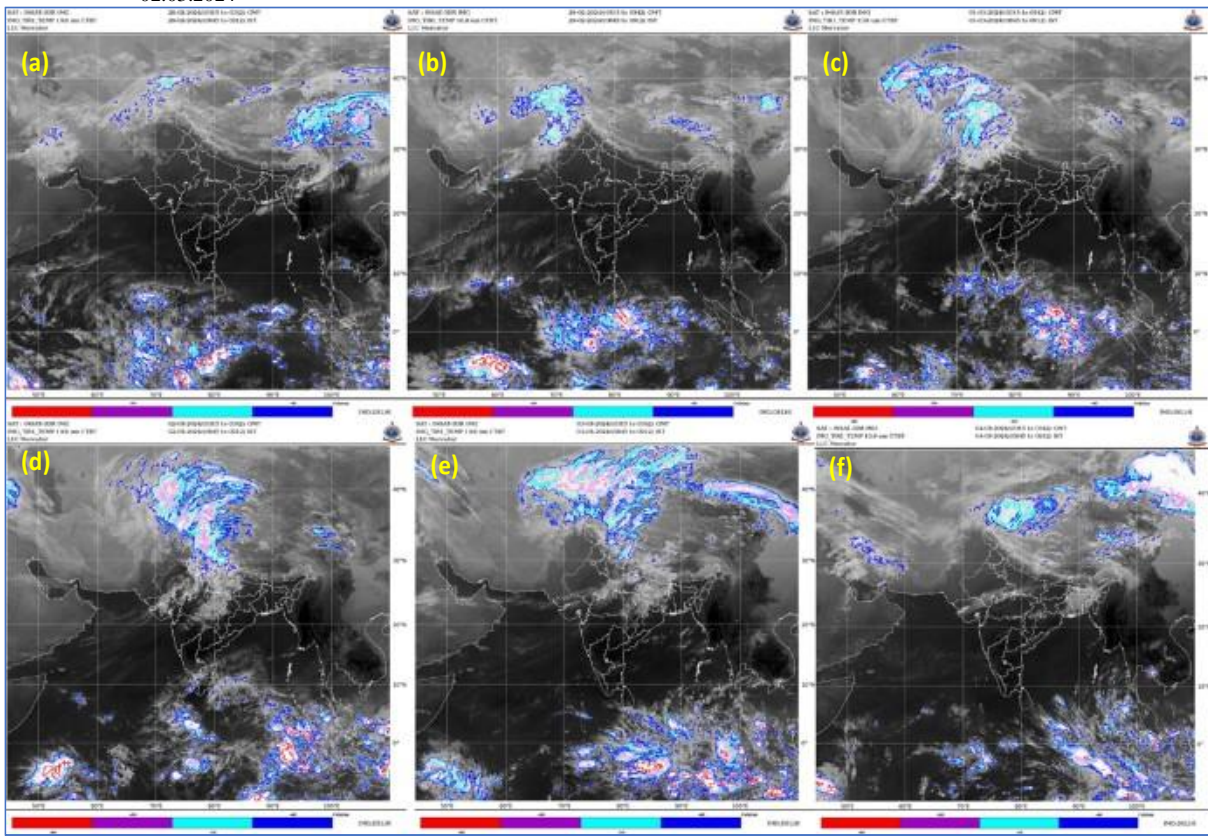


Fig. 17 (a-f). Satellite imagery (CTBT) INSAT-3DR detecting convective clouds during the period of event [0015-0042 UTC]; (a) 28.02.2024 (b) 29.02.2024 (c) 01.03.2024 (d) 02.03.2024 (e) 03.03.2024 (f) 04.03.2024 (Source: IMD)

TABLE1

Subdivision-wise Mult hazard colour coded warnings (5 days lead period) issued and observed weather on 1st March 2024 (Source: IMD)

Forecast issued	26 th Feb.	27 th Feb.	28 th Feb.	29 th Feb.	1 st March	Observed Weather on 1 st March
Jammu-Kashmir, Ladakh	HR/S, TS	HR/STS	VHR/STS	HR/S,TS,HL	HR/S,HL	HR/S & HL at isolated places
Himachal Pradesh	HR/S,TS	HR/SHL	VHR/S,HL	HR/S,HL	HR/S,HL	HR/S & HL at isolated places
Uttarakhand	HR, TS,HL	TS,HL	VHR/S,HL	HR/S,HL	HR,HL	
Punjab	TS	TS	TS,HL	TS,HL	TS,HL	
Haryana, Chandigarh & Delhi	TS	TS	TS	TS	TS,HL	Isolated HL
West Rajasthan	TS	TS,HL	TS,HL	TS,HL	TS,HL	Isolated HL
East Rajasthan	TS	TS,HL	TS,HL	TS	TS,HL	Isolated HL
West Uttar Pradesh	TS	TS	TS	TS	TS,HL	
East Uttar Pradesh	NIL	NIL	TS	NIL	TS	
West Madhya Pradesh	NIL	TS	TS	TS	TS,HL	Isolated HL
East Madhya Pradesh	NIL	TS	TS	TS	TS	Isolated HL

3.4. Performance of weather forecast and warning services

The color-coded Mult-hazard weather warnings issued by the IMD are presented in Tables 1&2. IMD began monitoring this WD on 25th Feb., noting in its official daily press release that a WD was likely to impact NWI, causing a wet spell from 29th Feb.- 03rd March, with a lead time of 5-7 days. Guidance on this was maintained until 26th Feb. On 27th Feb., the IMD issued first orange warning for isolated heavy to very heavy rainfall & snowfall on 01st & 02nd March for the WHR, with a lead time of 3-5 days. This warning was reiterated on 28th & 29th Feb.

On 01st March, a red colour warning was issued for J & K, and Himachal Pradesh, indicating the likelihood of severe weather on 02nd March over the WHR. An orange colour warning was also issued for the plains, including Punjab, Haryana, Chandigarh, Delhi, West UP, and MP, for 1st & 2nd March. Additionally, during this period, the IMD provided special numbered bulletins to the concerned and impacted states on a daily basis, sharing information with their Chief Secretaries, State Disaster Management Authorities (SDMAs), and State Relief Commissioners (SRCs) for safety actions. Impact-based forecasts and warnings were consistently issued in press releases with the same frequency.

Similar warnings were issued at the district level starting from 29th Feb., for J & K and Ladakh, Himachal Pradesh, Uttarakhand, Chandigarh, Haryana, and UP.

During the wet spell, all severe weather events were monitored in real-time using surface, satellite, and radar-

based observations, with temporal resolutions ranging from 10 minutes to 3 hours, tailored to specific areas and locations. District-level and location-specific nowcast warnings, colour - coded orange and red, were issued 1 to 3 hours in advance utilizing weather radar data and nowcasting models.

All forecasts, warnings, and observations were issued in a timely manner. Special numbered bulletins were distributed daily to the concerned and impacted states, including their chief secretaries, SDMAs, and SRCs for coordinated safety actions. Impact-based forecasts and warnings were also issued in press releases with the same frequency. Additionally, daily weather videos highlighting the current status of the event were uploaded to the IMD’s YouTube channel, Facebook page, and X (formerly Twitter). Regular updates on weather forecasts, warnings, and observations were shared through social media platforms, including Facebook, X, and Instagram. Timely updates were also circulated via various WhatsApp groups.

3.5. NWP models performance

As is visible from forecast charts based on 23rd Feb./00 UTC IMD GFS; 500, 700, 850 hPa charts valid for 01st (Fig. 18a-c) & 02nd March (Fig. 19a-c) and 24-hr accumulated rainfall valid for 03 UTC of 02nd (Fig. 18d) & 03rd March (Fig. 19d) that event was well predicted in terms of WD trough and the rainfall although the forecast trough didn’t have the amplitude as deep as the observed one. Therefore, as per IMD-GFS the event was predictable with 7-day lead period which was accordingly translated

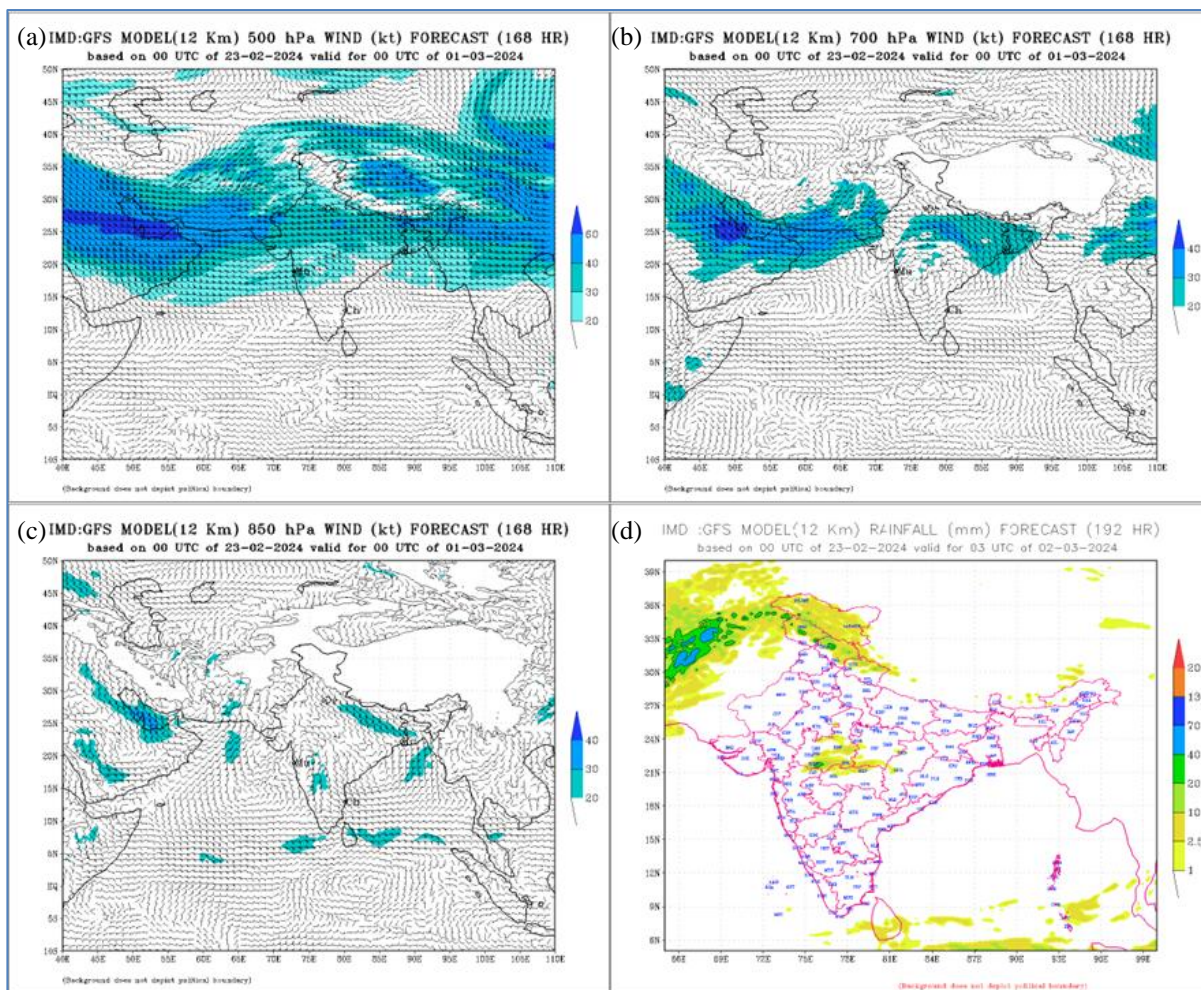


Fig. 18 (a-d). IMD-GFS model products winds (a) 500 hPa level (b) 700 hPa level (c) 850 hPa and (d) 24 hours cumulative rainfall based on 23rd February, 2024 valid for 1st March 2024 (Source: IMD)

TABLE 2

Subdivision-wise Mult hazard colour coded warnings (5 days lead period) issued and observed weather on 2nd March 2024 (Source: IMD)

Forecast issued	27 th Feb.	28 th Feb.	29 th Feb.	1 st March	2 nd March	Observed Weather on 2 nd March
Jammu-Kashmir, Ladakh	HR/S,TS	VHR/STS	HR/S,TS	HR/S,TS	HR/S,HL	HR/S to VHR/S at isolated places
Himachal Pradesh	HR/S,HL	VHR/S,HL	HR/S,HL	HR/S	HR/S,HL	HR/S & HL at isolated places
Uttarakhand	HR/S,HL	VHR/S,HL	HR/S,HL	HR/S	HR/S,HL	HR/S to VHR/S at isolated places
Punjab	HR,TS,HL	VHR/S,HL	HR,TS,HL	HR,TS,HL	HR,TS,HL	Isolated HL
Haryana, Chandigarh & Delhi	TS,HL	TS,HL	TS,HL	TS,HL	TS,HL	HR & HL at isolated places
West Rajasthan	TS	TS	TS	TS	TS	Isolated HL
East Rajasthan	TS	TS	TS,HL	TS,HL	TS,HL	Isolated HL
West Uttar Pradesh	TS,HL	TS,HL	TS,HL	TS,HL	TS,HL	Isolated HL
East Uttar Pradesh	TS	TS	TS,HL	TS,HL	TS,HL	Isolated HL
West Madhya Pradesh	TS	TS	TS,HL	TS,HL	TS,HL	Isolated HL
East Madhya Pradesh	TS	TS	TS,HL	TS,HL	TS,HL	Isolated HL

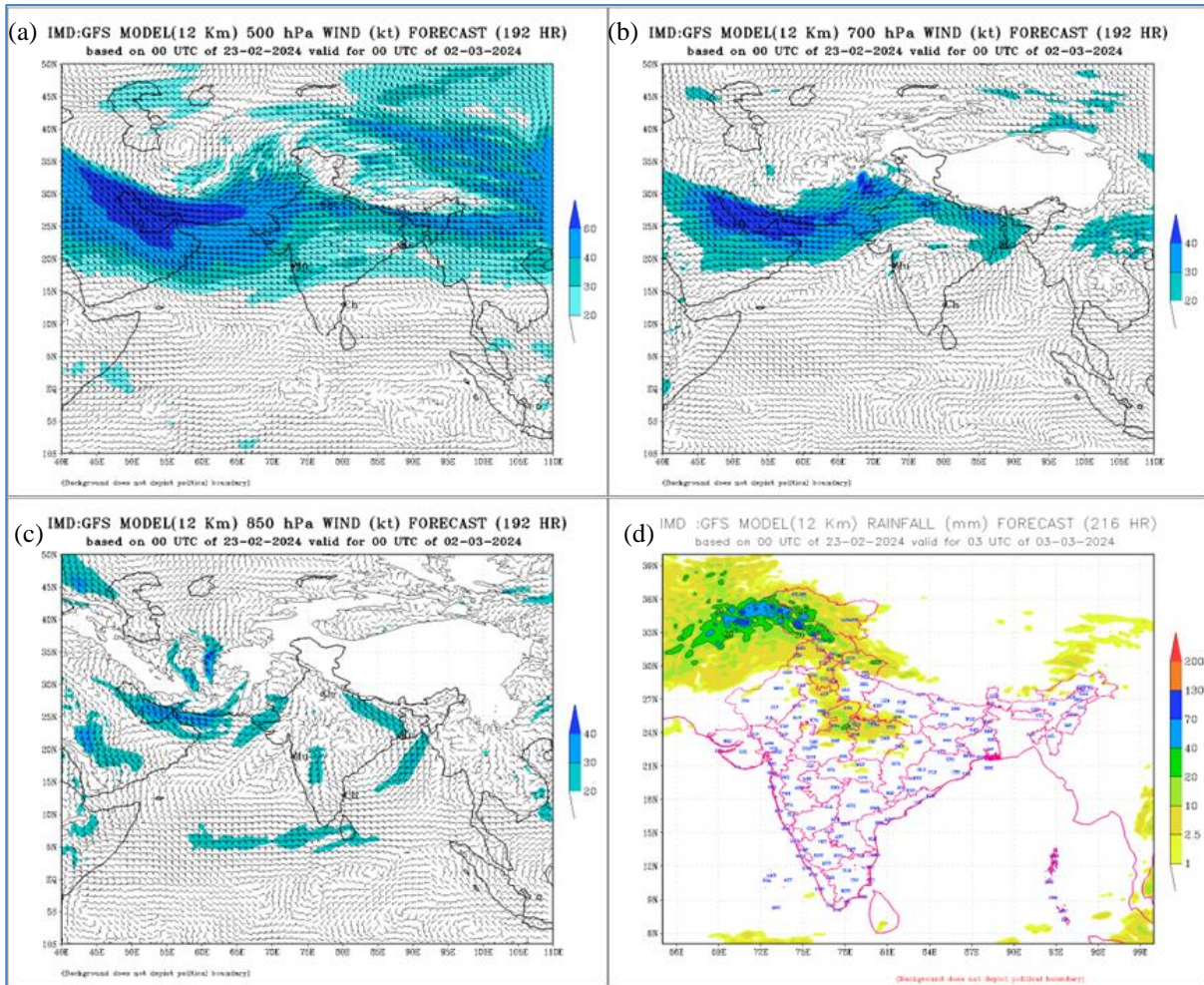


Fig. 19 (a-d). IMD-GFS model products winds (a) 500 hPa level (b) 700 hPa level (c) 850 hPa and (d) 24 hours cumulative rainfall based on 23rd February,2024 valid for 2nd March 2024 (Source: IMD)

TABLE 3

Other Weather Events due to western disturbance over NWI & adjoining central India during March

Weather Event	Major Synoptic Systems	Region affected	Realized weather
18 th -21 st March, 2023	1 st WD (15 th -19 th March 2023) 2 nd WD (19 th & 20 th March 2023)	Northwest & adjoining central India	HR reported over UP, Haryana, Punjab, Himachal Pradesh and East MP with VHR over East UP and light to moderate rainfall over remaining subdivisions of the region.
14 th & 15 th March, 2020	WD (11 th -15 th March 2020)	Northwest India including Delhi & NCR	Hail storms reported at many places over Delhi; a few places over Uttarakhand & Haryana; at isolated places over Punjab & West UP. Moderate rainfall was reported over the plains of NWI. Delhi also experienced the rainfall with Safdarjung:37.0 mm; Lodhi road: 47.6 mm and Ridge: 19.4 mm.

into IMD’s operational forecast discussed in section 4. The model maintained its consistency of the above forecast for 1st& 2nd March in the upcoming days and started showing

heavy rainfall activity over the WHR from 24th Feb. for 01st March as well as 2nd March and further continued the same. Similar type of accuracy is also observed in the

deterministic model forecast of NCUM, GEFS and NEPS from 23rd Feb. Also, the probabilistic NEPS forecast had quite a good accuracy from day 7 itself.

4. Conclusions

This paper examines a significant wet spell that occurred in the first week of March, marked by heavy rainfall, intense thunderstorms, and hailstorms in both areas. The wet spell during 1st-3rd March, 2024 was mainly driven by a WD, which resulted in the development of induced cyclonic circulation and low-pressure systems. These atmospheric conditions provided a favourable setting for heavy rainfall/snowfall. Furthermore, a consistent influx of moisture from the Arabian Sea played a crucial role in this event. This moisture surge increased the intensity of rainfall with heavy to very heavy rainfall/snowfall and promoted the formation of severe thunderstorms and hail.

This scientific study emphasizes the complex connection between WDs and moisture supply in producing winter precipitation events in the WHR and NWI. Gaining insight into these interactions is essential for enhancing weather forecasting and managing the impacts of extreme weather in the region. Future research should examine the long-term effects of these weather patterns in light of climate change.

Two other cases when WD affected the NWI & adjoining central India are included (Table 3). The first case when the Region was affected by a WD during 18th - 21st March, 2023 which was seen as a cyclonic circulation in middle and upper tropospheric levels over east Iran on 15th March, 2023 with induced cyclonic circulation over central Parts of Rajasthan; it lay over Afghanistan on 16th with induced over southwest Rajasthan; seen as a trough 68°E/25°N on 17th; over 74°E/25°N on 18th; 78°E/22°N on 19th and another WD seen over east Iran adjoining west Afghanistan on same day and the second WD was seen as trough 72°E/25°N on 20th and it lay over 79°E/28°N. In this episode, Patiala received record-breaking rainfall of 36.1mm on 21st March, 2023, and Jaipur 11.8 mm on 18th March, 2023, and both stations stood in the 8th rank in the order during 1924-2023. In another case, a WD affected NWI (including Delhi-NCR) during 14th & 15th March 2020 (Table 3). In this case, Delhi experienced hail storm activity with record-breaking rainfall over Safdarjung (37 mm) on 15th March, which was ranked 6th in the climatological records in March.

During the present episode, some of the stations, mainly from the WHR region, like J & K (Karta and Jammu), and Himachal Pradesh (Nahan and Manali), received record-breaking rainfall and were placed in the

top 5 categories in climatological records. Also, on 03rd March, the subdivisions of J & K and Uttarakhand recorded the highest rainfall, with some stations receiving 12 cm, followed by Haryana at 10cm. On 2nd March, the highest number of stations in the Himachal Pradesh subdivision reported heavy rainfall, followed by J & K. The significant hail storm activity occurred on 1st & 2nd March and was concentrated mainly at isolated locations over Uttarakhand, MP, and UP on 3rd March.

The event was well predicted by the IMD with a 5-day lead time and was also captured by the models. This scientific investigation highlights the intricate relationship between WDs and moisture supply in generating winter precipitation events in the WHR and NWI. Understanding these interactions is vital for improving weather forecasting and managing the effects of extreme weather in the region. Future research should explore the long-term implications of these weather patterns in the context of climate change.

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Competing Interests

The authors have no relevant financial or non-financial interests to disclose.

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Abbreviations

J & K: Jammu & Kashmir; UP: Uttar Pradesh; MP: Madhya Pradesh; HR/S: Heavy rainfall/snowfall; VHR/S: Very Heavy rainfall/snowfall; HR: Heavy rainfall; VHR: Very Heavy rainfall; TS: Thunderstorms accompanied with lightning; HL or HS: Hailstorm. WHR: Western Himalayan Region; NWI: Northwest India; WD: Western Disturbance; NCR: National Capital Region; IMD: India Meteorological Department; GFS: Global Forecasting System; NCMRWF: NCMRWF Unified Model; NCMRWF: National Centre for Medium Range Weather Forecasting; GEFS: Global Ensemble Forecasting System; NEPS: NCMRWF Ensemble Prediction System; UTC: Coordinated Universal Time; CTBT: Cloud Top Brightness Temperature; CC: Cyclonic circulation; CIMSS: Cooperative Institute for Meteorological Satellite Studies

Legends/criteria

Isolated: 1-25% stations reported the weather event in a sub-division in 24 hours; Heavy Rainfall:7-11cm/24 hours; Very Heavy Rainfall:12-20 cm/24 hours;Heavy snowfall:70-110cm/24hours; Very Heavy snowfall:120-200cm/24 hours.

