



## Assessment of intense precipitation over Northwest India during 05<sup>th</sup>-09<sup>th</sup> January 2022

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**सार-** उत्तर-पश्चिम भारत (NWI) में सामान्यतः नवंबर से मार्च तक आर्द्र अवधि (wet spells) रहती है, जो शीत ऋतु के दौरान मुख्यतः हिमपात के रूप में होती है। यह स्थिति मुख्यतः पूर्व की ओर गतिशील पवनों तथा भारत, पाकिस्तान, नेपाल, बांग्लादेश और भूटान में विभिन्न वायुमंडलीय स्तरों पर पश्चिमी विक्षोभ (Western Disturbances-WDs) के रूप में पहचाने जाने वाले उष्णकटिबंधीय-बाह्य तंत्रों से प्रभावित होती है। कभी-कभी इन पश्चिमी विक्षोभों से संबद्ध मध्य-स्तरीय पछुआ पवनों तथा निचले स्तर की पूर्वी पवनों के बीच अंतःक्रिया से उत्तर-पश्चिम भारत में शीत ऋतु के दौरान तीव्र वर्षण की घटनाओं और ओलावृष्टि के लिए अनुकूल परिस्थितियाँ उत्पन्न होती हैं।

5 से 9 जनवरी, 2022 के दौरान उत्तर-पश्चिम भारत में भारी से बहुत भारी वर्षण के साथ ओलावृष्टि वाली आर्द्र अवधि देखी गई। इस शोध-पत्र में उत्तर-पश्चिम भारत में इस आर्द्र अवधि से संबंधित पर्यावरणीय परिस्थितियों का अध्ययन किया गया है। यह पाया गया कि लगातार आए दो पश्चिमी विक्षोभों ने उत्तर-पश्चिम भारत को प्रभावित किया, जिससे दीर्घ अवधि तक आर्द्र स्थिति बनाए रखने के लिए अनुकूल परिस्थितियाँ उत्पन्न हुईं। इसी अवधि के दौरान अरब सागर और बंगाल की खाड़ी से उत्तर-पश्चिम भारत की ओर पर्याप्त मात्रा में नमी का अंतर्वाह भी हुआ। इसके अतिरिक्त, परिचालनात्मक वर्षा पूर्वानुमान के वितरण एवं चेतावनियों, उनकी उपयोगिता तथा विभिन्न संख्यात्मक मौसम पूर्वानुमान (Numerical Weather Prediction-NWP) मॉडलों की कार्यक्षमता का भी आकलन किया गया।

**ABSTRACT.** Northwest India (NWI) typically experiences wet spells from November to March mainly in the form of snow during the winter months, primarily influenced by eastward-moving winds, extra tropical system at different levels called western disturbances (WDs) in India, Pakistan, Nepal, Bangladesh & Bhutan. Occasionally, the interaction between middle-level westerly winds associated with these WDs and lower-level easterlies creates conditions favorable for intense precipitation events and hailstorms during the winter in NWI.

From January 5<sup>th</sup> to 9<sup>th</sup> January, 2022, NWI experienced a wet spell with heavy to very heavy precipitation, accompanied by hailstorms. This paper examines the environmental conditions associated with this wet spell over NWI. It is observed that two successive WDs influenced NWI, creating favorable conditions for a prolonged wet spell. Additionally, there was significant moisture incursion from the Arabian Sea and Bay of Bengal into NWI during the same period. The assessment of operational rainfall forecast distribution & warnings, their usability and performance of different NWP models has also been carried out.

**Key words-** Western disturbance, Northwest India, Winter precipitation.

### 1. Introduction

Severe winter precipitation over NWI adversely impacts the winter crops. For Rabi crops (wheat, mustard, barley, potato, onion, gram, etc.) during winter, the major agricultural crop season is over NWI. It is an important season for Rabi crops in NWI. Although winter precipitation is only about 15% of the annual precipitation, it is essential for Rabi crop production (Yadav *et al.*, 2012). Winter precipitation is variable, and variability has increased during the recent three decades (Yadav *et al.*, 2012). The primary reason for wet spells over the region during winter months are the WDs.

Structure, migration and dynamics of WDs are explained in a book written by Dimri and Chevuturi (2016). A systematic review on WDs was conducted was done by Dimri *et al.* (2015). Another updated review on WDs was published in 2025 by Hunt *et al.* (2025). The evolution, seasonality and impacts of WDs were documented by Hunt *et al.* (2018).

A wet spell accompanied by intense hailstorms creates enormous losses for crops in NWI. The occurrence of hailstorms and strategies to minimize their effect on crops have been discussed by Chattopadhyay *et al.* (2017). He discussed the farmer's aspect. An analysis of trends in

extreme precipitation events over the Western Himalayan Region (WHR) was conducted by Shekhar *et al.* (2017). Nageswara Rao *et al.* (2018) studied monthly and seasonal winter precipitation over NWI for the period 1901-2013 by using gridded data. They found that December precipitation is a good indicator of the performance of the rest of the winter months. Three hailstorm events and their influence on crop productivity in Hisar, Haryana, during March have been documented by Dhanda (2024). A case study on wet spell during November 2010 over NWI & west India was done by Yadav *et al.* (2013). Kumar *et al.* (2015) discussed winter frequency of WDs for the period of 1977-2010. Two WDs of January and March 2012 which impacted WHR was discussed by Singh *et al.* (2016).

NWI witnessed a wet spell with heavy to very heavy precipitation accompanied by hailstorms from January 5th to 9th, 2022. This study examines the environmental conditions associated with this wet spell over NWI and the forecast performance.

## 2. Data and methodology

In this paper, a precipitation event that occurred over NWI is selected for meteorological analysis. According to the India Meteorological Department (IMD), NWI has 9 meteorological subdivisions: Jammu, Kashmir & Ladakh, Himachal Pradesh, Uttarakhand, Punjab, Haryana, Chandigarh & Delhi, West Rajasthan, East Rajasthan, West Uttar Pradesh, and East Uttar Pradesh. Daily precipitation and hailstorm data are collected from the National Weather Forecasting Centre of IMD. In addition, Numerical Weather Prediction (NWP) model data are collected from the NWP division of IMD. Plotted charts from IMD are consulted for the synoptic systems. Lower-level convergence (LLC) and upper-level divergence (ULD) data are collected from CIMSS (<https://tropic.ssec.wisc.edu/archive/>).

Firstly, to detect the severe weather event, the precipitation data are collected from IMD. After scrutinizing the data, it is found that the event started on 5<sup>th</sup> January and persisted for 4-5 days. To investigate the associated weather and other environmental features, wind data at different levels are analyzed to detect the synoptic system. The LLC and ULD are analyzed to understand the dynamic conditions.

## 3. Results and discussion

### 3.1. Observational aspects and Impact over NWI

Very heavy snowfall activity occurred over northern Pakistan, Kashmir-Gilgit-Baltistan-Muzaffarabad causing

road blockades & landslides in these areas leading to loss of life and damage to public property. As per media reports, 22 tourists in the northern Pakistan region froze to death owing to this severe snowfall activity. The case is listed at the Wikipedia also, the link is cited here, ([https://en.wikipedia.org/wiki/2022\\_Murree\\_snowstorm#:~:text=At%20least%2022%20tourists%20died,the%20cars%2C%20causing%20the%20deaths](https://en.wikipedia.org/wiki/2022_Murree_snowstorm#:~:text=At%20least%2022%20tourists%20died,the%20cars%2C%20causing%20the%20deaths)).

Overcast skies with no sunlight over NWI for a continuous 3 days from 7<sup>th</sup> to 9<sup>th</sup> January were observed. Despite eastward passage of WD, lower tropospheric level easterlies persisted for subsequent 2-3 days, causing lower-level clouds to linger over NWI during the following week. It resulted in severe cold day conditions and overcast skies until 16<sup>th</sup> January. Press Release for the event was issued by IMD from 29<sup>th</sup> December 2021 onwards with a lead time of about one week.

Prompt preventive actions by State and National Disaster Management Authorities could be taken based upon high lead period heavy rainfall/snowfall and hailstorm warnings issued by IMD for the Western Himalayan Region (WHR) & the plains of NWI. It further helped mitigate losses to human lives & property.

### 3.2. Salient Features

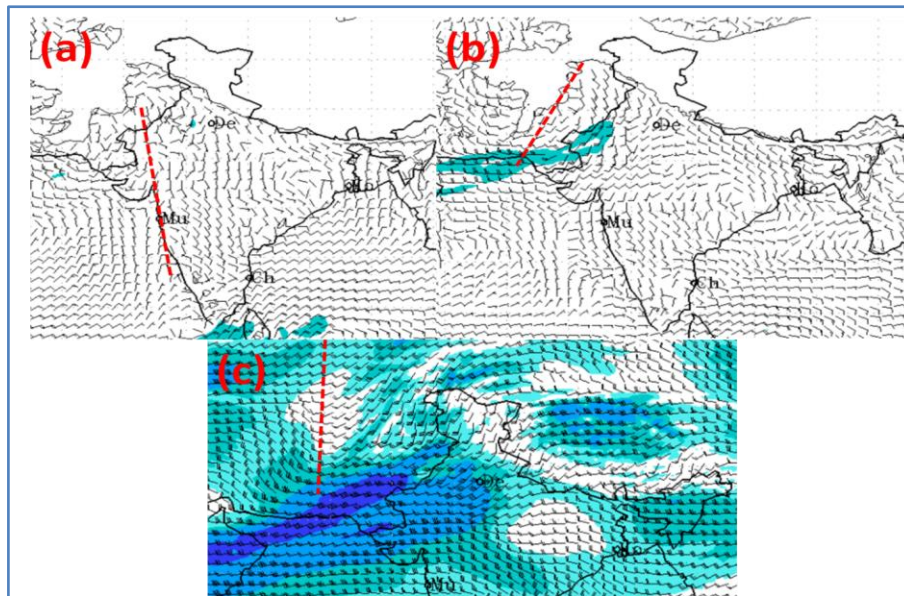
Two successive WDs impacted NWI during 05<sup>th</sup>-09<sup>th</sup> January. The first one (WD1) caused widespread (WS) light/moderate rainfall with isolated heavy rain/snowfall over the WHR on 06<sup>th</sup> January and the second one (WD2) caused WS light/moderate rainfall with isolated hailstorm and isolated heavy to very heavy rain/snowfall during 07<sup>th</sup>-08<sup>th</sup> January. These successive WDs had following salient features:

In general, most of the WDs affecting the Indian Region originate over Caspian & Mediterranean Sea whereas WD1 originated over the North Atlantic Ocean before 23<sup>rd</sup> December 2021 and moved eastwards to Himalayas.

Trough in lower and mid tropospheric levels associated with WD2 dipped far to the south of Lat 20°N, deeper into the Arabian Sea during 6<sup>th</sup>-8<sup>th</sup> January, 2022 which supplied high moisture from the Arabian Sea into the system.

Additionally, high moisture was supplied at lower tropospheric levels from the Bay of Bengal into the system.

WD2 was very intense as compared to WD1 having its vertical extension upto 9.5 Km amsl (above mean sea



**Figs. 1(a-c).** 05.01.2022:00UTC IMD GFS analysis winds for 925, 850 & 500 hPa

level). The weather caused by it was extremely severe as it remained almost stationary over north Pakistan for the period 07<sup>th</sup>-09<sup>th</sup> January.

### 3.3. Life history of western disturbance and realized weather

Impact of WD1 began over WHR from 04<sup>th</sup> January evening with FWS to WS snowfall/Rainfall over entire NWI on 5<sup>th</sup> January (Fig. 1). Most intense weather was observed over WHR on 5<sup>th</sup> by WD1 and from 6<sup>th</sup> January night to 7<sup>th</sup> January night by WD2 and over Punjab, Haryana, West UP, Rajasthan on 5<sup>th</sup> January by WD1 & on 7<sup>th</sup> January by WD2 (Tables: 1-2).

Brief intermission was observed in the rain/snowfall activity for 24 hours on 6<sup>th</sup> January. Moving eastwards from Long 50°E on 05<sup>th</sup> January, WD2 was located over north Pakistan region on 12UTC of 06<sup>th</sup> January and lay over the same region till 0300 UTC of 10<sup>th</sup> January thus spanning over a period of 60 hours as a trough between 1.5 & 9.5 km amsl from north Pakistan between Longitudes 64°E-70°E to the north of Latitude 15°N. A cyclonic circulation extending upto 9.5 km amsl was also embedded in this trough over the north Pakistan region.

The system received high moisture content at both lower & middle tropospheric levels from the Arabian Sea (AS) during 6<sup>th</sup>-8<sup>th</sup> January. At the same time, Bay of Bengal (BoB) also supplied significant moisture into the system through an easterly trough at 925 hPa level which extended from Telangana to the WD2 cyclonic circulation over north Pakistan during 7<sup>th</sup>-9<sup>th</sup> January (Figs. 2 & 3). Moisture incursion from both AS and BoB caused

interaction between middle & upper tropospheric level southwesterlies associated with the WD and the southeasterlies from lower tropospheric level trough in easterlies.

It further moved eastwards to be seen along Long 58°E to the north of Lat 20°N on 5<sup>th</sup> January; seen as a Low Pressure Area over central Pakistan embedded in a trough along Long 64°E to the north of Lat 15°N on 6<sup>th</sup> January. On 6<sup>th</sup> January, 9 cm rainfall was realized over Jammu and moderate snowfall realized over Kashmir region. With slight break in rainfall activity on 6<sup>th</sup> January, the second spell of intense rain/snow started from 7<sup>th</sup> January.

WD2 was seen as a Low Pressure Area on 7<sup>th</sup> January with associated cyclonic circulation extending upto 9.5 km amsl embedded in a trough along Long 70°E to the north of Lat 12°N supplying abundant moisture to the system. On this day North Pakistani town of Murree (Pakistan) recorded snowfall of more than 120 cm owing to which, according to media reports, 22 people had frozen to death in the night of 7<sup>th</sup> & early morning hours of 8<sup>th</sup> January ([https://en.wikipedia.org/wiki/2022\\_Murree\\_snowstorm#:~:text=At%20least%202022%20tourists%20died,the%20cars%2C%20causing%20the%20death%20](https://en.wikipedia.org/wiki/2022_Murree_snowstorm#:~:text=At%20least%202022%20tourists%20died,the%20cars%2C%20causing%20the%20death%20)). Due to this tragic event occurred over Murree this WD is also infamously recalled as Murree Snowstorm. As discussed above the WD2 lingered over north Pakistan on 8<sup>th</sup> January as well causing severe weather on 7<sup>th</sup> & 8<sup>th</sup> January over NWI. Indian National Capital Delhi (Palam) recorded 2<sup>nd</sup> highest rainfall for the month of January during last 63 years (1959-2022) and highest during last 27 years (1996-2022).

TABLE 1

24-hour accumulated rainfall distribution ending at 0830 hrs IST of the January 2022 day

| State          | 6 <sup>th</sup> | 7 <sup>th</sup> | 8 <sup>th</sup> | 9 <sup>th</sup> | 10 <sup>th</sup> |
|----------------|-----------------|-----------------|-----------------|-----------------|------------------|
| J & K          | WS              | FWS             | WS              | WS              | SCT              |
| HP             | WS              | ISOL            | WS              | WS              | WS               |
| Uttarakhand    | WS              | ISOL            | ISOL            | WS              | WS               |
| Punjab         | WS              | FWS             | WS              | WS              | ISOL             |
| Haryana        | WS              | SCT             | WS              | WS              | SCT              |
| West Rajasthan | FWS             | ISOL            | WS              | ISOL            | Dry              |
| East Rajasthan | FWS             | FWS             | WS              | SCT             | Dry              |
| West UP        | WS              | ISOL            | FWS             | FWS             | FWS              |
| East UP        | WS              | FWS             | FWS             | FWS             | FWS              |
| West MP        | ISOL            | FWS             | FWS             | SCT             | ISOL             |
| East MP        | ISOL            | SCT             | SCT             | FWS             | WS               |

### 3.4. Operational forecast performance

Sub-Division wise Daily Rainfall Distribution forecast & rainfall/snowfall warning has been verified as shown in Table 3 & 4 (Distribution and Intensity color: Hits correspond to Green, False Alarm to Yellow and Misses to Red in heavy rainfall warning). Table 3 & 4 suggest that at Met Subdivision level IMD has successfully predicted distribution as well as intensity of the rainfall/snowfall.

IMD started issuing forecast for this event from 29<sup>th</sup> December which has a lead time of 10 days. This forecast was consistently issued until the end of the event i.e. 10<sup>th</sup> January. This forecast was subsequently taken to the District/Block level by IMD's State Meteorological Centres (MC). In this case, MC Srinagar issued impact based warnings which helped Disaster Management Agencies and the District Administration in issuing Public Notices & Advisories which further helped General Public to follow preventive measures leading to zero loss of human life. In contrast, the same event led to dozens of casualties on Pakistan side.

### 3.5. Assessment of NWP Model Performance

The performance of various models in predicting the heavy rainfall episodes that occurred on 8<sup>th</sup> & 9<sup>th</sup> January has been assessed by analyzing the 24-hour cumulative rainfall outputs from global models including IMD GFS, NCEP GFS, GEFS, NCUM, and JMA. Respective images from models are placed in supplementary (Fig. 1-9).

#### 3.5.1. Model performance for 08<sup>th</sup> January Forecast

*Day 5 (120 hr lead time) Performance:* Grid rainfall data observed at 0830 hrs IST of 08<sup>th</sup> January shows 70-

130 mm rainfall observed over Jammu Division which is captured by only NCEP GFS and NCUM. JMA detects. Rainfall shown by IMD GFS and GEFS was two stage below i.e. 20-40 mm.

*Day 4 (96 hour lead time) Performance:* 70-130 mm rainfall was captured by NCEP GFS, NCUM and JMA both location and intensity wise. IMD GFS captures one stage below i.e. 40-70mm which is one level up from the Day 5 forecast.

*Day 3 (72 hour lead time) Performance:* NCEP and JMA continues to capture whereas NCUM has not been consistent. NCUM downgrades the forecast to 20-40 mm which is 2 stage below the observed rainfall. IMD GFS again downgrades and goes 2 stage below as in Day 5 forecast.

*Day 2 (48 hour lead time) Performance:* NCEP downgrades the forecast one stage below whereas it was predicting correctly till Day 3. GFS has reached closed to the observed rainfall only once during Day2-Day5 lead period. NCUM again picks up after losing the forecast on Day 3. JMA is consistent since Day 4 in predicting the accurate rainfall although it is showing 70-130mm over north Punjab also.

*Day 1 (24 hour lead time) Performance:* All the models have correctly predicted the rainfall in 24 hour forecast but since the NWP product availability and final forecast dissemination happen around between 7-8 UTC the lead time reduces to 19-20 hours instead of 24 hours.

Thus, the best model for this weather event proved to be JMA followed by NCEP GFS which however downgraded the forecast on Day 2.

TABLE 2

24-hour accumulated rainfall ending at 0830 hrs IST of the January 2022 day

| State          | 6 <sup>th</sup>                                                                                                                                                                                                               | 7 <sup>th</sup>                                                                                                                                       | 8 <sup>th</sup>                                                                                                                                                                                                      | 9 <sup>th</sup>                                                                                                                                  | 10 <sup>th</sup>                                                                                                                                                                                                                                                                   |
|----------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| J & K          | Jammu Aero-9, Batote-8, Udhampur IAF-7 each, Badarwah, Banihal, Katra & Samba AWS-6 each, Jammu, Govindpura AWS & Kawa AWS-5 each, Pahalgam, Gulmarg & Rajouri-4 each, Kukernag, Gund, Kupwara & Shalimar-2 each, Anantnag-1. | <1                                                                                                                                                    | Udhampur: Udhampur IAF-12, Kawa-7; Reasi: Katra-10; Jammu: Jammu Aero-10, Jammu-8, Jammu AWS-6, RSP Pura AWS-6; Doda: Badarwah-8; Ramban: Banihal-8, Batote & Govindpura-7 each; Rajouri-7; Kathua & Rajhani-6 each. | Batote-8, Tehri-6; Qazigund, Badarwah-5 each.                                                                                                    | <1                                                                                                                                                                                                                                                                                 |
| HP             | Una-5, Manali, Dharamsala-4, Bhuntar, Mandi, Sundernagar-3 each                                                                                                                                                               | <1                                                                                                                                                    | Chamba: Dalhousie & Kheri-5 each                                                                                                                                                                                     | <1                                                                                                                                               | Kandaghat-8, Dharampur, Solan, Pacchad-7 each, Rajgarh, Bharmaur, Khadrula, Kasauli, Sangrah, Shimla Airport, Sirmaur-6 each; Arki, Naina Devi, Baldwara, Jattion Barrage, Sundernagar, Nahan-5 each; Banjar, Kothi, Sarahan, Shimla, Mandi, Rampur, Karsog, Gohar, Manali-4 each. |
| Uttarakhand    | <1                                                                                                                                                                                                                            | <1                                                                                                                                                    | <1                                                                                                                                                                                                                   | Kotdwar-8                                                                                                                                        | Dehradun-3                                                                                                                                                                                                                                                                         |
| Punjab         | Patiala-3                                                                                                                                                                                                                     | Kapurthala: Kapurthala-9; Gurdaspur: Athwal-7, Gurdaspur Amfu-6, Batala & Tibri-5 each; Pathankot: Pathankot-6; Jalandhar: Adampur & Jalandhar-5 each | Ludhiana: Bul-13, Jagraon-9, Ludhiana-6, Pathankot: Phangota-9, Kapurthala: Kapurthala, Phagwara-6 each, Patiala: Samana, Nabha ARG-6 each, Gurdaspur: Tibri, Dhariwal-5 each, Jalandhar: Nakodar ARG-7              | <1                                                                                                                                               | <1                                                                                                                                                                                                                                                                                 |
| Haryana        | <1                                                                                                                                                                                                                            | <1                                                                                                                                                    | Gurgaon: Sohna-7, Manesar-5; Nuh: Taoru-6; Yamuna Nagar: Dadupur-8, Jagadhri-5 each; Central Delhi: Pusa-7; North Delhi: Delhi Ridge-5; South Delhi: Ayanagar-5; Southwest Delhi: Palam-5                            | Panipat: Bapouli-7, Karnal: Gharaunda-6, Karnal-5, Rohtak: Lakhanmajra-6, Yamunanagar: Chhachhrauli-6, Palwal-6, Dhansa (Southwest Delhi)-6 each | Yamuna Nagar, Panchkula-5 each; Ambala-4; Chandigarh-3                                                                                                                                                                                                                             |
| West Rajasthan | <1                                                                                                                                                                                                                            | <1                                                                                                                                                    | <1                                                                                                                                                                                                                   | <1                                                                                                                                               | <1                                                                                                                                                                                                                                                                                 |
| East Rajasthan | <1                                                                                                                                                                                                                            | <1                                                                                                                                                    | Alwar: Behror & Neemrana-7 each; Kishangarh SR-6; Jaipur: Jaipur & Viratnagar-5 each; Sikar: Srimadhampur-6                                                                                                          | Paota (Jaipur)-9, Alwar-7, Bharatpur-5                                                                                                           | <1                                                                                                                                                                                                                                                                                 |

3.5.2. Model performance for 09<sup>th</sup> January Forecast

*Day 5 (120-hour lead time) Performance:* Grid rainfall data observed at 08:30 IST (03 UTC) on 9<sup>th</sup> January shows 40-70 mm of rainfall over North Punjab, North Haryana, Jammu Division, and Himachal Pradesh. However, observed point rainfall at IMD stations exceeded 70 mm at five stations. Considering the point rainfall data, both IMD GFS and NCEP GFS accurately

predicted the rainfall, though they overestimated it compared to the gridded rainfall data. In contrast, NCUM and JMA predicted rainfall amounts exceeding 130 mm, one stage above the point rainfall and two stages above the gridded rainfall data.

*Day 4 (96-hour lead time) Performance:* Point rainfall data observed at IMD stations was accurately predicted by IMD GFS, NCUM, and JMA, while NCEP

TABLE 3

Subdivision-wise Verification of daily rainfall distribution forecast/rainfall/snowfall warning (7 January 2022)

| MET SUB-DIV/Days            | D5 (3 Jan)           | D4                   | D3                | D2               | D1(7 Jan)        | D0(Observed 8 <sup>th</sup> Jan rainfall at 0830ist ) |
|-----------------------------|----------------------|----------------------|-------------------|------------------|------------------|-------------------------------------------------------|
| Punjab                      | Fairly Widespread    | Widespread (H)       | Widespread        | Widespread (H)   | Widespread (H)   | Widespread (H)                                        |
| Haryana, Chandigarh & Delhi | FairlyWidespread     | FairlyWidespread     | FairlyWidespread  | Widespread       | Widespread       | Widespread (H)*                                       |
| WUP                         | Scattered            | Fairly Widespread    | Scattered         | Scattered        | Scattered        | Fairly Widespread                                     |
| E RAJ                       | FairlyWidespread     | FairlyWidespread     | FairlyWidespread  | FairlyWidespread | FairlyWidespread | Widespread (H)*                                       |
| W RAJ                       | FairlyWidespread     | FairlyWidespread     | FairlyWidespread  | FairlyWidespread | FairlyWidespread | Widespread                                            |
| J K                         | FairlyWidespread (H) | FairlyWidespread (H) | Widespread (H)    | Widespread (H)   | Widespread (HVH) | Widespread (HVH)                                      |
| HP                          | FairlyWidespread     | FairlyWidespread     | Fairly Widespread | Widespread       | Widespread (H)   | Widespread                                            |
| UTK                         | Fairly Widespread    | Scattered            | Scattered         | Scattered        | Scattered        | Isolated                                              |

TABLE 4

8 January 2022: Subdivisional Verification of daily rainfall distribution forecast&amp; warning

| MET SUB-DIV/Days            | D5 (4 Jan)       | D4               | D3               | D2                | D1(8 Jan)        | D0(Observed 9 Jan)    |
|-----------------------------|------------------|------------------|------------------|-------------------|------------------|-----------------------|
| Punjab                      | Widespread (H)   | Widespread (H)   | Widespread (H)   | Widespread (H)    | Widespread (H)   | Widespread (HVH)**    |
| Haryana, Chandigarh & Delhi | Widespread (H)   | Widespread (H)   | Widespread (H)   | Widespread (H)    | Widespread (H)   | Widespread (H)        |
| WUP                         | FairlyWidespread | FairlyWidespread | Widespread (H)   | Widespread        | Widespread       | Fairly Widespread (H) |
| E RAJ                       | Scattered        | Scattered        | Scattered        | Fairly Widespread | Scattered        | Scattered (H)*        |
| W RAJ                       | Scattered        | Isolated         | Scattered        | Scattered         | Isolated         | Isolated              |
| J K                         | Widespread (H)   | Widespread (H)   | Widespread (HVH) | Widespread (H)    | Widespread (HVH) | Widespread (H)        |
| HP                          | Widespread (H)   | Widespread (H)   | Widespread (H)   | Widespread (H)    | Widespread (HVH) | Widespread#           |
| UTK                         | Widespread       | Widespread (H)   | Widespread (H)   | Widespread        | Widespread (H)   | Widespread#           |

GFS forecasted rainfall one stage lower than observed values.

*Day 3 (72-hour lead time) Performance:*IMDGFS correctly predicted the rainfall intensity but showed significant spatial displacement compared to Days 5 and 4. JMA overpredicted the point rainfall by one stage, while NCEP GFS downgraded the rainfall by one stage.

*Day 2 (48-hour lead time) Performance:*NCEP GFS correctly captured the rainfall intensity whereas IMD GFS predicted rainfall one stage below the observed point data. Both JMA and NCUM accurately predicted the observed point rainfallata.

*Day 1 (24-hour lead time) Performance:* Similar to the event on 8<sup>th</sup> January, all models correctly predicted the rainfall in the 24-hour forecast. NCUM showed 70-130 mm of rainfall over Jammu, North Punjab, North Haryana, and Northwest Uttar Pradesh. Thus,

NCUM may be considered the best model for this event despite its overestimation in Western Uttar Pradesh.

### 3.6. Dynamical conditions

For the investigation of dynamical conditions, ULD, LLC and vorticity respective images from CIMSS are placed in supplementary (Fig. 10-15).

At 00 UTC on 5<sup>th</sup> January, ULD of the order  $30 \times 10^{-6} \text{ s}^{-1}$  was observed over Punjab-Northwest Rajasthan region. This divergence dissipated and was subsequently replaced by negative ULD advancing from the west. When the approaching WD merged with the previous WD on January 7<sup>th</sup> January, the ULD increased to around  $50 \times 10^{-6} \text{ s}^{-1}$  over Haryana and the surrounding area at 00 UTC on 8<sup>th</sup> January. This ULD then decreased to  $20 \times 10^{-6} \text{ s}^{-1}$  at 00 UTC on 9<sup>th</sup> January and further dropped to  $10 \times 10^{-6} \text{ s}^{-1}$  by 12 UTC on the same day.

At 00 UTC on 5<sup>th</sup> January, a LLC of approximately  $10 \times 10^{-6} \text{ s}^{-1}$  was observed over Pakistan, which increased to  $30 \times 10^{-6} \text{ s}^{-1}$  by 12 UTC on the same day. This LLC dissipated and was subsequently replaced by negative LLC advancing from the west. When the approaching WD merged with the previous WD on 7<sup>th</sup> January, the LLC increased to around  $30 \times 10^{-6} \text{ s}^{-1}$  over Haryana and the surrounding region at 00 UTC on 8<sup>th</sup> January. At this time, the LLC and ULD were vertically displaced, with both centered roughly at  $30^\circ\text{N}$ ,  $76^\circ\text{E}$ . The ULD moved eastward and decreased to  $20 \times 10^{-6} \text{ s}^{-1}$  by 00 UTC on 9<sup>th</sup> January and continued moving out of the Indian region by 12 UTC on the same day.

At 00 UTC of 5<sup>th</sup> January, the 850 hPa vorticity (Lower Level Vorticity, LLV) was observed as  $30\text{--}50 \times 10^{-6} \text{ s}^{-1}$  over Pakistan. This LLV increased to  $70\text{--}100 \times 10^{-6} \text{ s}^{-1}$  by 12 UTC on the same day. Although the LLV weakened, it did not dissipate and intensified again by 00 UTC on 8<sup>th</sup> January, when the approaching WD merged with the previous WD on 7<sup>th</sup> January. At 00 UTC on 8<sup>th</sup> January, the LLV increased to approximately  $80 \times 10^{-6} \text{ s}^{-1}$  over northern Pakistan and the surrounding area. It began to weaken and elongate from 12 UTC on 8<sup>th</sup> January.

At 00 UTC on 5<sup>th</sup> January, the 700 hPa vorticity (Vor 700) was observed at  $50 \times 10^{-6} \text{ s}^{-1}$  over Pakistan, increasing to  $70\text{--}100 \times 10^{-6} \text{ s}^{-1}$  by 12 UTC the same day. Although the LLV weakened, it did not dissipate and intensified again by 00 UTC on 8<sup>th</sup> January, when the approaching WD merged with the previous WD on 7<sup>th</sup> January. At 00 UTC on 8<sup>th</sup> January, the LLV increased to approximately  $80 \times 10^{-6} \text{ s}^{-1}$  over northern Pakistan and the surrounding area. It began to weaken and elongate from 12 UTC on 8<sup>th</sup> January.

At 00 UTC on 5<sup>th</sup> January, positive vorticity exceeding  $100 \times 10^{-6} \text{ s}^{-1}$  was observed, which became slightly weaker on 6<sup>th</sup> January. By 8<sup>th</sup> January, a circular vorticity pattern was visible over Pakistan, with values reaching up to  $150 \times 10^{-6} \text{ s}^{-1}$ . This pattern started dissipating by the evening of 8<sup>th</sup> January and became very weak by the morning of 9<sup>th</sup> January.

High positive vorticity was also observed at the 200 hPa level, reaching approximately  $120 \times 10^{-6} \text{ s}^{-1}$  at 00 UTC on 8<sup>th</sup> January. The system was so intense that it extended up to 200 hPa, whereas western disturbances generally extend only up to 400 hPa.

#### 4. Conclusions

Rainfall/Snowfall (in J&K, H.P, Ladakh and Uttarakhand) during the winter months in NWI is called as the winter monsoon. Among the major synoptic systems, intense WDs are known for causing significant spells of

heavy precipitation and severe weather events such as heavy snowfall and hailstorms in the region. The frequency of WDs during the winter months varies, and heavy rainfall and hailstorms can sometimes lead to widespread damage to standing crops. Therefore, documenting these winter weather events is crucial for forecasters, disaster managers, and decision-makers.

A notable case study from winter 2022 highlights a severe weather event. From 5<sup>th</sup> to 9<sup>th</sup> January 2022, NWI experienced a long spell of heavy to very heavy precipitation accompanied with hailstorms. The environmental conditions associated with this wet spell are analyzed in detail. It was observed that two WDs in quick succession affected NWI, creating favorable conditions for a prolonged wet spell. Additionally, there was significant moisture incursion from the Arabian Sea & Bay of Bengal (into NWI during this period. The assessment of operational forecasts and warnings, as well as the performance of different NWP models, was also conducted. It was found that the operational forecasts and warnings were very effective during this weather episode. The NWP models were able to detect the event.

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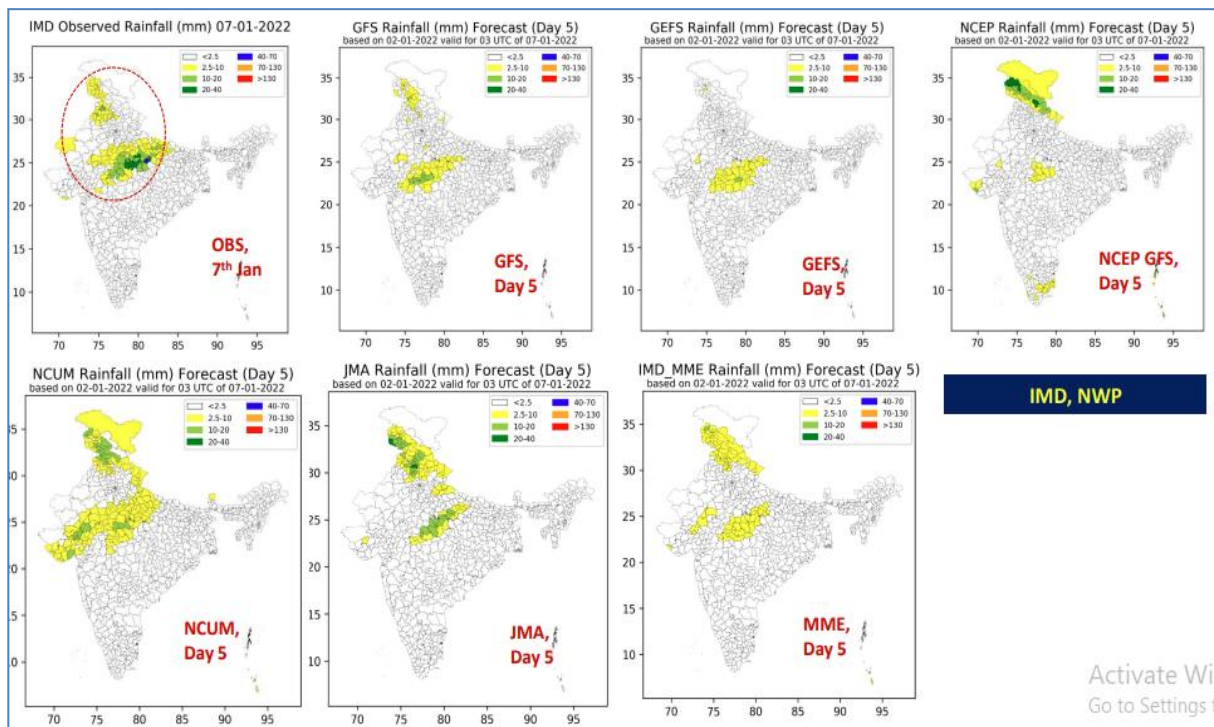
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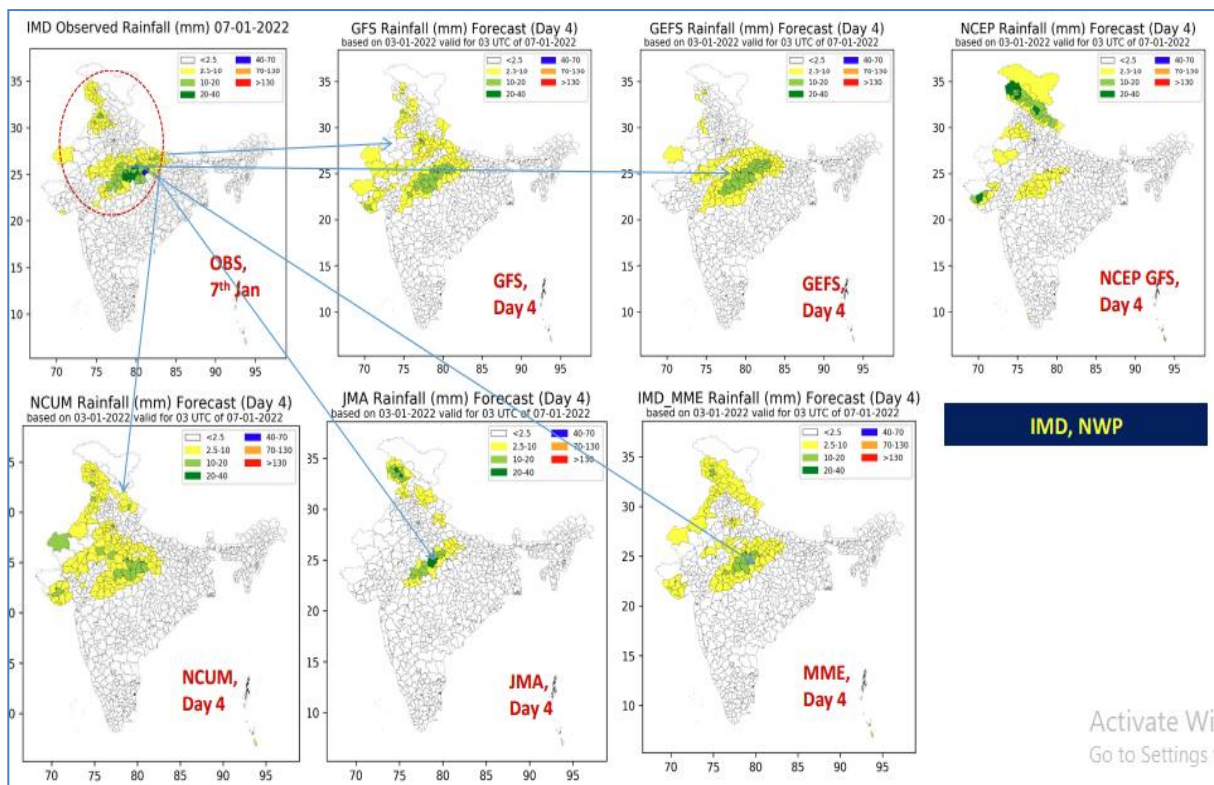
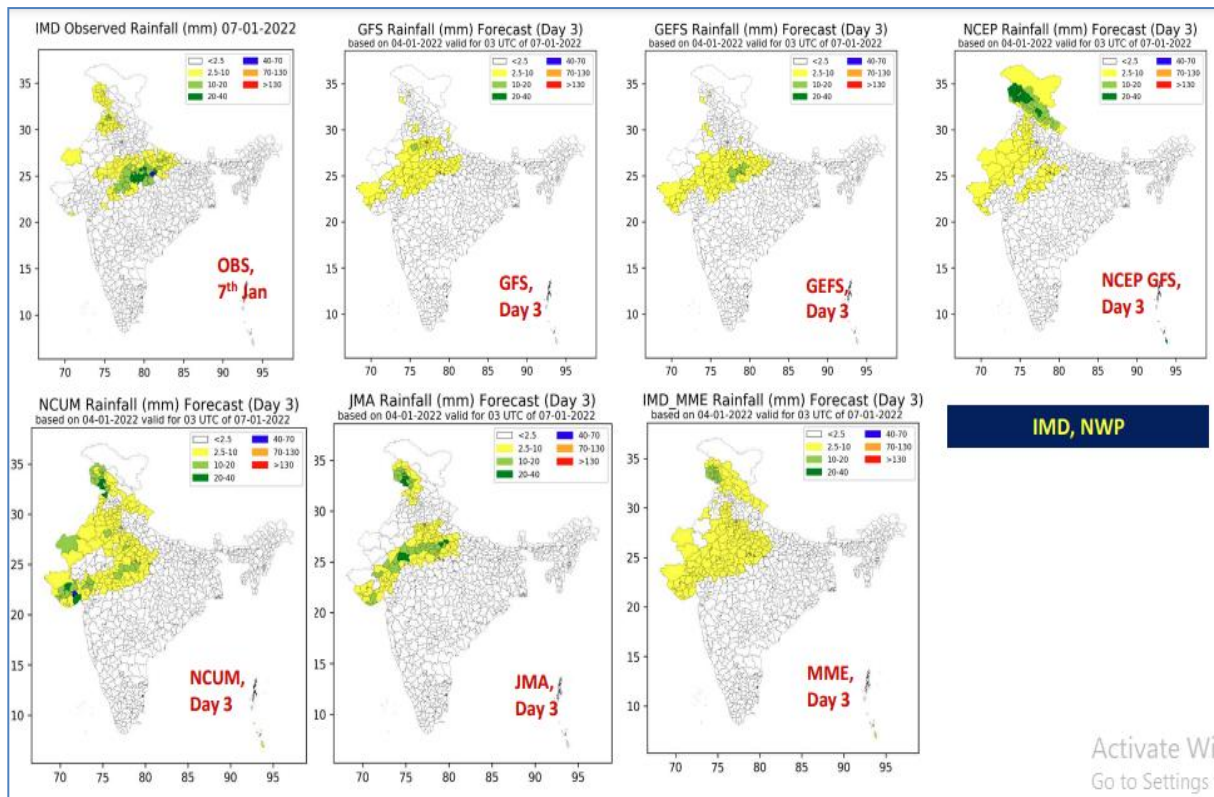
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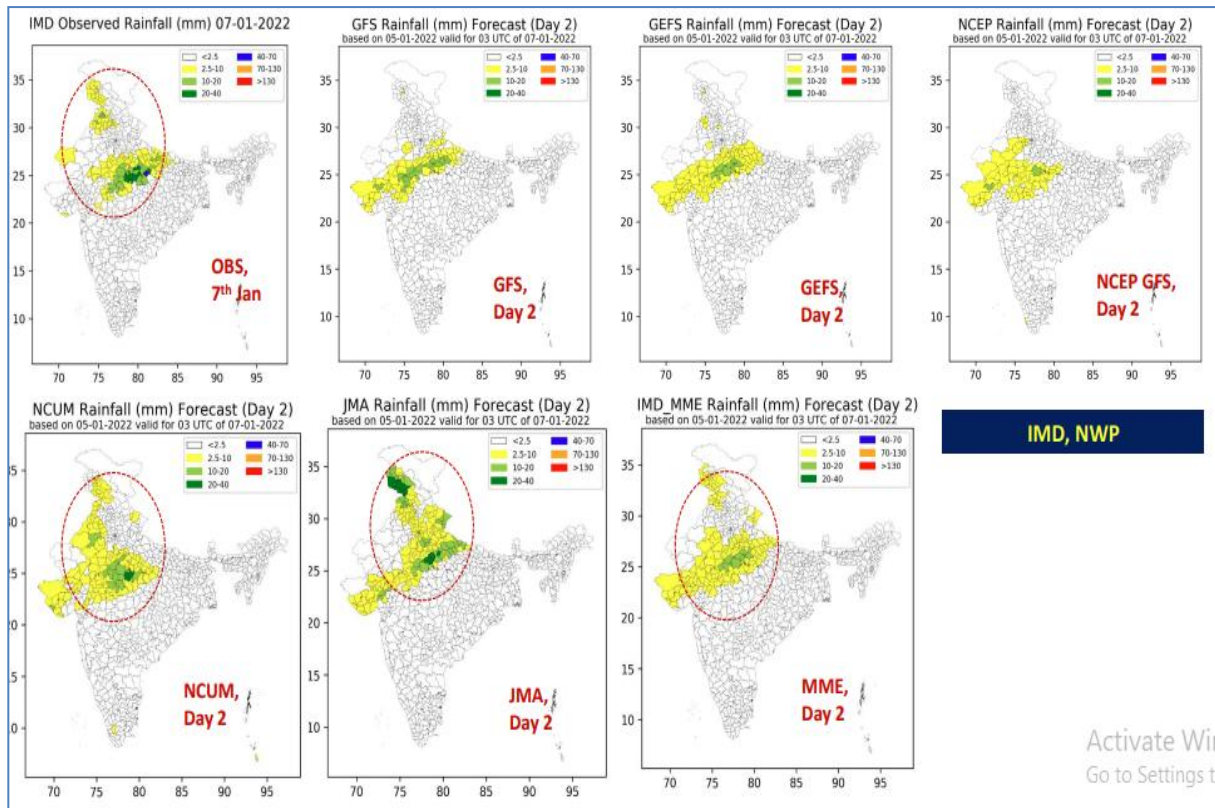
## List of Abbreviations

**NWI:** Northwest India, **WHR:** Western Himalayan Region, **IMD:** India Meteorological Department, **NWP:** Numerical Weather Prediction, **GFS:** Global Forecasting System, **NCU:** National Centre for Medium-range Weather Forecasting (NCMRWF) Unified Model, **GEFS:** Global Ensemble Forecasting System, **UTC:** Coordinated Universal Time, **NCEP:** National Centers for Environmental Prediction, **NOAA:** National Oceanic and Atmospheric Administration, **JMA:** Japan Meteorological Agency, **WD:** Western Disturbance, **hPa:** Hectopascal, **ULD:** Upper-level Divergence, **LLC:** Lower Level Convergence, **LLV:** Lower Level Vorticity, **CIMSS:** Cooperative Institute for Meteorological Satellite Studies, **MC:** Meteorological Center, **WUP:** West Uttar Pradesh, **E RAJ:** East Rajasthan, **W RAJ:** West Rajasthan, **H.P.:** Himachal Pradesh, **J & K:** Jammu & Kashmir, **UTK:** Uttarakhand, **H:** Heavy Rainfall, **HVH:** Heavy to very heavy rainfall.

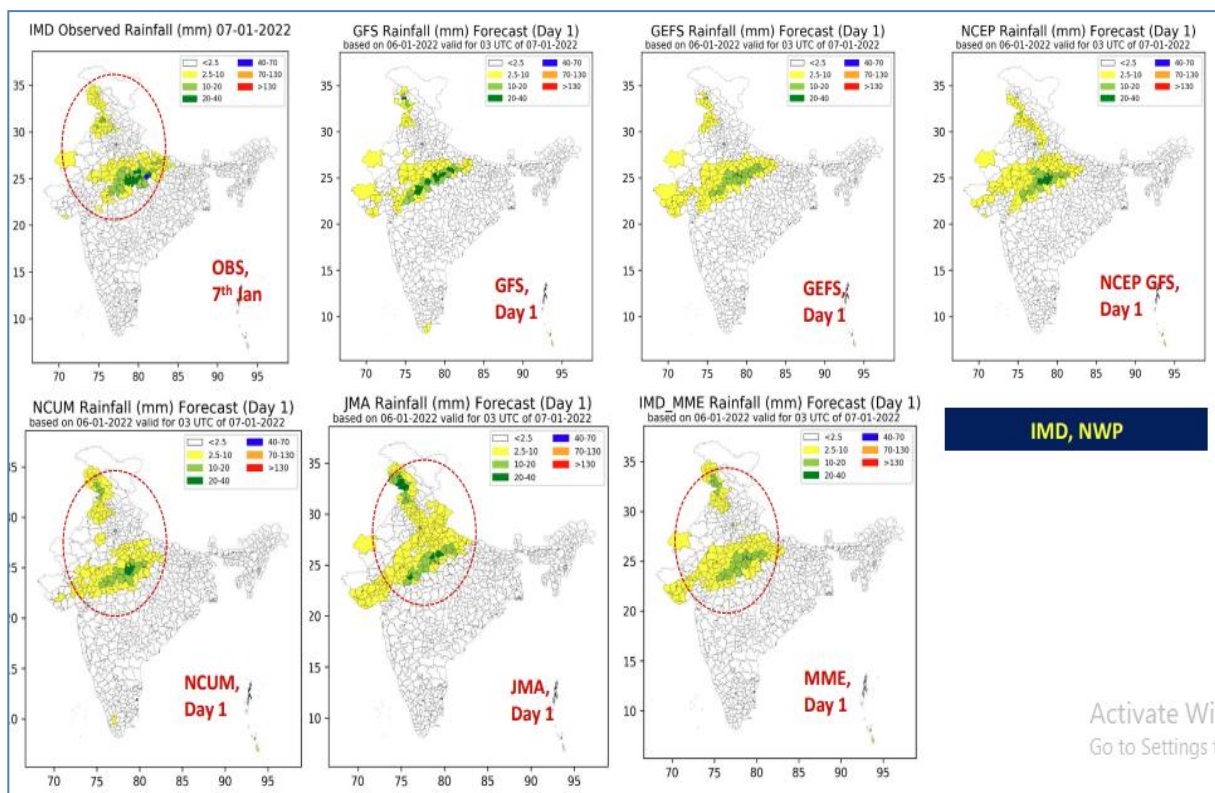
## Supplementary Figures



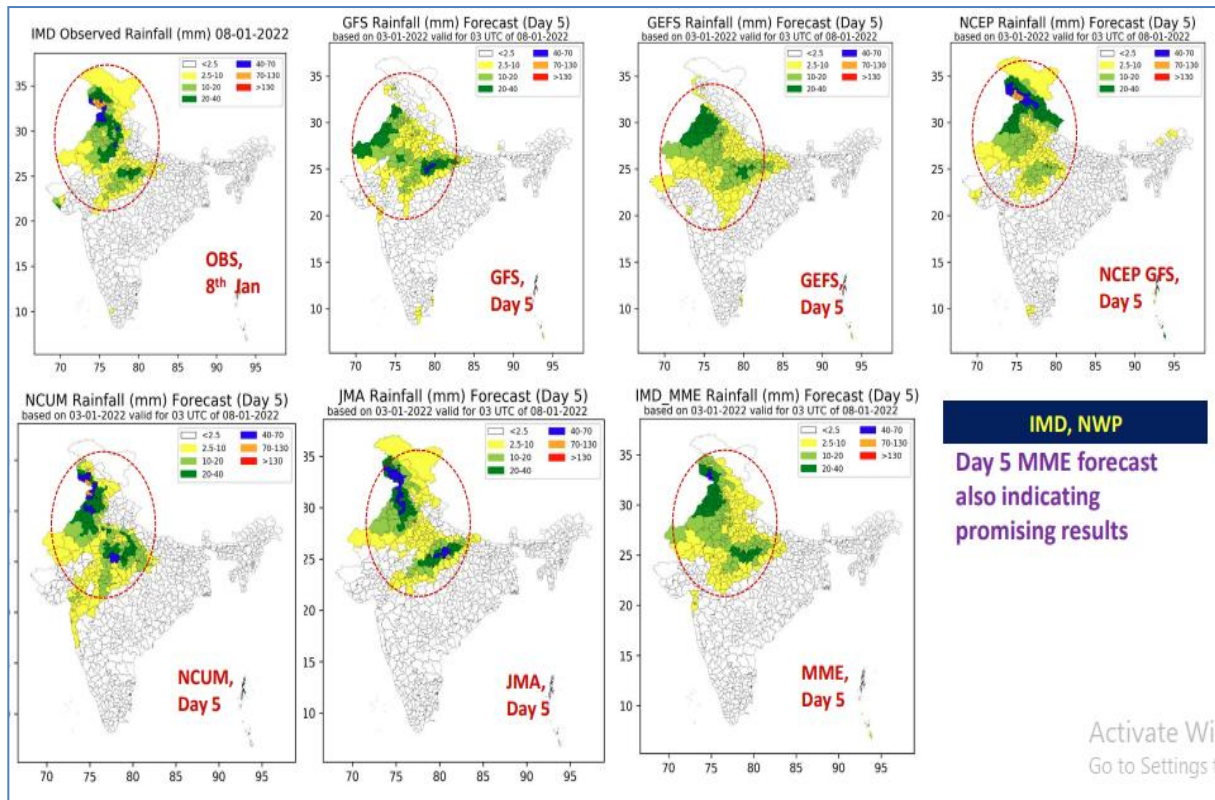
Supplementary Fig. 1. Model Performance for Day 4 & Day 5 on 07<sup>th</sup> January 2022



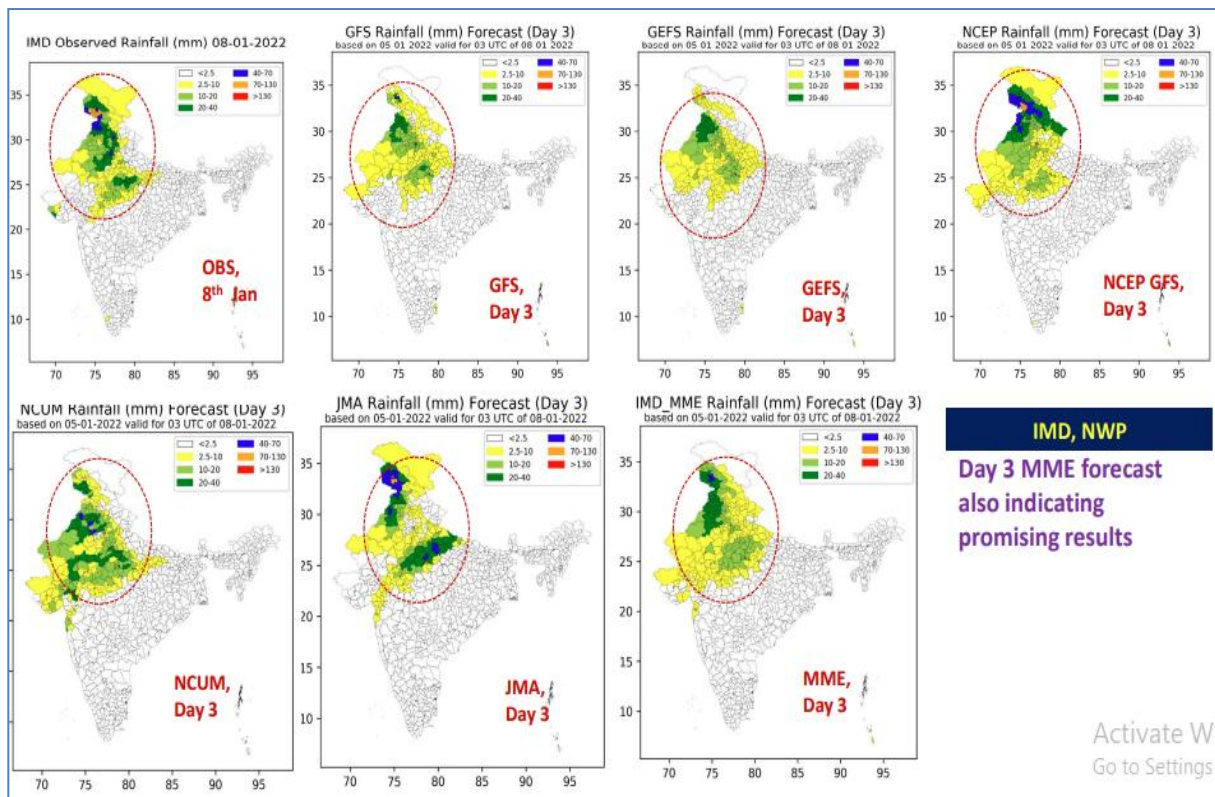
Supplementary Fig. 2. Model Performance for Day 2 & Day 3 on 07<sup>th</sup> January 2022

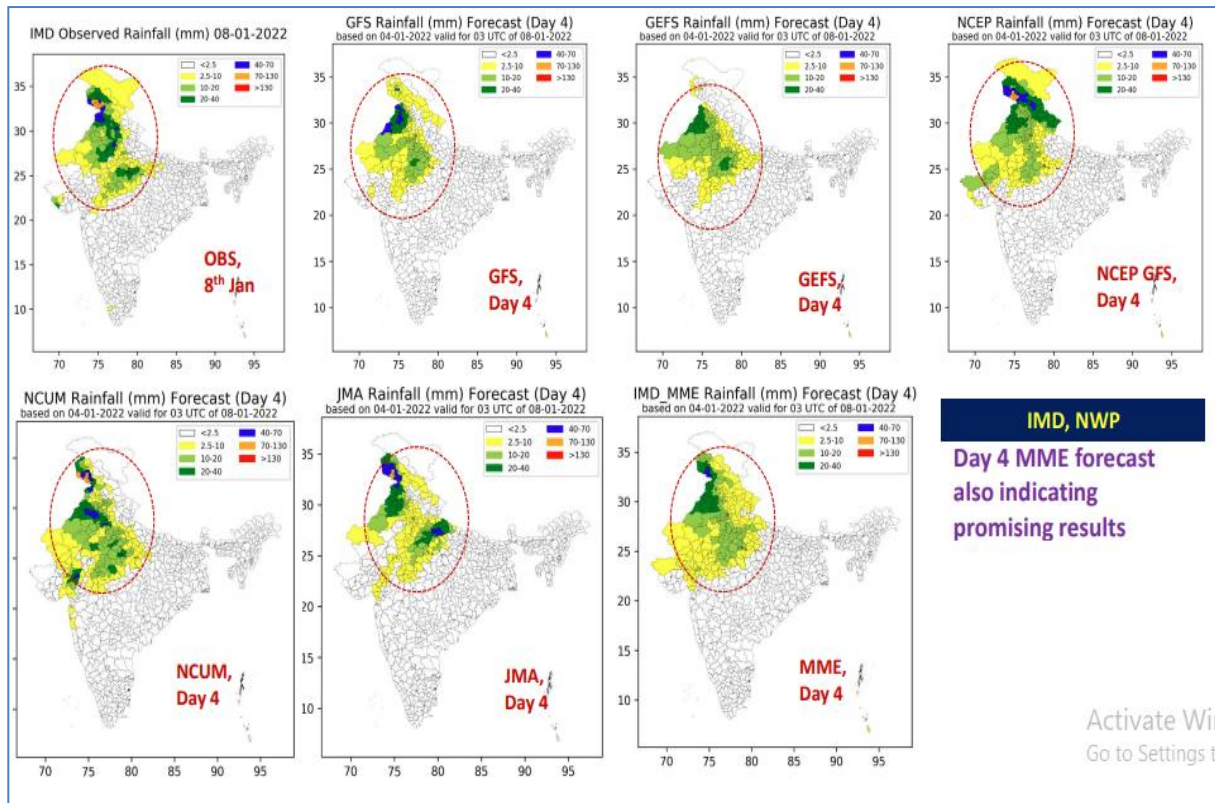


Supplementary Fig. 3. Model Performance for Day 1 on 07<sup>th</sup> January 2022

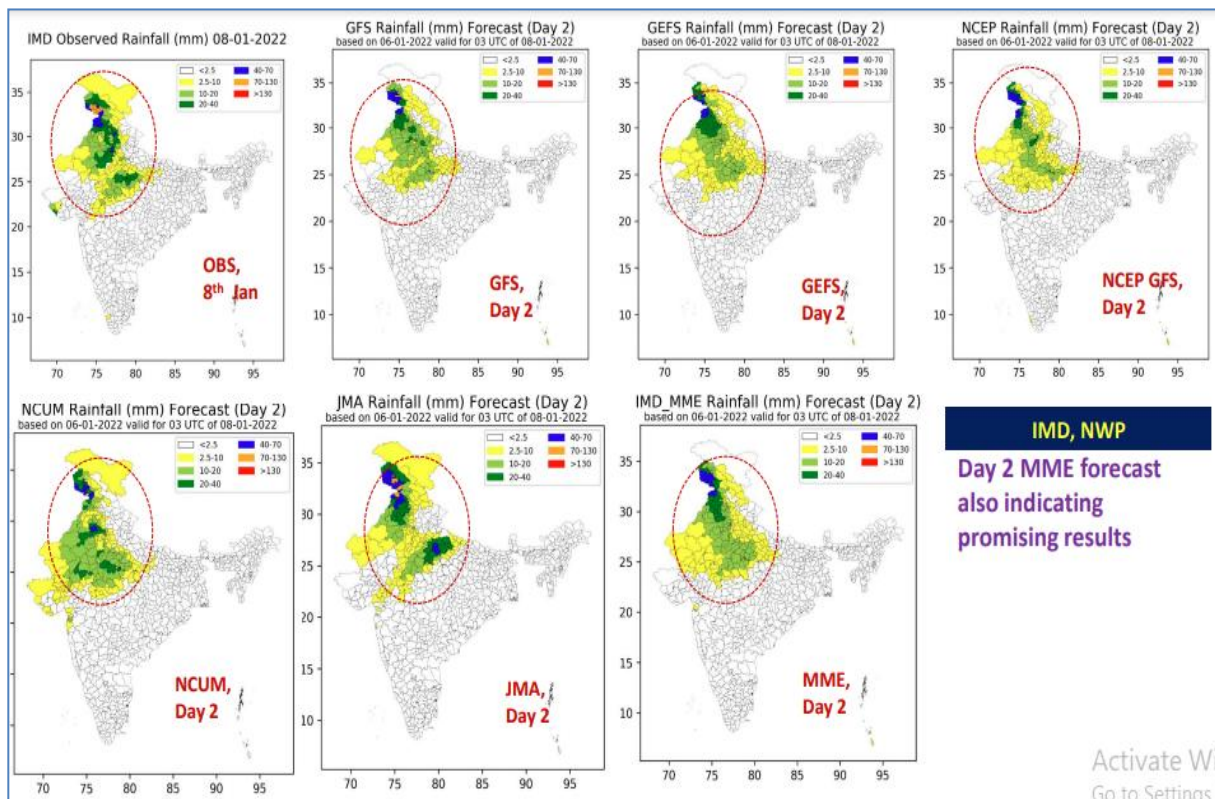


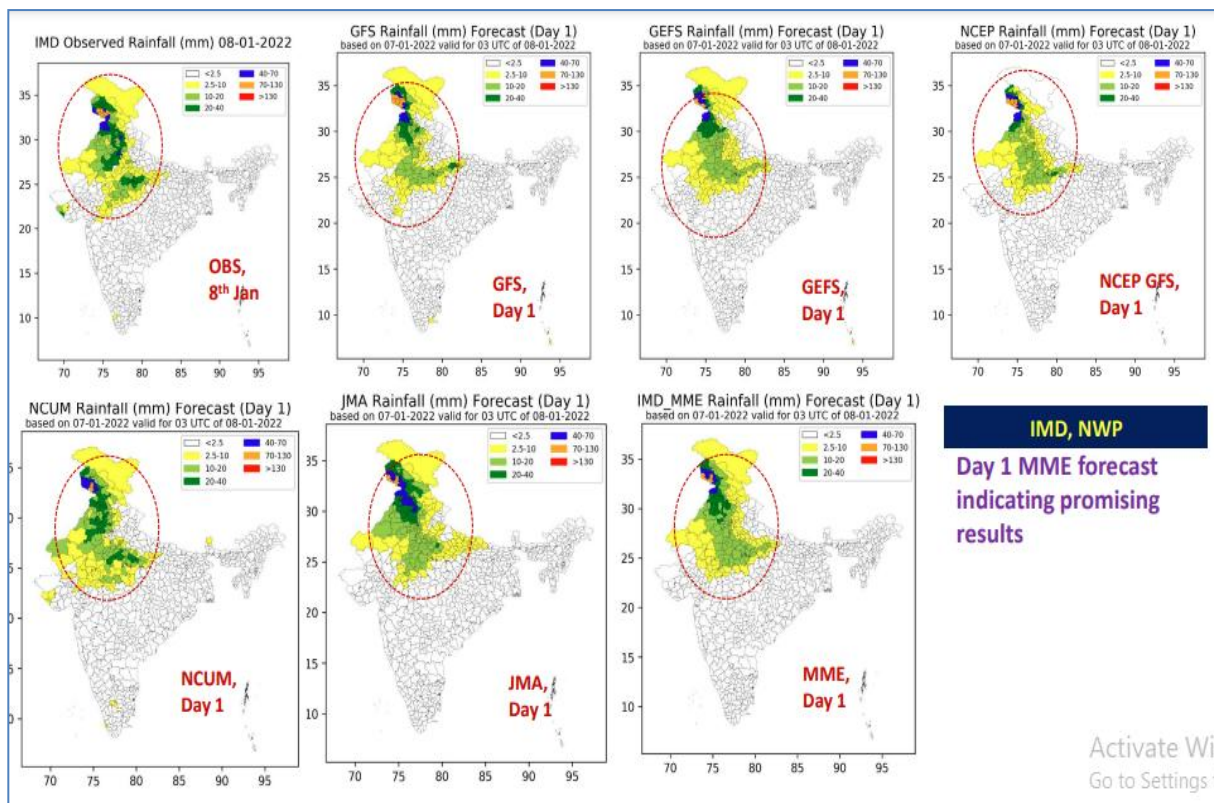
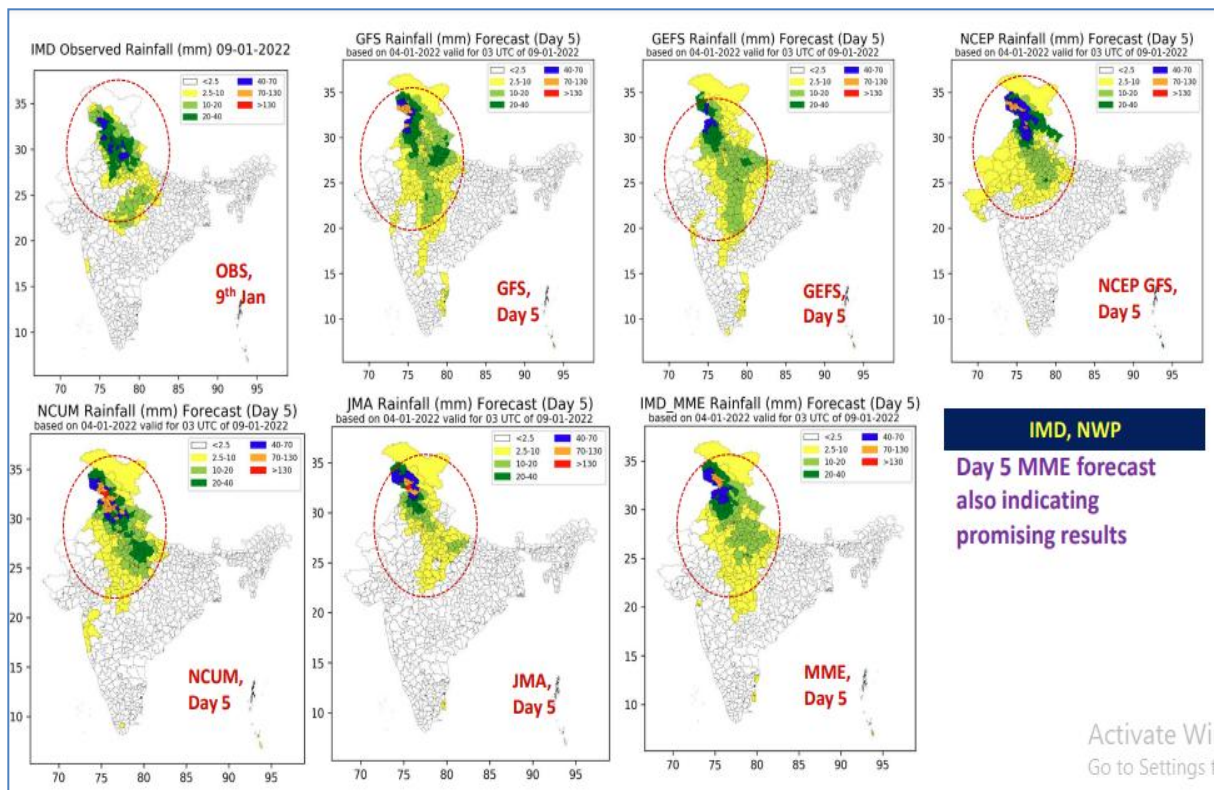
Supplementary Fig. 4. Model Performance for Day 5 on 08<sup>th</sup> January 2022

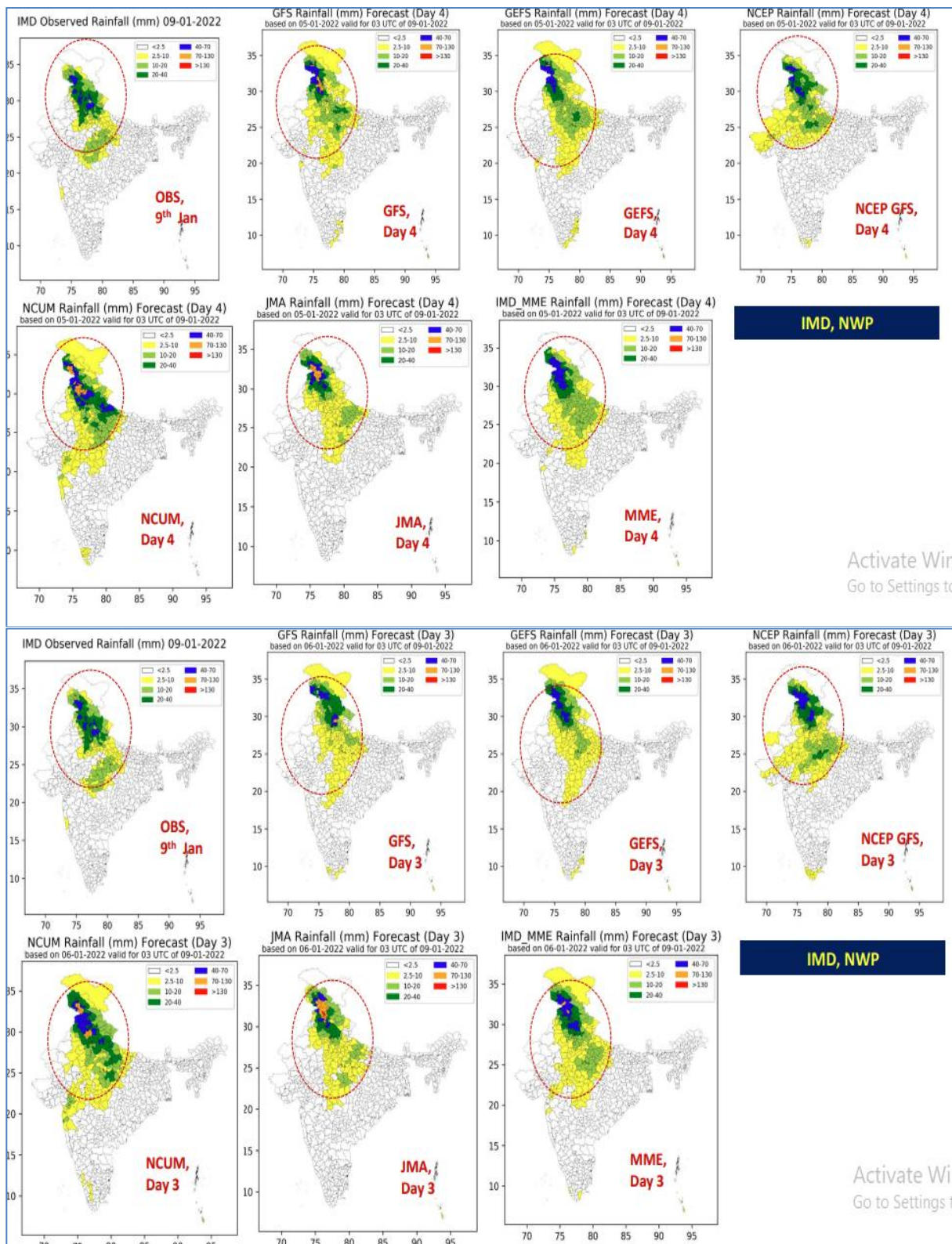




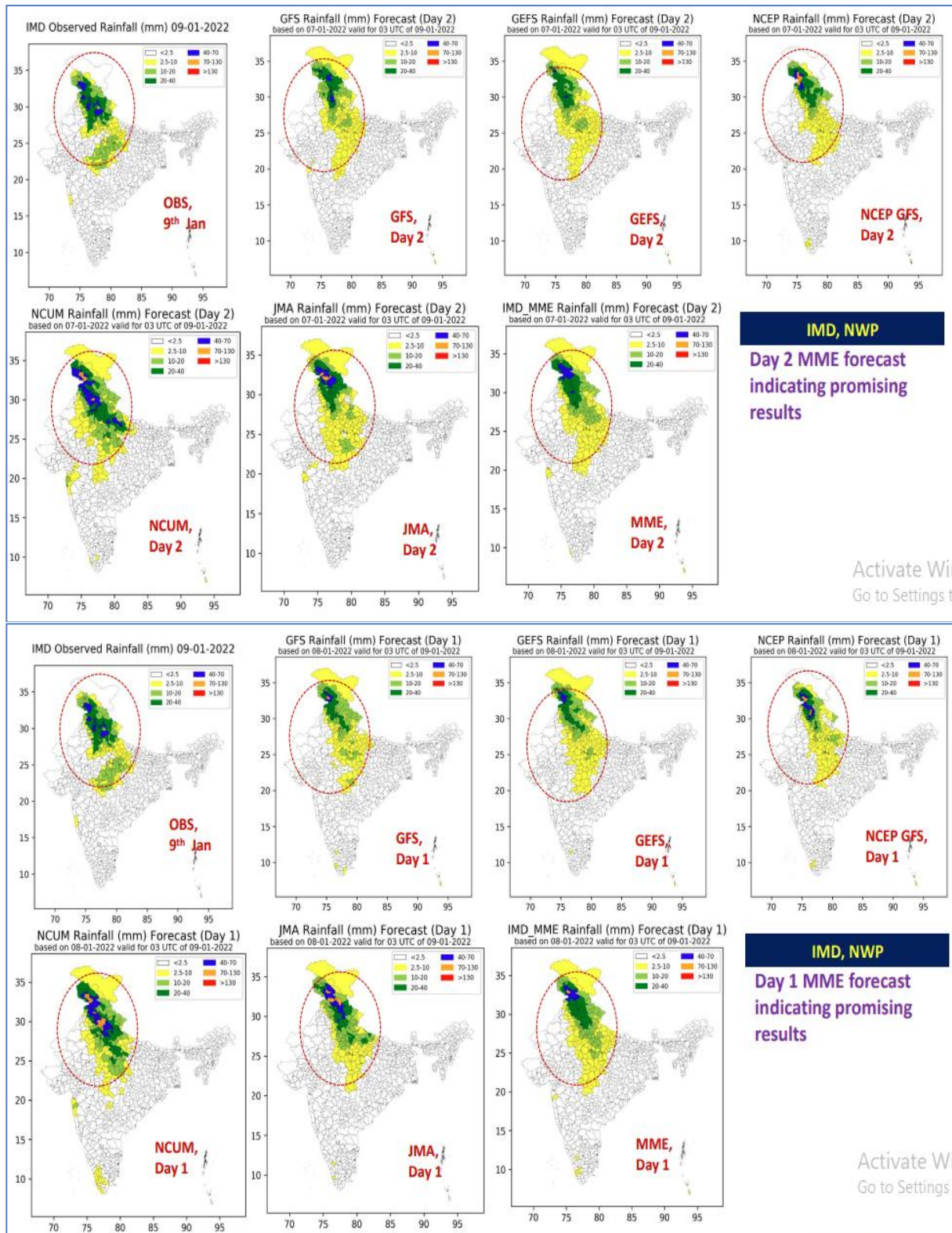
Supplementary Fig. 5. Model Performance for Day 4 (top panel) and Day 3 (bottom panel) on 08<sup>th</sup> January 2022

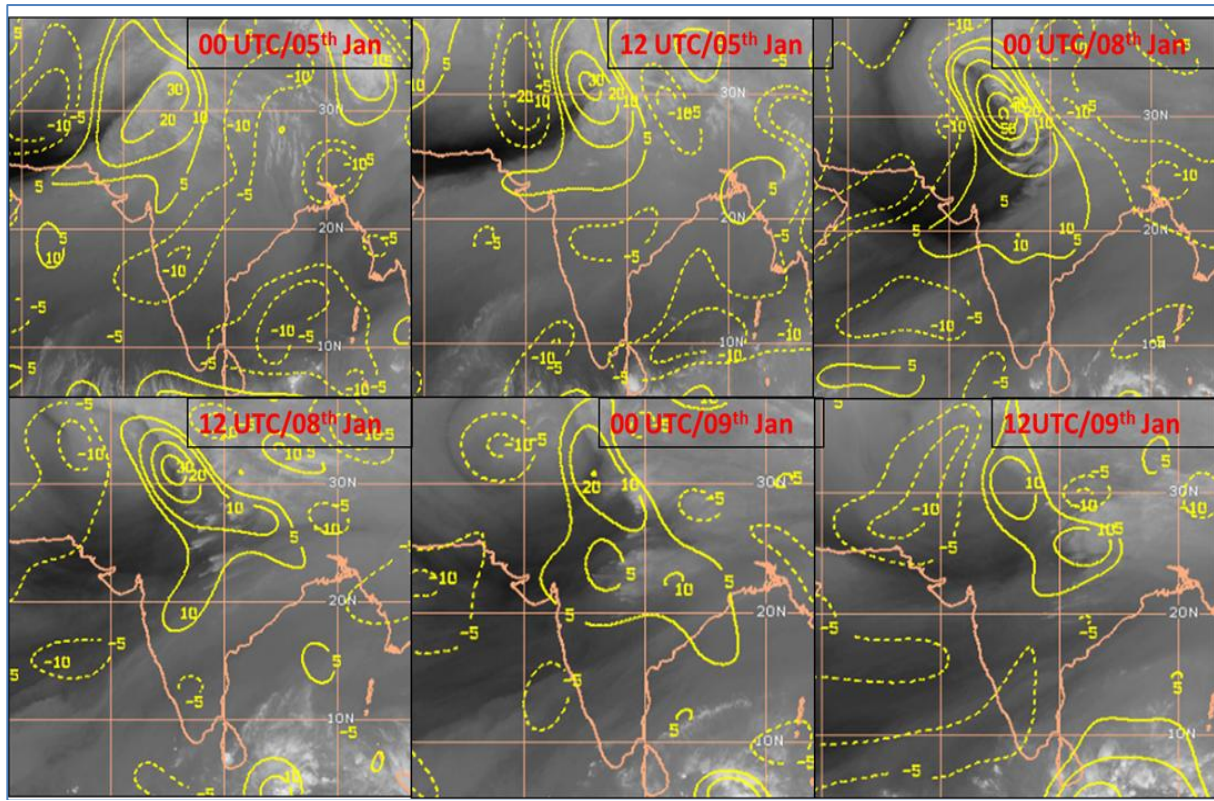


Supplementary Fig. 6. Model Performance for Day 2 (top panel) and Day 1 (bottom panel) on 08<sup>th</sup> January 2022Supplementary Fig. 7. Model Performance for Day 5 on 09<sup>th</sup> January 2022

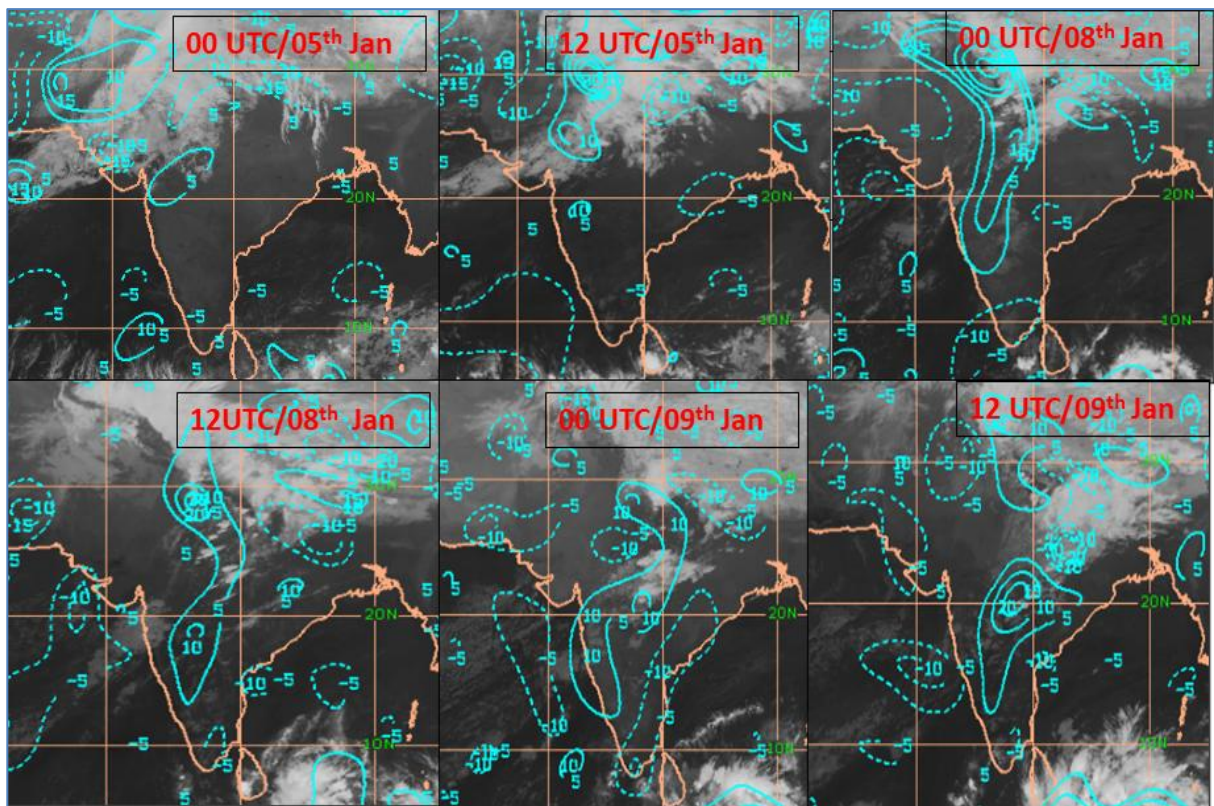


Supplementary Fig. 8. Model Performance for Day 4 (top panel) and Day 3 (bottom panel) on 09<sup>th</sup> January 2022

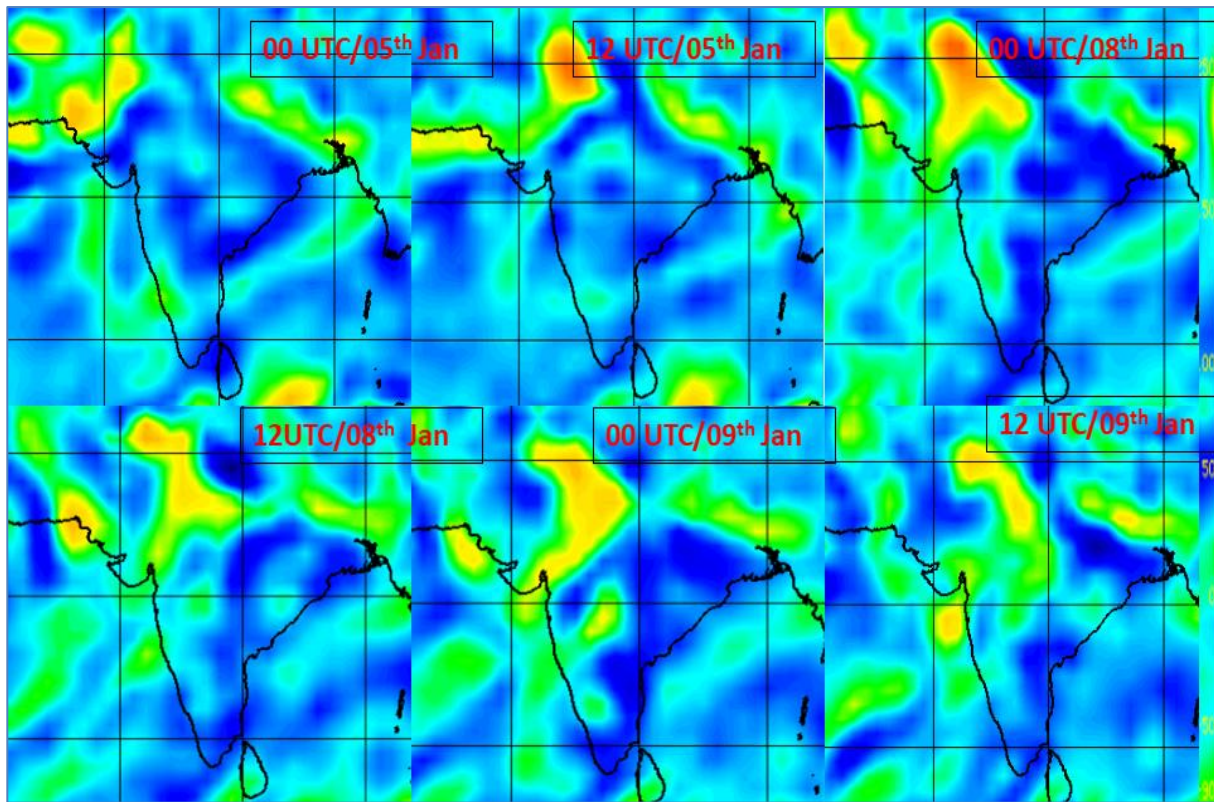
Supplementary Fig. 9. Model Performance for Day 2 (top panel) and Day 1 (bottom panel) on 09<sup>th</sup> January 2022



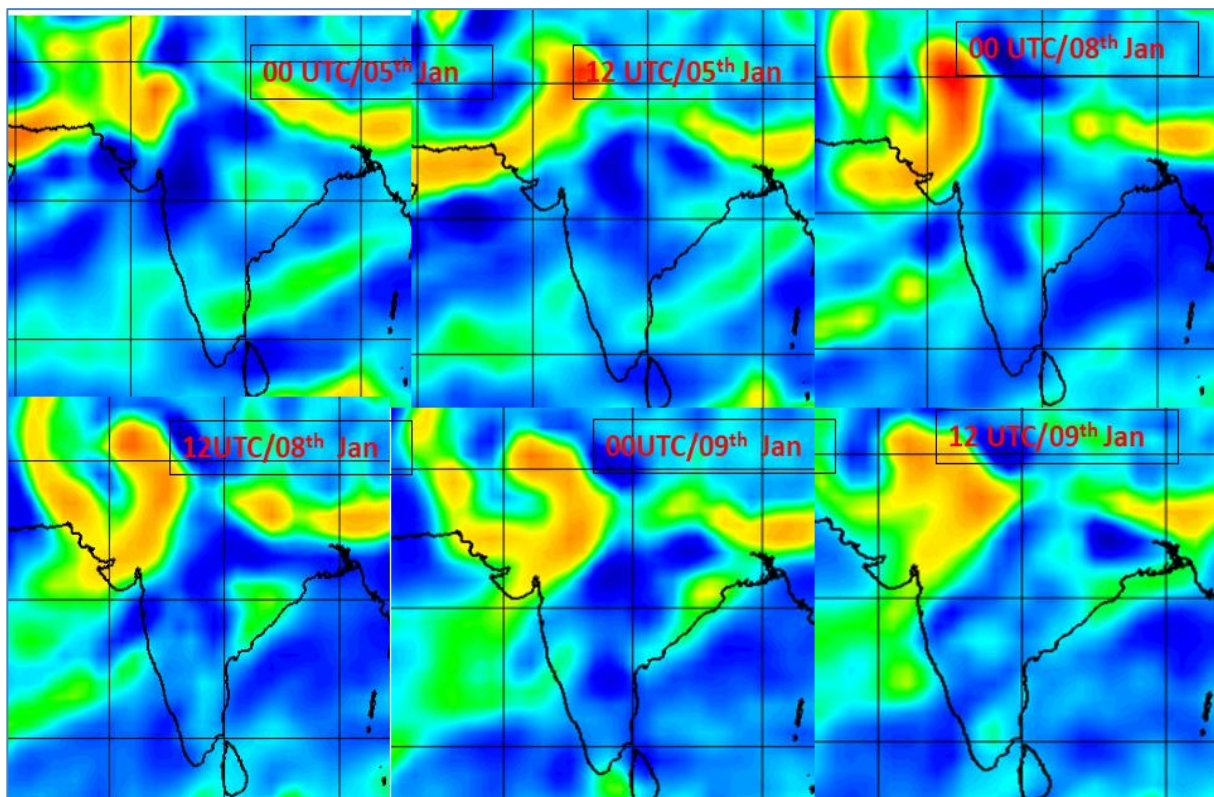
Supplementary Fig. 10. Upper-level Divergence on 5<sup>th</sup>, 8<sup>th</sup> & 9<sup>th</sup> January 2022



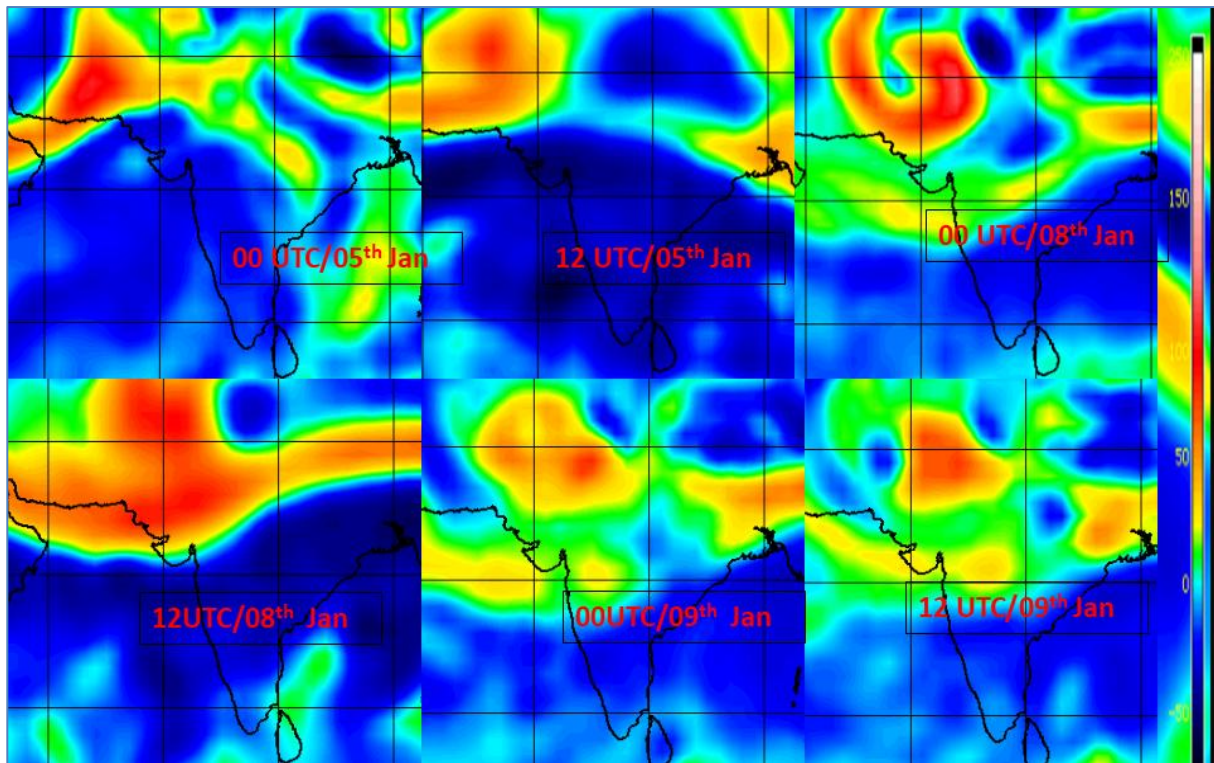
Supplementary Fig. 11. Lower Level Convergence on 5<sup>th</sup>, 8<sup>th</sup> & 9<sup>th</sup> January 2022



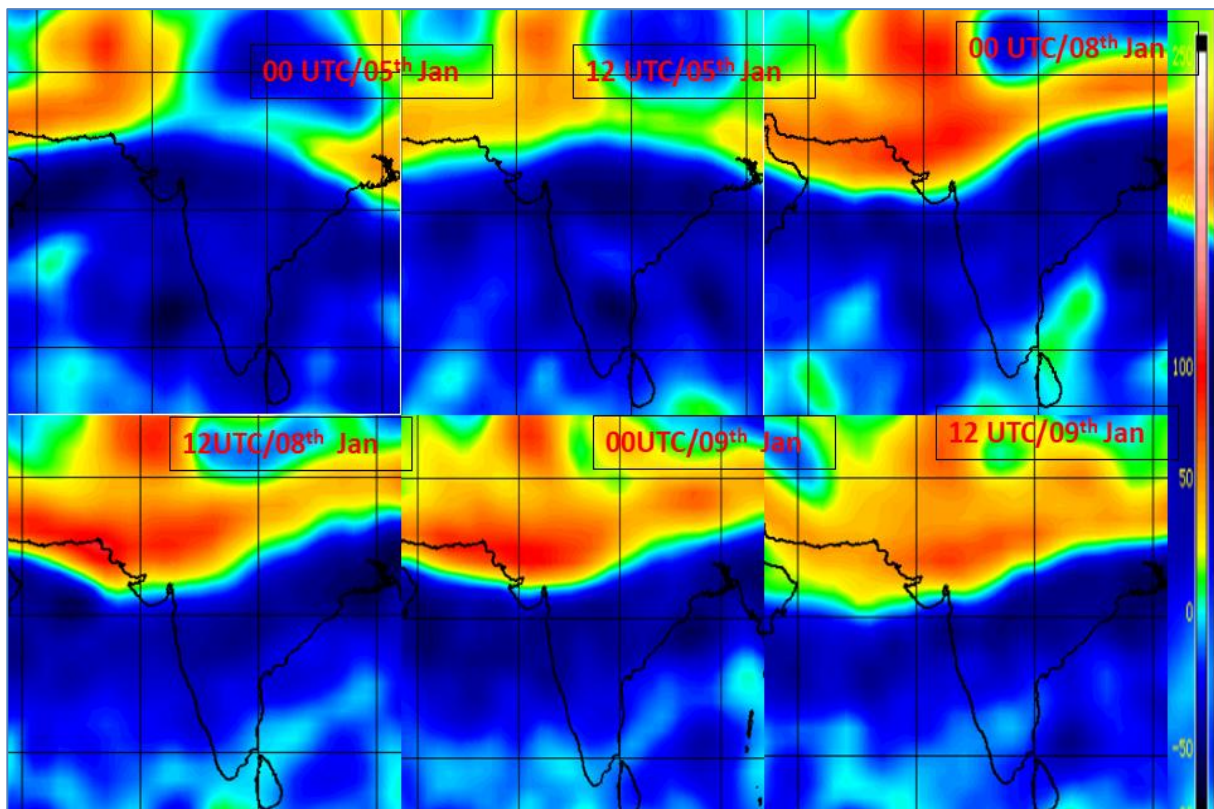
Supplementary Fig. 12. Vorticity at 850 hPa on 5<sup>th</sup>, 8<sup>th</sup> & 9<sup>th</sup> January 2022



Supplementary Fig. 13. Vorticity at 700 hPa on 5<sup>th</sup>, 8<sup>th</sup> & 9<sup>th</sup> January 2022



Supplementary Fig. 14. Vorticity at 500 hPa on 5<sup>th</sup>, 8<sup>th</sup> & 9<sup>th</sup> January 2022



Supplementary Fig. 15. Vorticity at 200 hPa on 5<sup>th</sup>, 8<sup>th</sup> & 9<sup>th</sup> January 2022

