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Heavy rainfall events over Rajasthan and Madhya Pradesh during 1st week of August 2021: a meteorological case study

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सार – दक्षिण-पश्चिम मॉनसून के दौरान देश के विभिन्न हिस्सों में आमतौर पर भारी वर्षा और बाढ़ की घटनाएँ देखी जाती हैं। इसलिए, उनका दस्तावेजीकरण और व्यवस्थित अध्ययन एक महत्वपूर्ण वैज्ञानिक कार्य है। इससे मौसम पूर्वानुमान में सुधार और संबंधित प्राकृतिक आपदाओं के शमन में भी मदद मिल सकती है। संबंधित मौसम संबंधी विशेषताओं की जांच परिचालन पूर्वानुमानकर्ताओं के लिए चिंता का विषय है। इस अध्ययन में, राजस्थान और मध्य प्रदेश के कुछ हिस्सों में अगस्त 2021 के पहले सप्ताह के दौरान हुई लगातार भारी वर्षा की घटनाओं के मामले पर विचार किया गया है। इन क्षेत्रों के कुछ स्टेशनों पर अगस्त 2021 में अब तक की सबसे अधिक 24 घंटे (RR24) संचयी वर्षण हुआ। इस घटना के कारण, बाढ़ आई और मध्य प्रदेश और आसपास के क्षेत्रों के कुछ हिस्सों में कृषि और बागवानी फसलों को भारी नुकसान हुआ। इस अध्ययन में इस भारी वर्षा की घटना से जुड़ी विभिन्न मौसम संबंधी विशेषताओं को समझने का प्रयास किया गया है। इस मौसम गतिविधि में निम्नलिखित मौसम संबंधी विशेषताएं अनुकूल पाई गई हैंसंक्षेप में, इस क्षेत्र पर एक अच्छी तरह से चिह्नित निम्न दबाव क्षेत्र/ निम्न दबाव क्षेत्र था, जिसके साथ संबद्ध चक्रवाती परिसंचरण मध्य/ऊपरी क्षोभमंडल स्तर तक फैला हुआ था। क्षेत्र पर निचले स्तरों पर निरंतर नमी की आपूर्ति की उपलब्धता। क्षेत्र पर ऊपरी क्षोभमंडल स्तर तक सापेक्ष भ्रमिलता जैसे अनुकूल गतिशील मापदंड, निम्न-स्तरीय अभिसरण के उच्च मूल्य और ऊपरी-स्तरीय अपसरण। राजस्थान और मध्य प्रदेश में 1000-2000 जूल/किलोग्राम के क्रम का सीएपीई मुख्य रूप से उत्तरी भागों में रहा, जिससे गहन संवहन के गठन में मदद मिली। सीएपीई के अलावा, राजस्थान और मध्य प्रदेश में 35-40 के क्रम का केआई 40-45 के अलग-अलग पैच के साथ दर्ज किया गया; देश के अधिकांश भागों में -2 से -4 के क्रम का तापमान दर्ज किया गया, कुछ स्थानों पर केवल -4 से -6 के क्रम का तापमान है, कुछ स्थानों पर -8 से -10 के क्रम का तापमान है तथा उत्तर-पश्चिमी मध्य प्रदेश और उससे सटे पूर्वी मध्य प्रदेश में SWEAT सूचकांक 400-500 °C के दायरे में है।

ABSTRACT. During southwest Monsoon, heavy rainfall and flood events are usually observed in different parts of the country. Therefore, their documentation and systematic study is an important scientific work. This can help in the improvement of weather forecasting and also mitigation of associated natural disasters. The investigation of associated meteorological features is a matter of concern for operational forecasters. In this study, a case of persistent heavy rainfall events is considered that occurred during the first week of August 2021 over some parts of Rajasthan and Madhya Pradesh. Some of the stations from these regions received an all-time high 24-hour (RR24) cumulative precipitation in August 2021. Due to this event, flooding occurred and a huge loss of agricultural and horticultural crops occurred in some parts of Madhya Pradesh and adjoining areas. The present study attempts to understand the various meteorological features associated with this heavy rainfall event. Following meteorological features are found to be favourable in this weather activity; (*i*) Synoptically, there was a well-marked low-pressure area/ low-pressure areas over the region with the associated cyclonic circulation extending up to middle/upper tropospheric levels. (*ii*) Availability of continuous moisture supply at lower levels over the region. (*iii*) Favourable dynamical parameters like relative vorticity up to upper tropospheric levels, high values of low-level convergence, and upper-level divergence over the region. (*iv*) CAPE of the order of 1000-2000 J/Kg reported over Rajasthan and Madhya Pradesh mainly over northern parts remained which helped formation of intense convection. (*v*) In addition to CAPE, KI of the order of 35-40 were reported over Rajasthan and Madhya Pradesh with isolated patches of 40-45; LI of the order of -2 to -4 are reported over most parts of the country except for the order of -4 to -6 with isolated patches of the order of -8 to -10 and SWEAT Index in the range of 400-500 °C over northwest Madhya Pradesh & adjoining east Madhya Pradesh.

Key words – Southwest monsoon 2021, Heavy rainfall, Meteorological analysis.

1. Introduction

Because of the geo-climatic conditions of India, different kinds of extreme weather conditions including heavy rainfall, flood, drought, cyclones, landslides, heatwaves, cold waves, *etc*. usually reported every year over different parts of the country in different seasons. Each extreme weather event usually has some unique attributes, either occurrences or their impact. Therefore, their scientific study is an important step in the knowledge enhancement and mitigation of further similar weather events. A brief review of the extreme weather events that occurred in India for the period 1991-2004 studied by De *et al*. (2005). They included extreme weather events, namely floods, droughts, cyclones, hail storms, thunderstorms, heat and cold waves.

The Spatio-temporal distribution of extreme weather events in India was discussed by Singh & Patwardhan (2012)**.** Goswami *et al*. (2006) studied the trends of rain extremes under the impact of a warming environment. They studied extreme events namely, floods, tropical cyclones (TC), heat wave (HW), cold waves (CW), gales, squalls, lightning, dust-storm, (DS) hailstorm, and thunderstorm (TS) to study their recent past Spatio-temporal pattern over India. "Weather-related disasters increase over the past 50 years, causing more damage but fewer deaths" documented by WMO in a Press Release in 2021(https://wmo.int/news/media-centre/weather-related-disasters-increase-over-past-50-years-causing-more-damage-fewer-deaths). Spatial-temporal trends of mean & extreme rainfall and temperature for the 33 cities of Rajasthan, India studied by Santosh *et al*. (2014).

The heavy rainfall events that occurred during the first week of March 2015 have been organized by Kumar *et al* (2017). In their study, they analyzed the case at different tropospheric levels. In a recent study, the meteorological features associated with the heavy rainfall events observed on 14th July 2016 at Yamuna Nagar (Haryana, India) have been documented by a recent study by Narasimha *et al*. (2021). Both studies are related to the study of heavy rainfall events during the pre-monsoon period. Recently, Saini *et al*. (2022) studied the regional variations in respect of onset dates of monsoon for the period of 67 years (1951–2017) under different global circulations *i.e*., El Niño & La Niña, & also the Indian Ocean Dipole (IOD, with the help of objective method & statistical techniques. They also tried to link the monsoonal rainfall over different parts of the country in association with the onset dates over the regions.

If we look at the climatology (1969-2019) of previous flood events (https://imdpune.gov.in/hazardatlas /index.html), Rajasthan and Madhya Pradesh fall in the category of low (11-30) to moderate category (31-50) (refer Fig. 1).

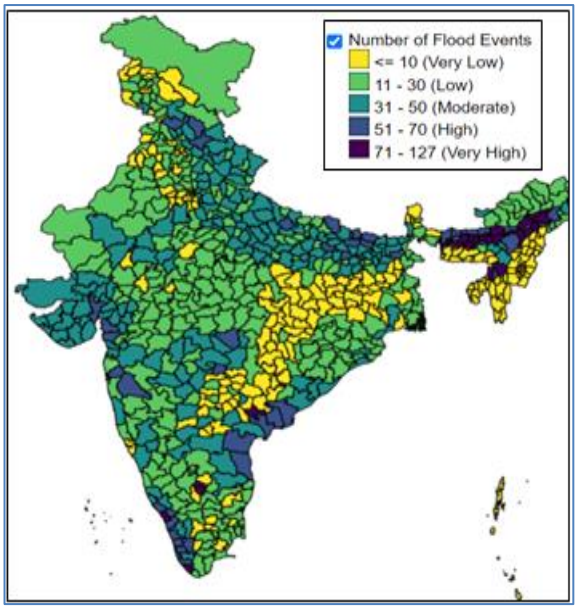

Fig. 1. Total Number of Flood Events during the Period from 1969 to 2019. Source: Climate Hazards and Vulnerability Atlas (IMD Pune) https://imdpune.gov.in/ hazardatlas/index.html.

The rest of the paper is structured as follows. The next section described 'Study areas, data and methodology' followed by the 'result and discussion' in Section 3. The paper ends with 'conclusion' in Section 4.

2. Study areas, data and methodology

2.1. *Study areas*

Unprecedented precipitation along with heavy falls occurred over many parts of Rajasthan and Madhya Pradesh during the first week of August 2021. During the first week of August, ten districts of Madhya Pradesh (Ashoknagar, Bhind, Datia, Gwalior, Guna, Morena, Rewa, Sheopur, Shivpuri, Singrauli) reported impacts due to flood and heavy rainfall (for details refer to IMD Climate Summary August 2021; https://imdpune.gov.in/ mcs.php). Accordingly, the Indian states of Rajasthan and Madhya Pradesh are study areas in this work.

2.2. *Data and methodology*

If we look at the rainfall amounts realized during the period, Shivpuri from west Madhya Pradesh reported record breaking 24 hours of accumulated rainfall on 3rd August 2021 (Table 1). Flood situations prevailed over these districts of Madhya Pradesh during the period. Accordingly, the climate of these districts is also placed in Table 2. Fig. 2 reflects the number of stations with the

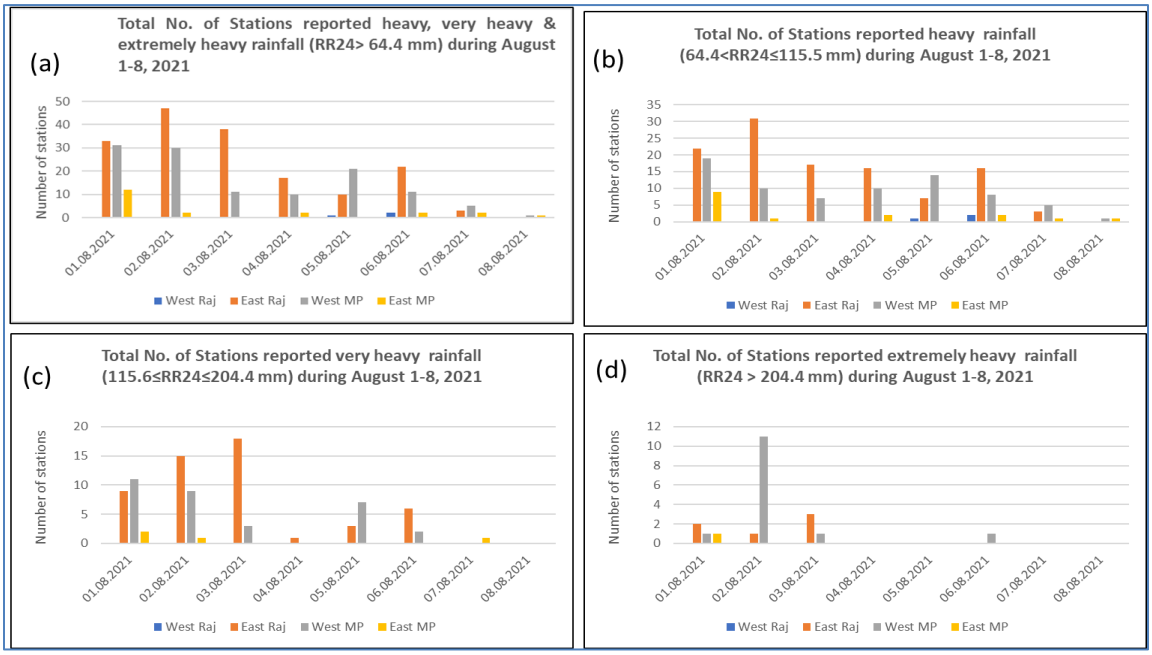

Fig. 2. No. of stations during August 1-8, 2021 (a) reported (RR24>64.4) (b) reported (64.4<RR24≤115.5 mm) (c) (115.6≤RR24≤204.4 mm) (d) (RR24 > 204.4 mm) (Source: IMD)

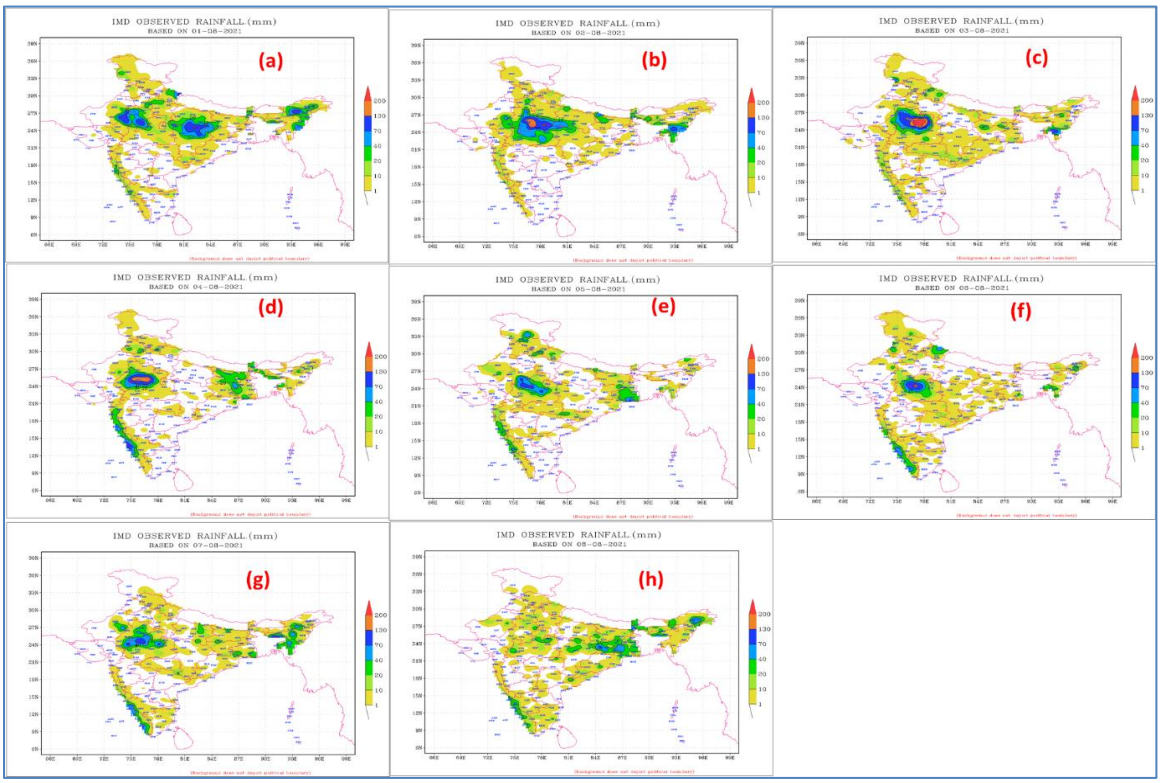

Fig. 3. IMD observed rainfall (a) 01.08.2021 (b) 02.08.2021 (c) 03.08.2021 (d) 04.08.2021(e) 05.08.2021 (f) 06.08.2021 (g) 07.08.2021 (h) 08.08.2021

TABLE 1

24-hour record rainfall and its previous record over Madhya Pradesh

Station	RR24	Previous Record
Shivpuri	470 mm (03-08-2021)	155mm (25-08-1991)

Source: *Climate Summary for August 2021 (IMD Pune; https://imdpune.gov.in/mcs.php)*

TABLE 2

Total Number of Flood Events during the Period from 1969 to 2019

District	Flood events (1969-2019)
Ashoknagar,	12
Bhind,	15
Datia,	13
Gwalior,	16
Guna,	17
Morena,	16
Rewa,	7
Sheopur,	10
Shivpuri,	12
Singrauli	10

Source: *Climate Hazards and Vulnerability Atlas (IMD Pune) https://imdpune.gov.in/hazardatlas/index.html*

different heavy rainfall categories. This is based on the observatory data collected from IMD. This shows that very heavy to extremely heavy rainfall is reported mainly during the period of 1-3 August. The reason behind considering this case study is its disastrous impact on the region.

Fig. 3 represents the IMD observed rainfall received from the NWP division of IMD. Fig. 3(a) shows that the rainfall received (of the order of 7-13 cm) in two zones; one over west Madhya Pradesh & adjoining east Rajasthan and another over northeast Madhya Pradesh & adjoining areas of north Chhattisgarh, southeast Uttar Pradesh, and Jharkhand. Fig. 3(b) shows an increase in the rainfall intensity on 2nd August and it mainly occurred in most places in Madhya Pradesh (rainfall up to the order of 13-20 cm). Fig. 3(c) shows a further increase in the rainfall intensity and is mainly concentrated over west Madhya Pradesh & adjoining areas of east Rajasthan (rainfall up to the order of ≥ 20 cm). Fig. 3 (d) shows little reduction in the rainfall intensity on 4thAugust, but the zone of rainfall was still the same (rainfall up to the order of 13-20 cm). Fig. 3 (e-g) shows a further reduction in the rainfall intensity during 5th-7th August but the zone of rainfall was still the same (rainfall up to the order of 7-13 cm, isolated patches of 13-20 cm on 6th August). Fig. 3 (h) shows a significant reduction in rainfall intensity (< 7 cm).

Overall, Fig. 3 shows the peak rainfall activity observed during 2-4th August with a reduction from the 5th and least on the 8th and the highest on the 3rd of August 2021. The main region was the western parts of Madhya Pradesh & adjoining east Rajasthan. If we look at the precipitation estimates of the Satellite (HE product), it is found that peak activity was observed on the 1st, 2nd & 5th of August and significant rainfall on the 8th of August. The zone of rainfall was also the same as west Madhya Pradesh & adjoining east Rajasthan (refer to Fig. 4).

If we compare the actual rainfall values with the above two rainfall information, we see that record-breaking location-specific rainfall occurred on 3rd August over Shivpuri in northwest Madhya Pradesh, the same is consistent with the peak activity seen in Fig. 3(c). Also, a decreasing trend in the heavy rainfall events is from 7th August with less heavy rainfall events on 4th August also along with those on 7th & 8th August 2021. The same information is consistent with the precipitation estimates from the Satellites also.

The two Figs. 5 & 6 which are self-explanatory depicting data sources, materials and methods used in this case study.

2.3. *Availability/sources of the images/data*

Most of the analysis written in this paper is based on images/data but they are not placed in the text. However, the images with respect to NWP are available from NWP Division of IMD and satellite imageries from Satellite Division of IMD data/images with respect to dynamical parameters (relative vorticity, convergence and divergence *etc*.) are freely available at https://tropic.ssec.wisc.edu/ & reanalysis data for omega and upper levels temperature, humidity at http://psl.noaa.gov/**.**

3. Results and discussion

In this section, meteorological analysis is done. As mentioned in Fig. 5, the analysis is done at different tropospheric levels.

3.1. *Wind Analysis*

The analysis from IMD-GFS winds (based on 00 UTC during 31st July to 8th August) & scrutiny of analyzed upper air wind charts it is found that the associated cyclonic circulations with the low pressure area and well marked low pressure areas had created a favourable mechanism for heavy rainfall over the region. Moisture incursion from Arabian Sea into the regions of northwest and adjoining central India including the states of Rajasthan and Madhya Pradesh continued till 4th August and the moisture feed started weakening from 5th August.

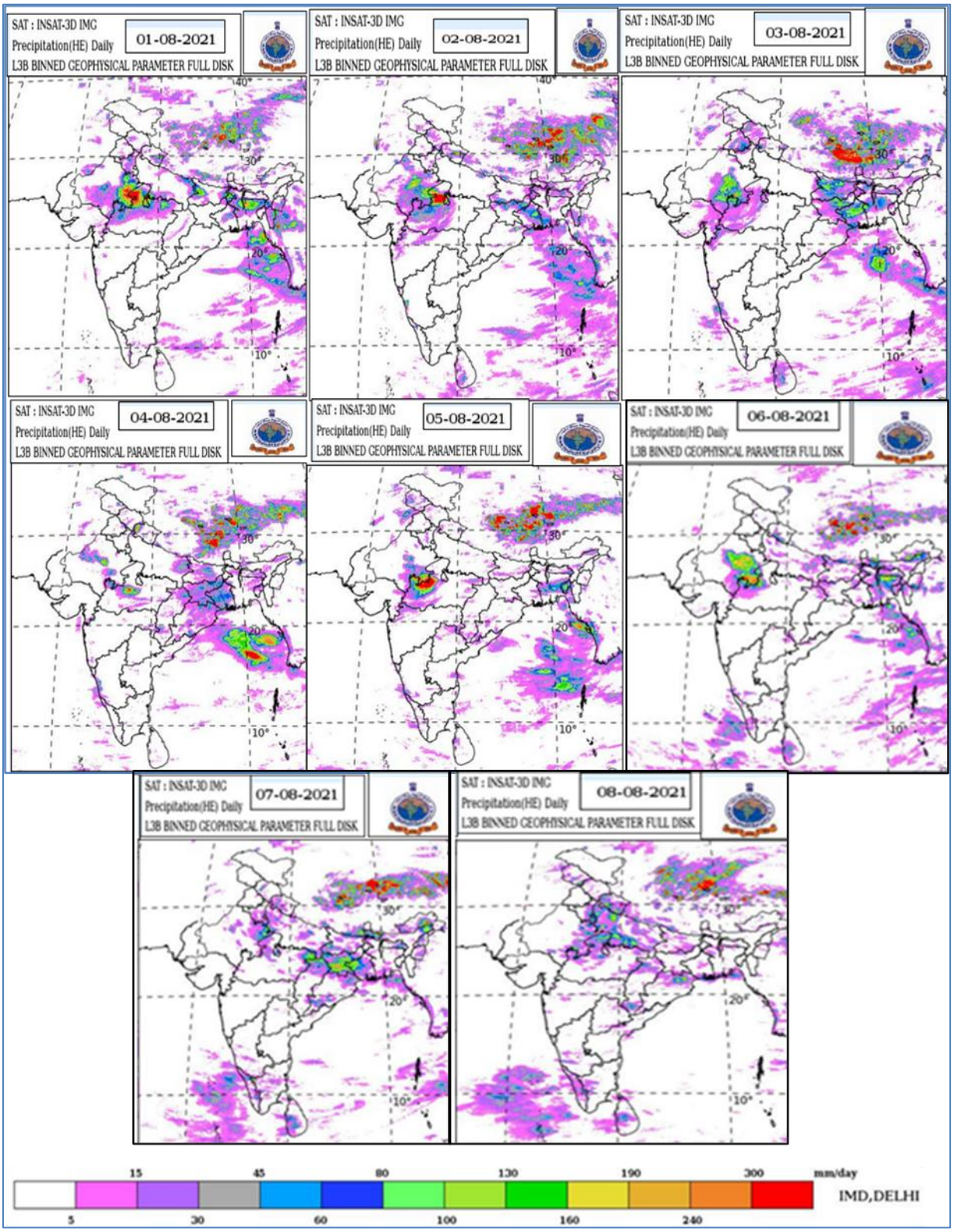

Fig. 4. Satellite (INSA-3D) Precipitation daily from 01-08 August 2021 (Source: IMD)

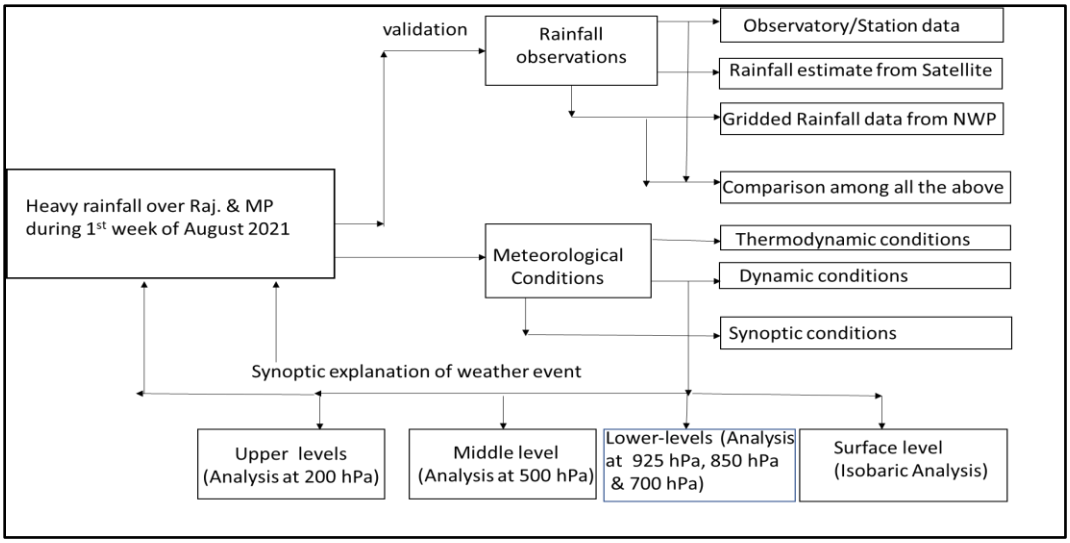

Fig. 5: Schematic Diagram showing materials and methods.

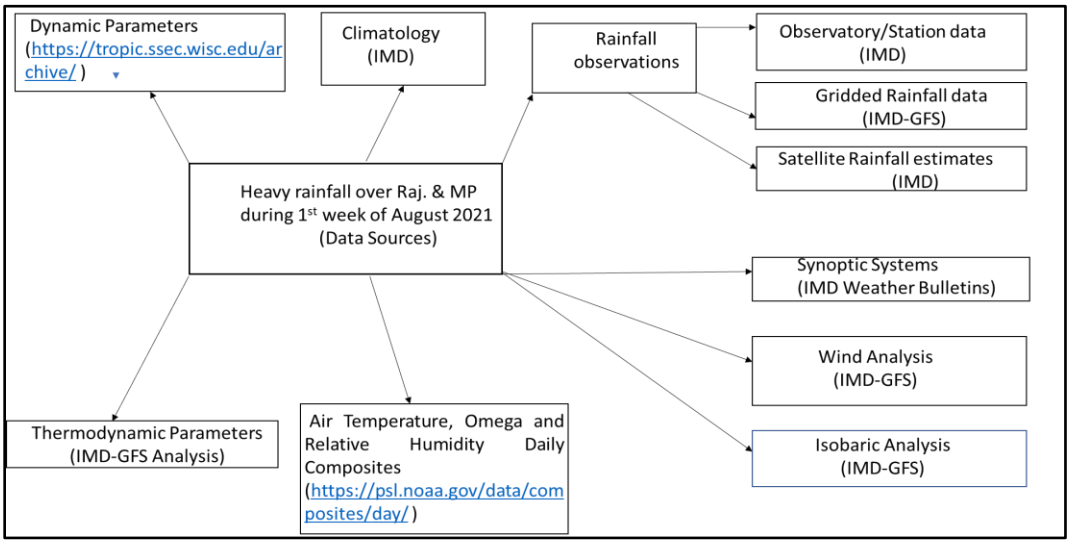

Fig. 6: Schematic Diagram showing data sources

Overall, it is concluded from the above discussion that the CC & winds were favourable during the period, and the moisture feed was also there from Arabian Sea till 05th August. Accordingly, with the reduction in wind speed and moisture feed lead to reduction in rainfall activity from 5th August onwards over the region.

3.2. *Vorticity Profile*

At lower levels, the vorticity profile remained most favourable (100-120 units) during the period of 31st July to 5th August and less favourable during the period of 6th to 8th August 2021.

As regards, the middle level, the vorticity profile remained most favourable during the period of 31st July to 4th August & less favourable during the period on 5th to 8th August 2021. At 200 hPa, the vorticity profile remained favourable during the period of 31st July to 3rd August and less favourable during the period of 4th to 8th August.

3.3. *Upper-level divergence (ULD)*

This section is concerned with the analysis of ULD (refer to Fig. 7). ULD were seen of the order of 5-10 units occasionally 10-20 units mainly over west Madhya Pradesh & adjoining east Rajasthan during 31st July-6th August

with reduction on 7th & 8th August. Over all the ULD was remained favourable for the heavy spells over the region.

3.4. *Analysis of Air Temperature*

Motivated by the study of Kumar *et al*. (2017), the upper air temperature analysis is included in this study. High temperatures at 200 hPa are favourable for generation of high jet stream. At lower tropospheric levels, it can explain mixing of warm and cold core areas.

Daily composites are used by NOAA physical science laboratory available at https://psl.noaa.gov/data/reanalysis/reanalysis.shtml. At 500 hPa, from 31st July to 07th August, temperatures of the order of 270K-273K reported over north & central India, including Madhya Pradesh and Rajasthan. A change in the profile was reported on 8thAugust and temperatures of the order of 269K-270K reported over the region. At 850 hPa**,** on 31st July, two warm core highs were reported; one over Iran (peak temperature 304-305K over south Iran) and another over the north of Nepal. The warm core high over Iran extended from Rajasthan (temperature 297K) and over Nepal extended from central India (Madhya Pradesh, temperature 292-295K). Accordingly, the zone of rainfall in this study fell between two warm core highs. On 1st August, two warm core highs; one over south Iran & adjoining areas of Afghanistan-Pakistan and another over the north of Nepal (Lat. 33° N/ Long. 88° E) with temperatures of 299-302K over Rajasthan and 293-297K over Madhya Pradesh. Another warm - core high started developing over the western Himalayan region. On 2nd August, three warm core highs were visible; one over south Pakistan; the second over the north of Nepal (Lat. 33° N/ Long. 88° E) and the third highest over the western Himalayan region with a 299-300K over Pakistan & adjoining west Rajasthan and 293-297K over Madhya Pradesh & the remaining parts of Rajasthan. A similar situation persisted over the region on 3rd August. On 4th August, a similar temperature profile persisted with temperatures of 299-301K over Pakistan & adjoining west Rajasthan and 292-295K over Madhya Pradesh & the remaining parts of Rajasthan. A similar temperature profile persisted with a little oscillation during 5th - 8th August 2021.

3.5. *Lower-Level Convergence (LLC)*

For analysis of LLC (refer Fig. 8). The mathematical framework related to convergence may be seen in the published literature. It is found that LLC of the order of 15-20 units occasionally 30 units were seen (in a closed circular form) over Madhya Pradesh & adjoining Rajasthan region during 31st July-4th August. From 5th August, LLC started reducing and seen of the order of 5-10 units over the region. Overall, the convergence conveyed an indication of the reduction in rainfall activity over Rajasthan & Madhya Pradesh, compared to other days since 31stJuly 2021. Therefore, the convergence was more favourable during 31st July- 4th August as compared to the period of 5th - 8th August.

3.6. *Analysis at Surface Levels*

First, we will discuss the isobaric analysis of IMD GFS. At 00 UTC on 31st July, a well-marked low-pressure area was seen over south Bihar & adjoining areas of Jharkhand-north Chhattisgarh-southeast Uttar Pradesh-northeast Madhya Pradesh. At 00 UTC on 1st August, the well-marked low-pressure area was seen over south Uttar Pradesh & neighbourhood. At 00 UTC on 2nd August, WML saw over northwest Madhya Pradesh and adjoining areas of southwest Uttar Pradesh and northeast Rajasthan. At 00 UTC on 3rd August, WML persisted over the same region. At 00 UTC on 4th August, WML weakened into a low-pressure area over the same region. At 00 UTC on 5th August, a low-pressure area was seen over southwest Uttar Pradesh & neighbourhood. At 00 UTC during 6th-8th August, a low-pressure area persisted over the same region in a week category.

Using IMD's All India weather Bulletins, Track of Well Marked low pressure area is prepared (Fig. 9). Another low pressure Area lay over southern parts of central Uttar Pradesh and neighbourhood with the associated cyclonic circulation extending upto 7.6 km above mean sea level on 30th July 2021, both the Low pressure area and the associated cyclonic circulation have merged with the Well Marked Low pressure Area and its associated cyclonic circulation over southwest Uttar Pradesh & adjoining northwest Madhya Pradesh on 2nd August 2021. The movement of low pressure area over the region was favourable for the heavy rainfall spell.

3.7. *Analysis of Thermodynamic Parameters*

3.7.1. *CAPE Analysis*

It is inferred that a CAPE of the order of 1000-2000 J/Kg was reported over the parts of north Rajasthan and north Madhya Pradesh during the period.

3.7.2. *K-Index (KI) Analysis*

It is inferred that the KI of the order of 35-40 was reported over Rajasthan and Madhya Pradesh with isolated patches of 40-45 over the same regions during the period of study.

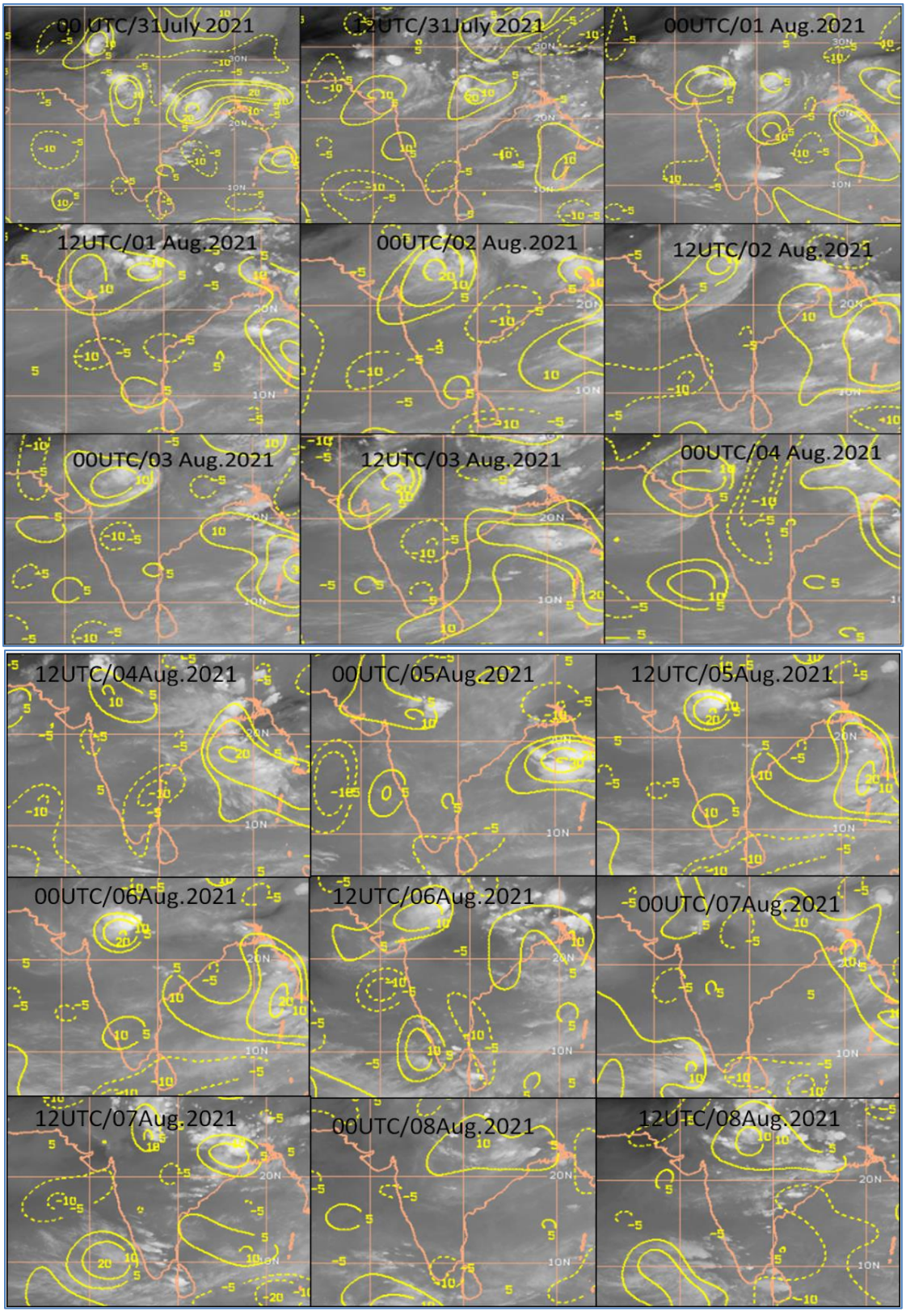

Fig. 7. Upper level divergence during 31st July-08th August 2021. (Source: CIMSS)

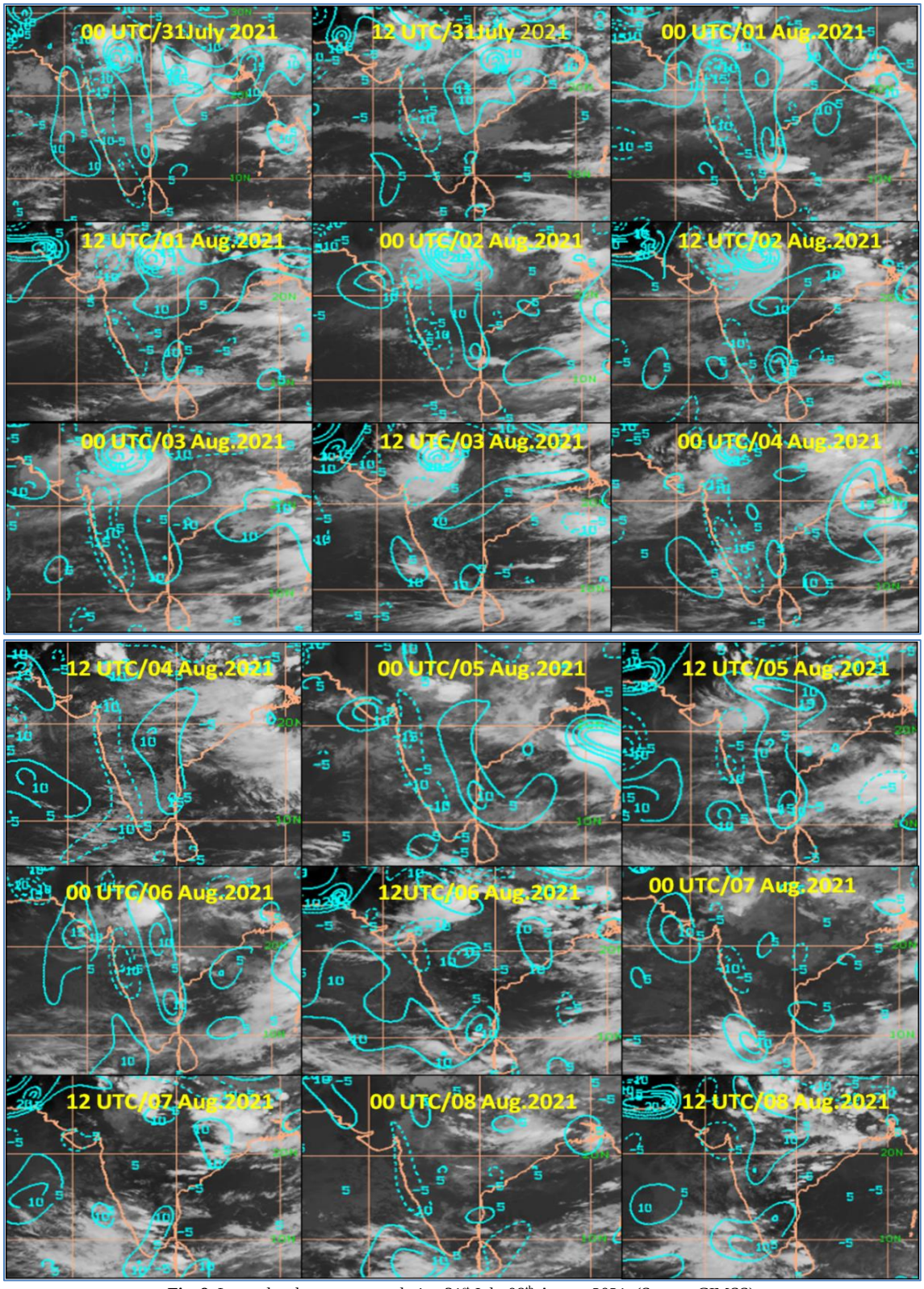

Fig. 8. Lower level convergence during 31st July-08th August 2021. (Source: CIMSS)

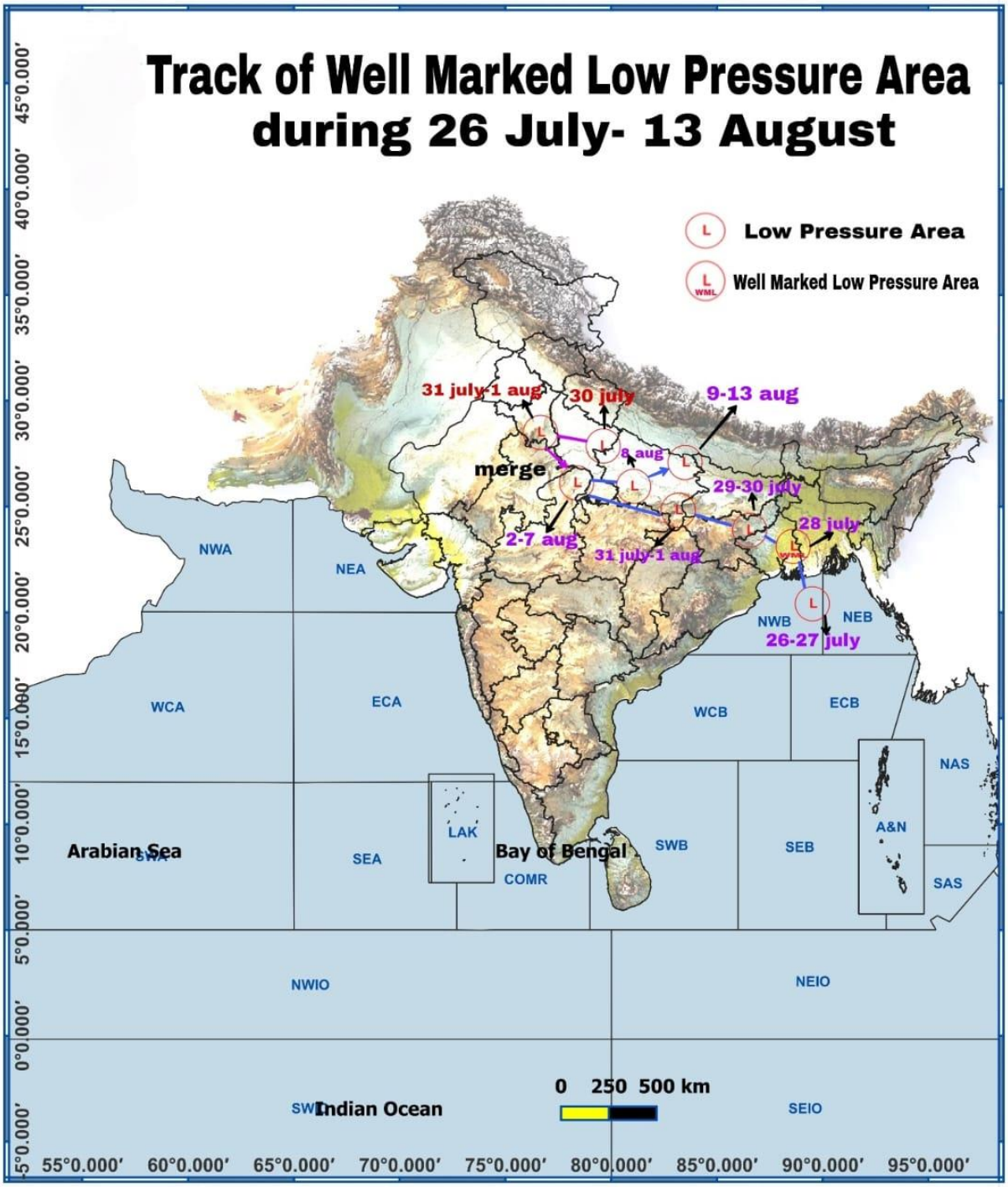

Fig. 9. Track of Well Marked Low Pressure Area with details (Source: IMD)

3.7.3. *Lifted Index (LI)*

It is inferred that the LI of -2 to -4 is reported over most parts of the country except of -4 to -6 with isolated patches of the order of -8 to -10 seen over parts of Rajasthan and Madhya Pradesh during the period of study.

3.7.4. *SWEAT Index*

It is inferred that the SWEAT Index of 300-400 °C seen over most parts of the country except in isolated packets of 400-500 °C over parts of west Rajasthan during the period of study and on 2nd & 3rd August over northwest Madhya Pradesh & adjoining east Madhya Pradesh.

4. Conclusions

During the Monsoon, heavy rainfall and flood events are usually observed in different parts of the country. Their distribution and intensity change from year to year and season to season. In fact, each extreme weather event is unique and has the potential for a different understanding and approach for a scientific temperament. Therefore, the documentation and systematic study of each extreme weather event is an important scientific work. This will help in the improvement of weather forecasting and, at the same time, it is also helpful for the mitigation of associated disasters also. The associated meteorological features play an important role. In summary, we can say that extreme weather events are left with some lesson-learning. An attempt is made in this paper for such an extreme weather event.

In this case study, a case of persistent heavy rainfall events is considered that occurred during the first week of rainfall in August 2021 over Rajasthan and Madhya Pradesh. Unprecedented precipitation along with heavy falls occurred over many parts of Rajasthan and Madhya Pradesh during the first week of August 2021. Some of the stations from these regions received an all-time high 24 hr (RR24) cumulative precipitation of August 2021 during this period.

Due to this event, flooding occurred and a huge loss of agricultural and horticultural crops occurred in some parts of Madhya Pradesh and adjoining areas. In the present study, an attempt is made to understand the various meteorological features associated with this heavy rainfall event over Rajasthan and Madhya Pradesh. Accordingly, the following meteorological features are found:

(*i*) The well-marked low-pressure area / low-pressure areas over the region with the associated cyclonic circulation extending up to middle/upper tropospheric levels during the period. Initially, two low pressure areas seen and merged later as are in the detailed surface analysis. Continuous moisture availability has also led to persistent weather activity over the region.

(*ii*) Favourable dynamical parameters like relative vorticity profile up to upper tropospheric levels, the vorticity profile at middle tropospheric levels remained most favourable during the period from 31st July to 4th August and less favourable during the period from 5th to 8th August 2021.The vorticity profile at upper tropospheric levels, remained favourable during the period from 31st July to 3rd August and less favourable during the period from 4th to 8th August. The vorticity profile at 700 hPa remained most favourable during the period of 31st July to 4th August and less favourable during the period of 5th to 8th August 2021; at 850 hPa, the vorticity profile remained most favourable during the period of 31st July to 5th August and less favourable during the period of 6th to 8th August 2021.

(*iii*) Favourable low-level convergence and upper-level divergence profiles also remained favourable for the activity over the region.

(*iv*) CAPE of the order of 1000-2000 J/Kg reported over the parts,of Rajasthan and Madhya Pradesh, mainly over the northern parts remained favourable and helped in the instability over the region and therefore, it helped in the formation of intense convection during the period of study.

(*v*) Other than CAPE, the thermodynamic parameters like KI of the order of 35-40 were reported over Rajasthan and Madhya Pradesh with isolated patches of 40-45 over the same regions.

(*vi*) LI of the order of -2 to -4 are reported over most parts of the country except for the order of -4 to -6 with isolated patches of the order of -8 to -10 seen over parts of Rajasthan and Madhya Pradesh.

(vii) SWEAT Index has been seen in the range of 300-400 °C over most parts of the country except in isolated packets of the order of 400-500 °C seen over parts of west Rajasthan during the period of study and on 2nd & 3rd August over northwest Madhya Pradesh & adjoining east Madhya Pradesh.

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Authors' contributions

Shashi Kant: Conceptualization, Formal analysis, Methodology, Writing – original draft.
Rizwan Ahmed: Visualization, Writing -review & editing.

Sunil Kumar: Investigation, Visualization.

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