



Real-time Extremely Heavy Rainfall Forecast and Warning over Rajasthan During the Monsoon Season (2016)

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Abstract—Two events of extremely heavy rainfall occurred over Rajasthan during 7–9 August 2016 and 19–21 August 2016. Due to these events, flooding occurred over east Rajasthan and affected the normal life of people. A low-pressure area lying over northwest Madhya Pradesh on 7 August 2016 moved north-westward and lay near east Rajasthan and adjoining northwest Madhya Pradesh on 8 and 9 August 2016. Under the influence of this low-pressure system, Chittorgarh district and adjoining areas of Rajasthan received extremely heavy rainfall of 23 cm till 0300 UTC of 8 August 2016 and 34 cm on 0300 UTC of 9 August 2016. A deep depression lying over extreme south Uttar Pradesh and adjoining northeast Madhya Pradesh on 19 August 2016 moved westward and gradually weakened into a depression on 20 August 2016. It further weakened into a low-pressure area and lay over east Rajasthan on 21 and 22 August 2016. Under the influence of this deep depression, Jhalawar received 31 cm and Baran received 25 cm on 19 August. On 20 August 2016, extremely heavy rainfall (EHR) occurred over Banswara (23.5 cm), Pratapgarh (23.2 cm) and Chittorgarh (22.7 cm) districts. In this paper, the performance of the National Centers for Environmental Prediction (NCEP) global forecast system (GFS) model for real-time forecast and warning of heavy to very heavy/EHR that occurred over Rajasthan during 7–9 August 2016 and 19–21 August 2016 has been examined. The NCEP GFS forecast rainfall (Day 1, Day 2 and Day 3) was compared with the corresponding observed gridded rainfall. Based on the predictions given by the NCEP GFS model for heavy rainfall and with their application in real-time rainfall forecast and warnings issued by the Regional Weather Forecasting Center in New Delhi, it is concluded that the model has predicted the wind pattern and EHR event associated with the low-pressure system very accurately on day 1 and day 2 forecasts and with small errors in intensity and space for day 3.

Key words: Low pressure system, extremely heavy rainfall (EHR), GFS model, monsoon trough.

1. Introduction

Extremely heavy rainfall (EHR) is a natural hazard which mainly leads to flooding, risk to human life, loss of crops and damage to infrastructure and buildings. Disruption to communication and transport system happens due to landslides that occur due to heavy rainfall and EHR. Heavy rainfall (HR) over India occurs mainly in association with the weather systems such as cyclones, depressions/low-pressure systems formed during monsoon seasons and their interaction with the trough in the westerlies, easterly waves, western disturbance, cloud burst and severe thunderstorms.

There have been several cases of HR events over India in the past couple of years. Some of the important HR events are rainfall observed during 15th to 16th June 2013 in Mumbai, Maharashtra (approximately, 300% more than the average), heavy rainfall during 13–19 June 2013 in Kedarnath and adjoining areas in Uttarakhand (approximately, 800% more than the average) reported by the Climate Diagnostics Bulletin of India, June 2013 issue by Srivastava and Guhathakurta (2013). Ray et al. (2014) analyzed the catastrophic rainstorm that occurred during 4–6 September 2014 over Jammu and Kashmir (J&K), due to which 24 h accumulated rainfall exceeded the previously determined 1-day severe rainstorm limits of 20 cm for a number of stations on 5 and 6 September 2014. Rajeevan et al. (2008) examined variability and long-term trends of extreme rainfall events over central India, using 104 years (1901–2004) of high-resolution daily gridded rainfall data and found that the increasing trend of extreme rainfall events in the last five decades could be associated with the increasing trend of

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sea surface temperatures (SSTs) and surface latent heat flux over the tropical Indian Ocean. Trends in summer monsoon rainfall over South as well as East Asia could also be related to SSTs over the Indian Ocean and west Pacific Ocean (Preethi et al. 2017). Joseph et al. (2015) noticed that both CFS126 and CFS382 could predict the extreme event 10–12 day in advance, with CFS382 performing better in predicting the magnitude of rainfall. Even the formation and northwestward movement of the low-pressure system over the Bay of Bengal are better predicted by CFS382. Naresh et al. (2015) carried out the study on the verification of operational HR forecast over India during the monsoon season (June to September) using the data of the recent 12 years (2002–2013) and found that there was a significant improvement in skill scores as observed for 24 h HR events forecast over India. Batla et al. (2010) concluded in their study that all the heavy rainfall-related disastrous weather events formed over different states in India were not entirely due to systems developed over oceans, rather local atmospheric phenomenon was an important contributor of similar effects, particularly for northern and western India.

To reduce the damage to life and property due to these heavy rain fall events, there is a need to issue reliable and timely warning of such events. Therefore, value-added forecasts and warnings are issued by various forecasting centers by utilization of model forecast and experience of weather forecasters. Several numerical weather prediction (NWP) models, which include many complex physical processes and advanced data assimilation schemes, have been developed around the globe, e.g., NCEP Global Forecast System (GFS) at the National Centers for Environmental Prediction (NCEP), Unified Model (UM) at the UK Met Office, the Global Environmental Multiscale Model (GEM) at the Environment Canada and Integrated Forecast System (IFS) at the European Centre for Medium Range Weather Forecasting (ECMWF) (Kalnay et al. 1990; Kanamitsu et al. 1991; Brown et al. 2012; IFS 2012; Côté et al. 1998). Most of these models provide weather forecasts for medium range. McBride and Ebert (2000) noted that global models are more successful at predicting the presence of precipitation than estimating its magnitude and/or location. Dravitzki and McGregor (2011)

investigated the predictability of heavy precipitation occurring over the Waikato River basin of New Zealand and concluded that the general synoptic structures of heavy precipitation events were often identified at long lead times and heavy rainfall was identified by GFS at accurate location and timing at 48 h lead time. Stensrud (2013) and Gao et al. (2013) implemented a real-time, weather-adaptive three-dimensional variational data assimilation (3DVAR) system for the National Oceanic Atmospheric Administration (NOAA) Warn-on-Forecast (WoF) project to incorporate all available radar observations from multiple Weather Surveillance Radars-1988 Doppler (WSR-88Ds) with NCEP forecast products as a background state within a moveable analysis domain. Forecasters found its utility in an early warning decision; it also proved the ability of short-range ensemble forecasts of hazardous convective weather events in providing guidance that could be used to extend warning lead times for tornadoes, hailstorms, damaging windstorms, and flash floods. Srivastava and Bhardwaj (2014) demonstrated the capability of the NWP model Advanced Regional Prediction System (ARPS) with assimilation of Doppler weather radar data in predicting extreme weather events like cyclone, cloudburst and thunderstorm in real time over the Indian region. Srivastava and Bhardwaj (2011) concluded that with the assimilation of both radial wind and reflectivity observations simultaneously, the model could reproduce the rainfall pattern in a more realistic way and improve the short-range mesoscale forecasts.

Two events of extremely heavy rainfall (EHR) that occurred over Rajasthan during 7–9 August 2016 and 19–21 August 2016 are studied here. Due to the EHR, flooding occurred over Chittorgarh and Bhilwara districts of Rajasthan. This affected the normal life of people. Rainwater entered the homes and most people were evacuated; seven died and huge loss of property also occurred. Synoptic analysis showed that the southwest monsoon was active over east Rajasthan on 7 August 2016, vigorous over east Rajasthan on 8 August 2016 and active over Rajasthan on 9 August 2016. A low-pressure area laid over northwest Madhya Pradesh on 7 August 2016, which moved north westward and was over east Rajasthan and adjoining northwest Madhya Pradesh on 8 August 2016, with associated upper air cyclonic circulation

extending up to 7.6 km above mean sea level. The system persisted at the same area till 9 August 2016. During this period, the axis of the monsoon trough also passed through Bikaner (Rajasthan). This enhanced the sharp rainy spells over east Rajasthan. Chittorgarh district and adjoining areas had recorded extremely heavy rainfall of 23 cm on 08:30 IST of 8 August 2016 and 34 cm on 08:30 IST of 9 August 2016.

During 19–21 August 2016, there was a deep depression over south Uttar Pradesh and adjoining northeast Madhya Pradesh on 19 August 2016, which moved westward and gradually weakened into a depression on 20 August 2016. The system kept on moving westward and further weakened into a low-pressure area and laid over east Rajasthan and adjoining area on 21 and 22 August 2016 along with the associated upper air cyclonic circulation extending up to 7.6 km above mean sea level. Under the influence of this deep depression, Jhalawar received 31 cm and Baran received 25 cm on 19 August, while Banswara, Pratapgrah and Chittorgarh received extremely heavy rainfall of 23.5, 23.2 and 22.7, respectively, on 20 August 2016.

The Regional Meteorological Center (RMC), Delhi, issued a weather forecast and warning for the entire northwest India including east Rajasthan and west Rajasthan subdivisions. The forecast generated by NCEP GFS model is considered significantly for issuing the weather forecast and warning for the region of RMC, Delhi.

The main objective of this study is to examine the performance and demonstrate the utilization of NCEP GFS model for real-time forecast and warning of heavy/heavy to very heavy rainfall. In this paper, extremely heavy/heavy to very heavy rainfall events that occurred over Rajasthan during 7–9 August 2016 and 19–21 August 2016 have been examined. The NCEP GFS forecast rainfall (day 1, day 2 and day 3) are also compared with the corresponding observed gridded rainfall.

In Sect. 2, the study domain and terrain height are described. Data and methodology are explained in Sect. 3. Two events of EHR that occurred over

Rajasthan are discussed in Sect. 4. The results of the experiments are summarized in Sect. 5.

2. Study Domain

In this study extremely heavy rainfall events occurred over east Rajasthan subdivision are considered. Hence, we have considered northwest India as the study domain as shown in the left panel of Fig. 1. Figure 1 also depicts the terrain heights (m), in which north–south oriented Arawali Hills divides Rajasthan into east Rajasthan and west Rajasthan subdivisions. The right panel of Fig. 1 shows the districtwise map of Rajasthan.

3. Data and Methodology

3.1. Customization and Processing of Data

National Centers for Environmental Prediction (NCEP) Global Forecasting System (GFS) data of 0.25 degree resolution at three hourly intervals in real time have been downloaded from the NCEP website (<http://www.ncep.noaa.gov/>). This data is received in real time in high power computing system (HPCS) named as ADITYA system. Various customized products such as rainfall (3 h accumulation, 24 h accumulation for RMC domain, 24 h accumulation for Flood Met Office domain) and winds are plotted based on the requirement and utility in real-time weather forecasting at the Regional Weather Forecasting Center (RWFC), New Delhi. These products are available on RMC New Delhi website. For the verification of the forecast issued by RWFC New Delhi, the observed parameters are received in real time from various meteorological observatories situated within the domain of the study.

3.2. Terminologies

Based on the spatial distribution of the rainfall within the subdivision, terminologies followed in IMD are as listed in Table 1. Table 2 illustrates the classifications for heavy rainfall followed by IMD for 24-h accumulated rainfall

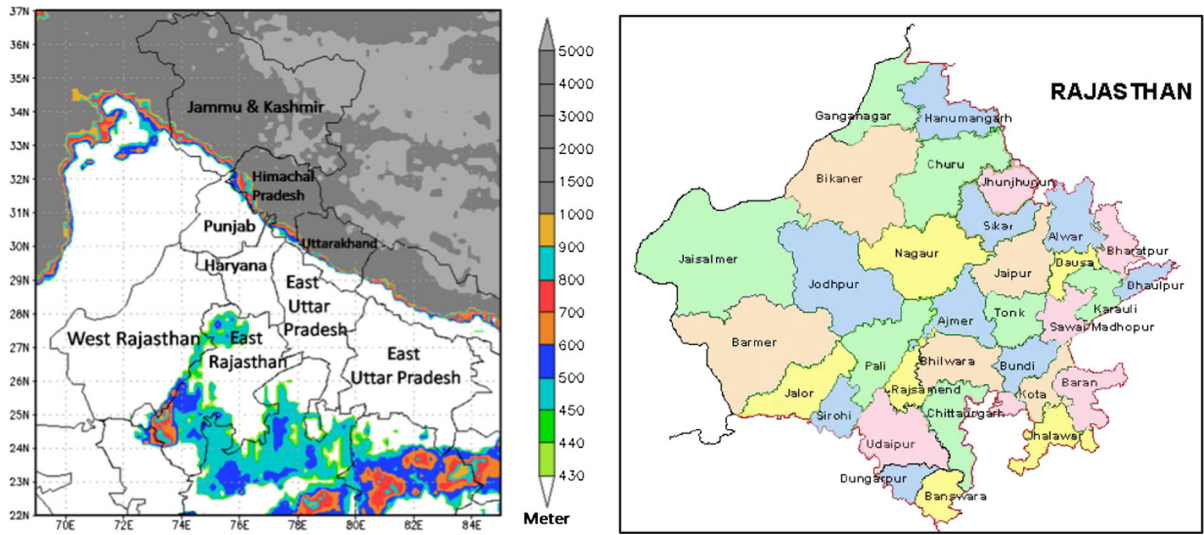


Figure 1
Domain of study (including terrain heights in meters) and districtwise map of Rajasthan

Table 1

Terminology for the spatial distribution of the rainfall

Spatial distribution of rainfall	Descriptive term used	Criteria
Dry	Dry	No station reported rainfall
Isolated	One or two places	≤25% of stations get rainfall
Scattered	At a few places	(26–50)% of stations get rainfall
Fairly widespread	At many places	(51–75)% of stations get rainfall
Widespread	At most places	(76–100)% of stations get rainfall

Table 2

Classifications for heavy rainfall for a station

S. no	Terminology	Rainfall range (cm)
1	Heavy rainfall (HR)	6.4–11.5
2	Very heavy rainfall (VHR)	11.5–20.4
3	Extremely heavy rainfall (EHR)	Greater or equal to 20.4
4	Exceptionally heavy rainfall	When the amount is a value near about the highest recorded rainfall at or near the station for the month or season. However, this term will be used only when the actual rainfall amount exceeds 12 cm

4. Results and Discussion

4.1. Event of 7–9 August 2016

In this section, heavy to very heavy rainfall that occurred over the east Rajasthan subdivision during 7–9 August 2016 has been discussed.

4.1.1 Meteorological Analysis of Heavy to very Heavy Rainfall During 7–9 August 2016

Rainfall data show that the southwest monsoon was vigorous over Jammu and Kashmir and Punjab and active over Himachal Pradesh and east Rajasthan on 7 August 2016, vigorous over east Rajasthan and active over Jammu and Kashmir on 8 August 2016 and active over Rajasthan on 9 August 2016. Figure 2 depicts the visible images of satellite at 09:00 UTC for the period 7 August to 10 August 2016. Analysis of wind pattern and the observed gridded rainfall for day 1, day 2 and day 3 are shown in Figs. 3, 4, 5, 6, 7 and 8, respectively.

Analyses of wind pattern for the period 7 August to 10 August 2016 suggest that there was a low-pressure area over northwest Madhya Pradesh and neighborhood on 7 and 8 August 2016 which moved westward and lay over east Rajasthan and adjoining west Madhya Pradesh on 9 August 2016 along with associated upper air cyclonic circulation that persisted, extending up to 7.6 km above mean sea level.

Figure 3 depicts that on 7 August 2016, the axis of the monsoon trough at mean sea level passed through Bikaner, Guna, center of low-pressure area over northeast Madhya Pradesh and neighborhood, Jamshedpur, Digha and thence southeastward to east-central Bay of Bengal. Figure 5 shows that on 8 August 2016, the axis of monsoon trough level passed through Bikaner, Jaipur, center of low-pressure area over northwest Madhya Pradesh and neighborhood, Sidhi, Daltonganj and thence southeastward to east-central Bay of Bengal. Figure 7 depicts that on 9 August 2016, the axis of monsoon trough passed through Bikaner, Guna, center of low-pressure area over east Rajasthan and adjoining west Madhya Pradesh, Daltonganj center of well marked low-pressure area over northwest Bay of Bengal and adjoining coastal areas of west Bengal, thence

southeastward Bengal and then southeastward to east-central Bay of Bengal.

On 7 August 2016, a western disturbance (WD) as a trough in mid tropospheric westerlies lay along 71°E to the north of 30°N. With the eastward movement WD lay along 75°E and north of 32°N. Afterward, WD moved east-northeastward.

4.1.2 Analysis Based on Satellite Images

The satellite image in Fig. 2 shows that there is intense cloud over east Rajasthan and northwest Madhya Pradesh on 7 August. With the westward movement of the low-pressure system, intense clouds associated with the system also moved westward and lay over both east and west Rajasthan on 7 and 8 August. With the weakening and westward movement of the system, scattered clouds were seen over entire Rajasthan on 10 August 2016.

4.1.3 Forecast of Rainfall Distribution and its Verification

4.1.3.1 Wind Pattern and Rainfall Distribution on 7 August 2016

Figure 3 depicts the model analyzing wind at 925, 850, 700 and 300 hPa associated with a low-pressure area over northwest Madhya Pradesh and neighborhood at 00UTC of 7 August 2016. At 925 hPa, cyclonic circulation associated with a low-pressure area lay over northwest Madhya Pradesh. The low pressure area tilted southeastward with height and the associated cyclonic circulation at 850 and 700 hPa lay over east Madhya Pradesh. At 300 hPa, the wind flow was anti-cyclonic. The wind pattern suggested that the low-pressure system obtained moisture supply from both the Arabian Sea and Bay of Bengal from the surface to 700 hPa.

NCEP GFS forecasts with a lead time of 24 h (day 1), 48 h (day 2) and 72 h (day 3) were examined. D1, D2 and D3 are used to denote day 1, day 2 and day 3 forecast. Figure 4a depicts the observed gridded rainfall and Fig. 4b–d depicts model rainfall forecast by the NCEP GFS for D1 (24 h), D2 (48 h) and D3 (72 h) valid at 03 UTC of 8 August 2016. On comparing with gridded rainfall over east Rajasthan, the observed widespread rainfall was very close to the model-predicted widespread rainfall for D1 and D2

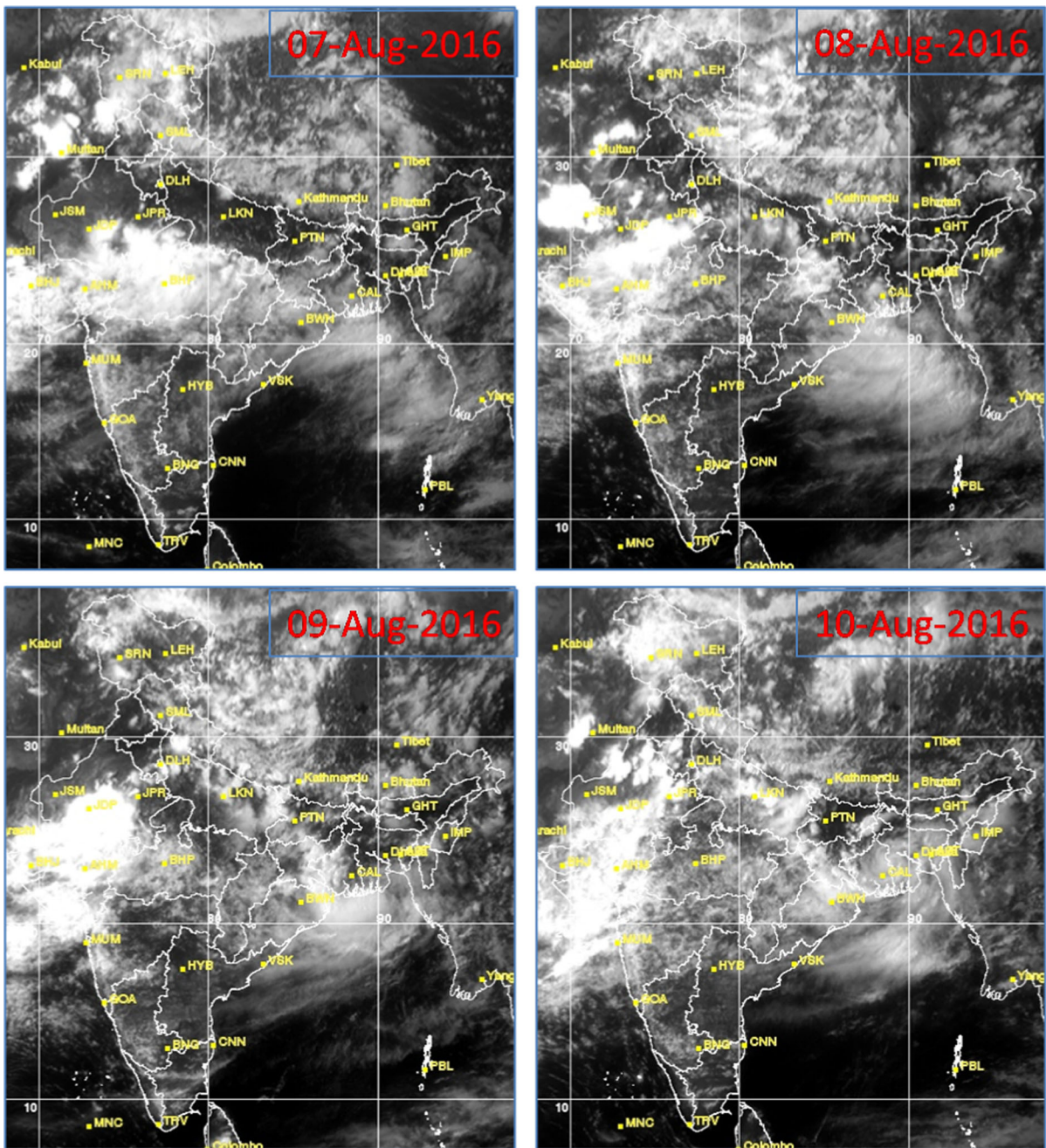


Figure 2
Satellite images during 07 August to 10 August 2016

and value-added forecast by RWFC of fairly widespread for D1, widespread for D2 and fairly widespread for D3. Model has also predicted rainfall more than 7 cm at most of the places (with one or two places more than 20 cm) at southern part of east Rajasthan, which is very close to the locations of

actual rainfall occurred in D1 and D2 forecast, similar to gridded rainfall.

4.1.3.2 Wind Pattern and Rainfall Distribution on 8 August 2016 The low-pressure area over north-west Madhya Pradesh and neighborhood on 7

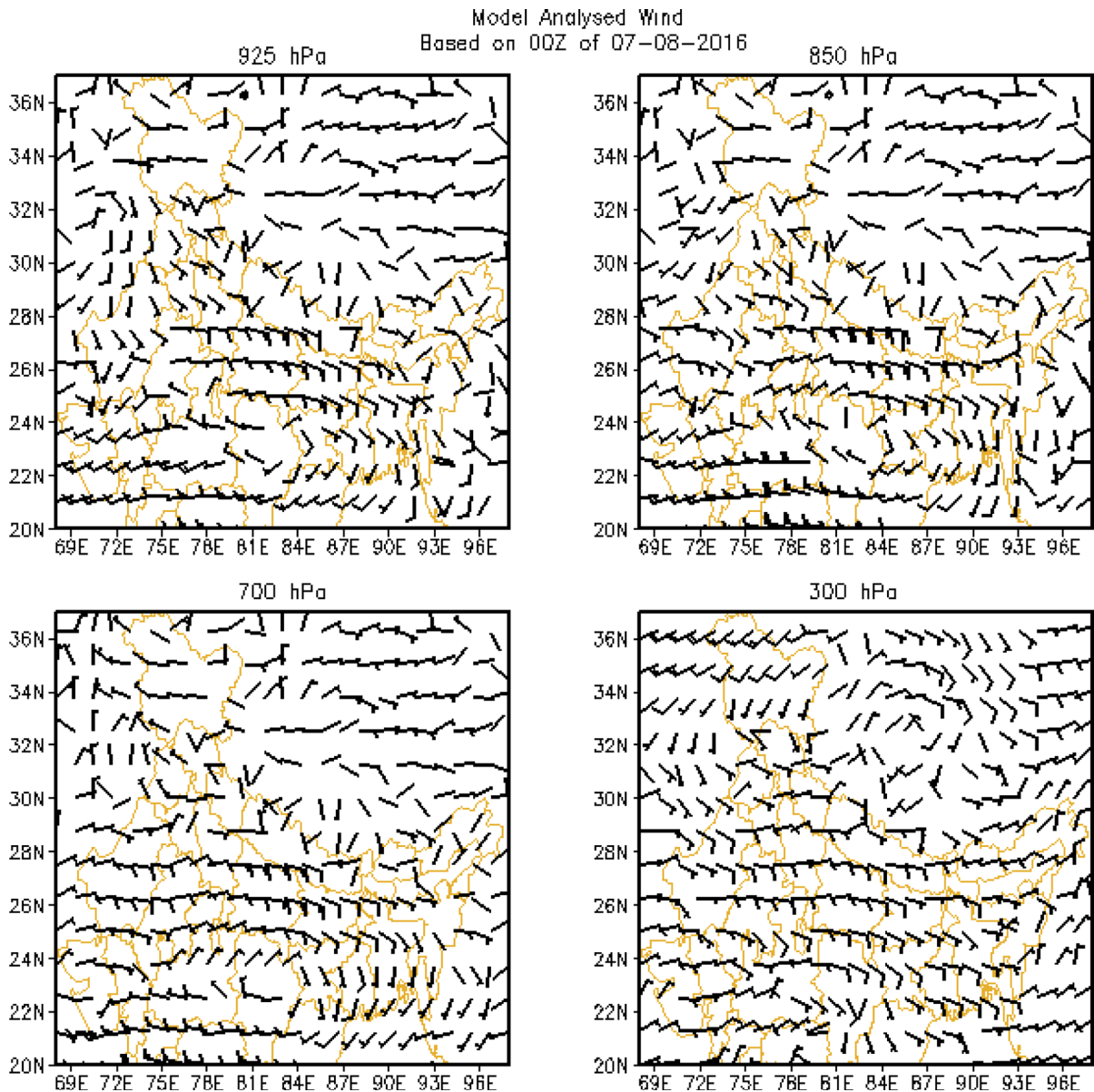


Figure 3
Model analyzed wind at 925, 850, 700 and 300 hPa at 00 UTC on 07 August 2016

August slightly moved northwestward. Figure 5 shows that cyclonic circulation associated with the low-pressure area lay over northwest Madhya Pradesh and adjoining east Rajasthan at 925 hPa. The vertical extension of the low-pressure area is up to 700 hPa at the same area. At 300 hPa, the wind flow is anti-cyclonic. Similar to the previous day, the low-pressure system gets moisture supply

from both the Arabian Sea and Bay of Bengal from the surface up to the 700 hPa level. Synoptically in case of northwestward moving low-pressure system, the maximum amount of rainfall occurs mostly in the southwest sector, so with sufficient supply of moisture from both Arabian Sea and Bay of Bengal in the lower levels there is a possibility of heavy rainfall over the northwestern parts of

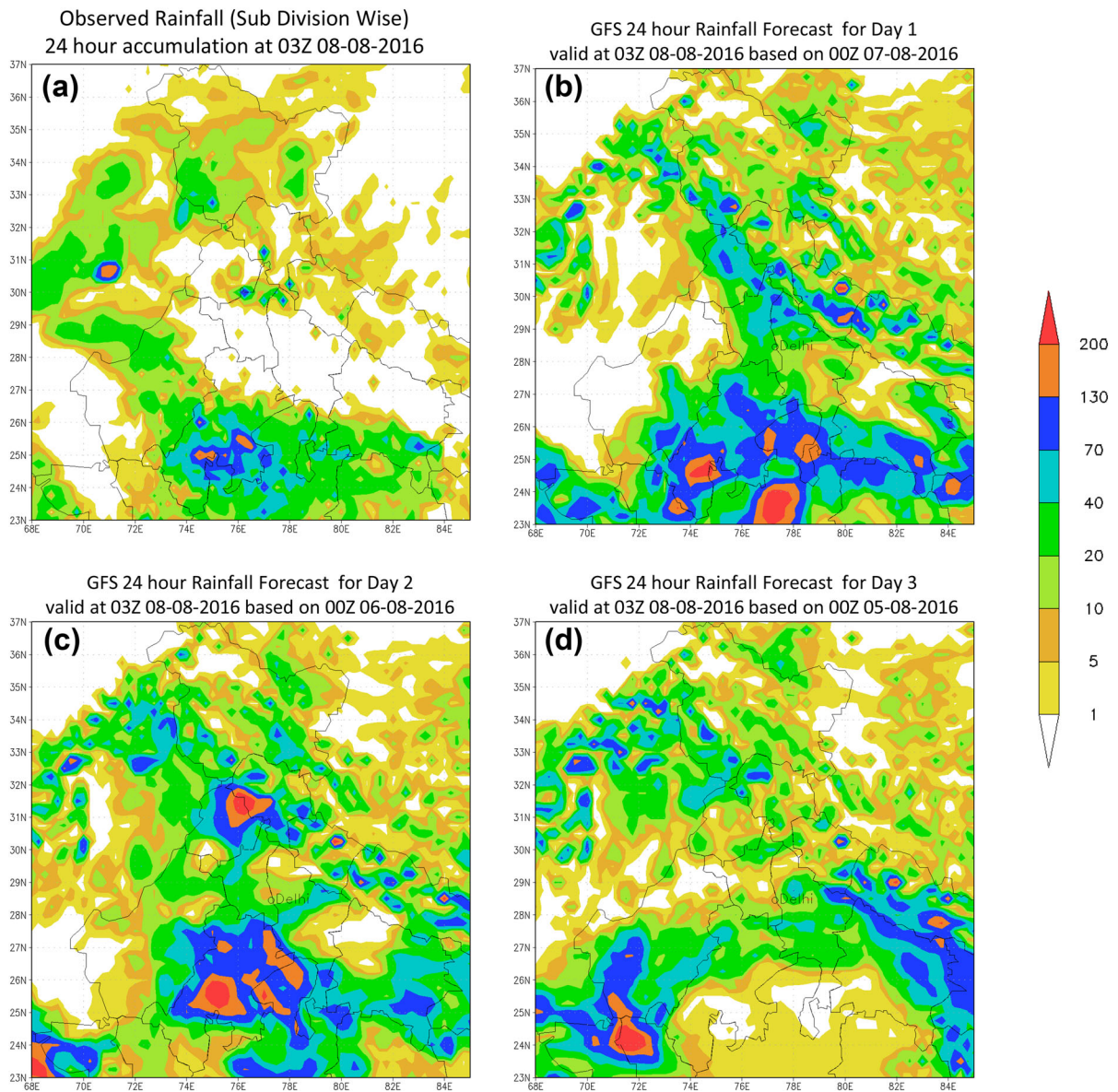


Figure 4

Spatial variations of **a** observed gridded rainfall and forecast rainfall for **b** day 1, **c** day 2 and **d** day 3 valid at 03 UTC of 08 August 2016

Madhya Pradesh and the southern parts of east Rajasthan.

The observed gridded rainfall distribution shown in Fig. 6a depicts that widespread rainfall occurred over east Rajasthan. Thus, the observed widespread rainfall is similar to both the model-predicted and value-added forecast by RWFC New Delhi of widespread rainfall for D1 and D2. The model has

also predicted rainfall more than 7 cm (some places more than 20 cm) at the southern part of east Rajasthan very close to the observed gridded rainfall locations in the D1 and D2 forecast.

4.1.3.3 Wind Pattern and Rainfall Distribution on 9 August 2016 The low-pressure area moved westward and lay over east Rajasthan and adjoining Madhya

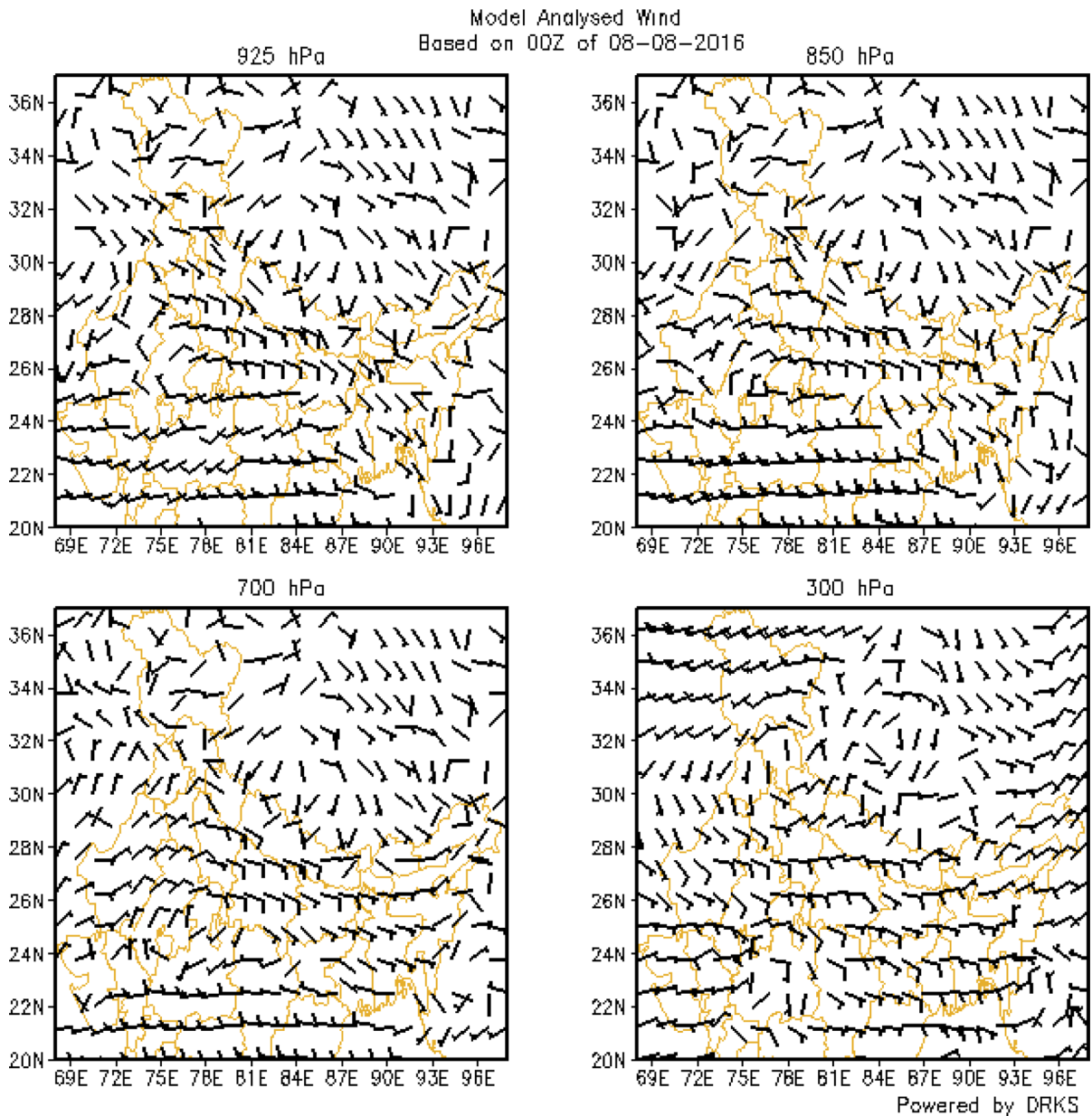


Figure 5
Model analyzed wind at 925, 850, 700 and 300 hPa at 00UTC on 08 August 2016

Pradesh on 9 August 2016. Figure 7 shows that the cyclonic circulation associated with the low-pressure area now lay over east Rajasthan and adjoining northwest Madhya Pradesh with southwestward vertical tilting and vertical extension up to 300 hPa. The low-pressure system continued to get moisture supply from both Arabian Sea and Bay of Bengal from the

surface up to the 925 hPa level. Moisture feeding to this system between 925 and 700 hPa was only from the easterly winds coming from the Bay of Bengal. So there is sufficient supply of moisture from both the Arabian Sea and Bay of Bengal in the lower levels for the occurrence of heavy rainfall over the southern parts of east and west Rajasthan.

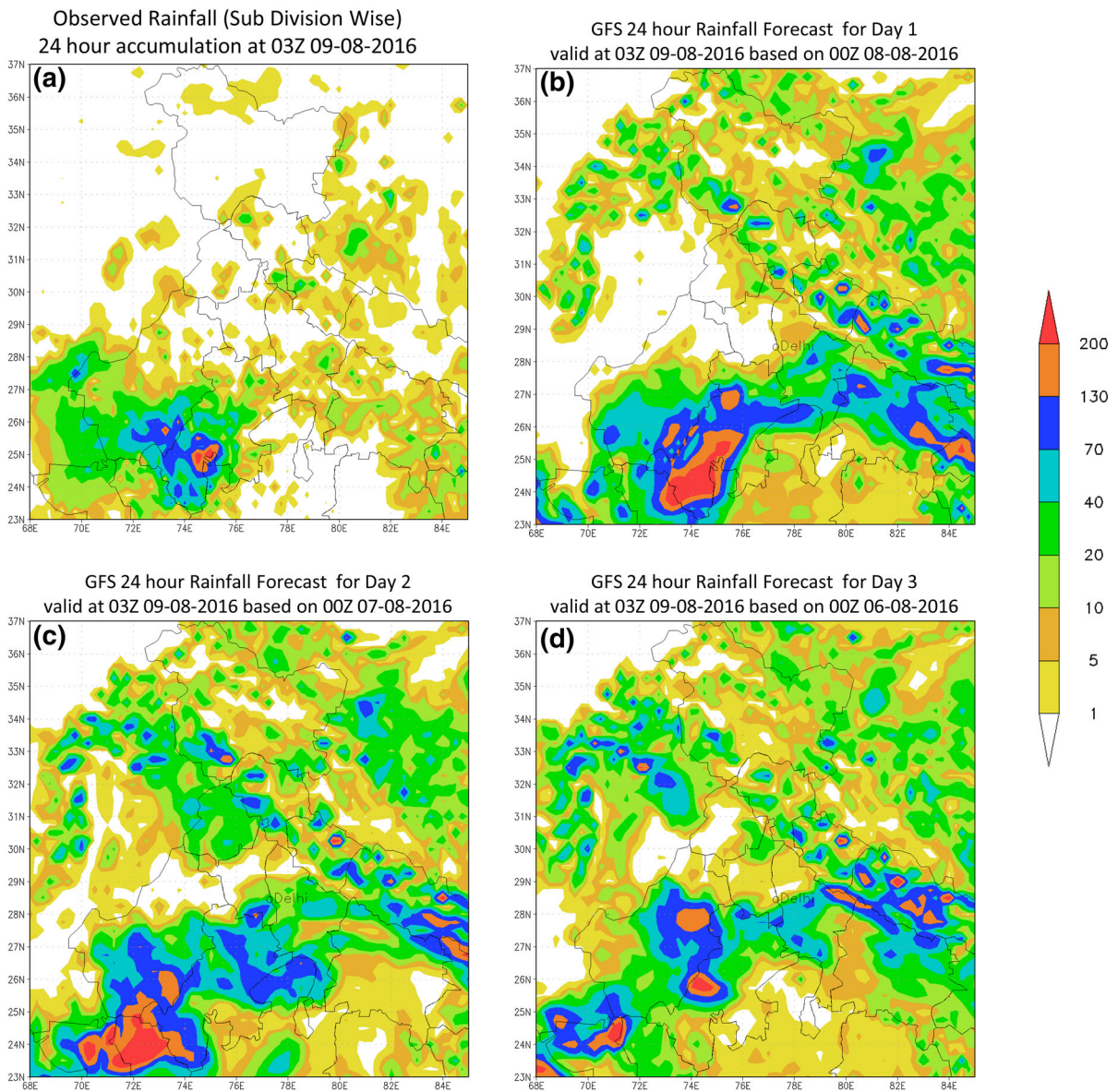


Figure 6

Spatial variations of **a** observed gridded rainfall and forecast rainfall for **b** day 1, **c** day 2 and **d** day 3 valid at 03 UTC of 09 August 2016

The observed gridded rainfall distribution in Fig. 8 shows that widespread rainfall occurred over east Rajasthan. The observed widespread rainfall is similar to both the model-predicted and value-added forecast by RWFC New Delhi of widespread rainfall for D1 and D2. The observed gridded rainfall distribution shows that rainfall more than 7 cm

(some places more than 20 cm) occurred over the southern parts of the boundary of east and west Rajasthan. Model has also predicted rainfall more than 7 cm at most of the places (with one or two places more than 20 cm) at southern of actual rainfall occurred very close to those in the D1 and D2 forecast.

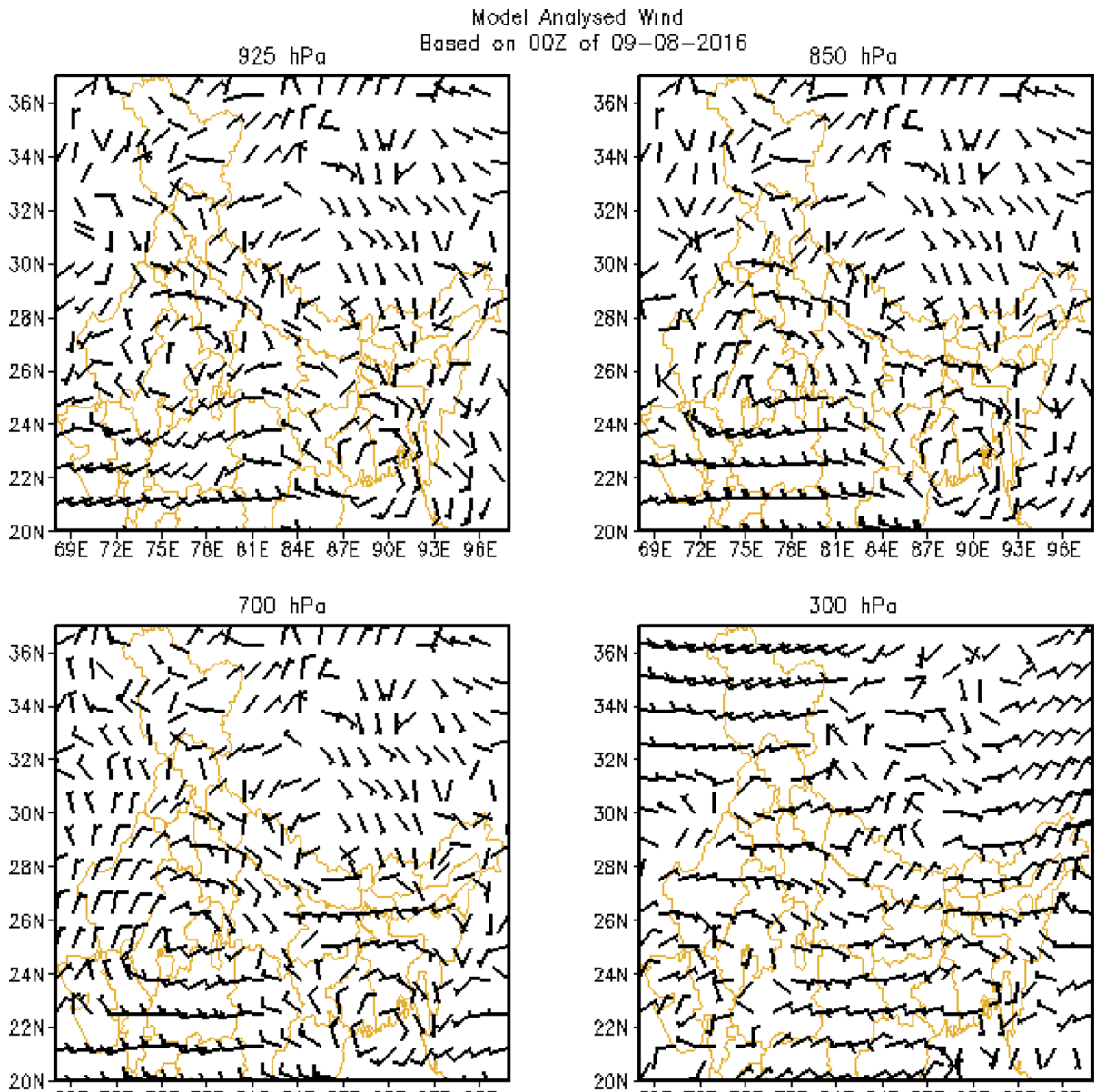


Figure 7
Model analyzed wind at 925, 850, 700 and 300 hPa at 00UTC on 09 August 2016

4.1.4 Real-Time Warning of EHR Events and Their Verification

4.1.4.1 EHR Warning for 7 August 2016 The model predicted an easterly/east-northeasterly wind pattern over east Rajasthan on day 1, day 2 and day 3 forecast, which is similar to the analyzed/observed wind. The NCEP model predicted scattered HR (with

isolated EHR) warning for D1 and D2 for east Rajasthan and no warning for west Rajasthan for D1, D2 and D3. The real-time warning issued on 7 August by RWFC as shown in Fig. 9a in the D1, D2 and D3 bulletins was isolated heavy rainfall over east Rajasthan and the actual weather for east Rajasthan was also scattered HR (with isolated EHR). No HR warning was issued for west Rajasthan and none of

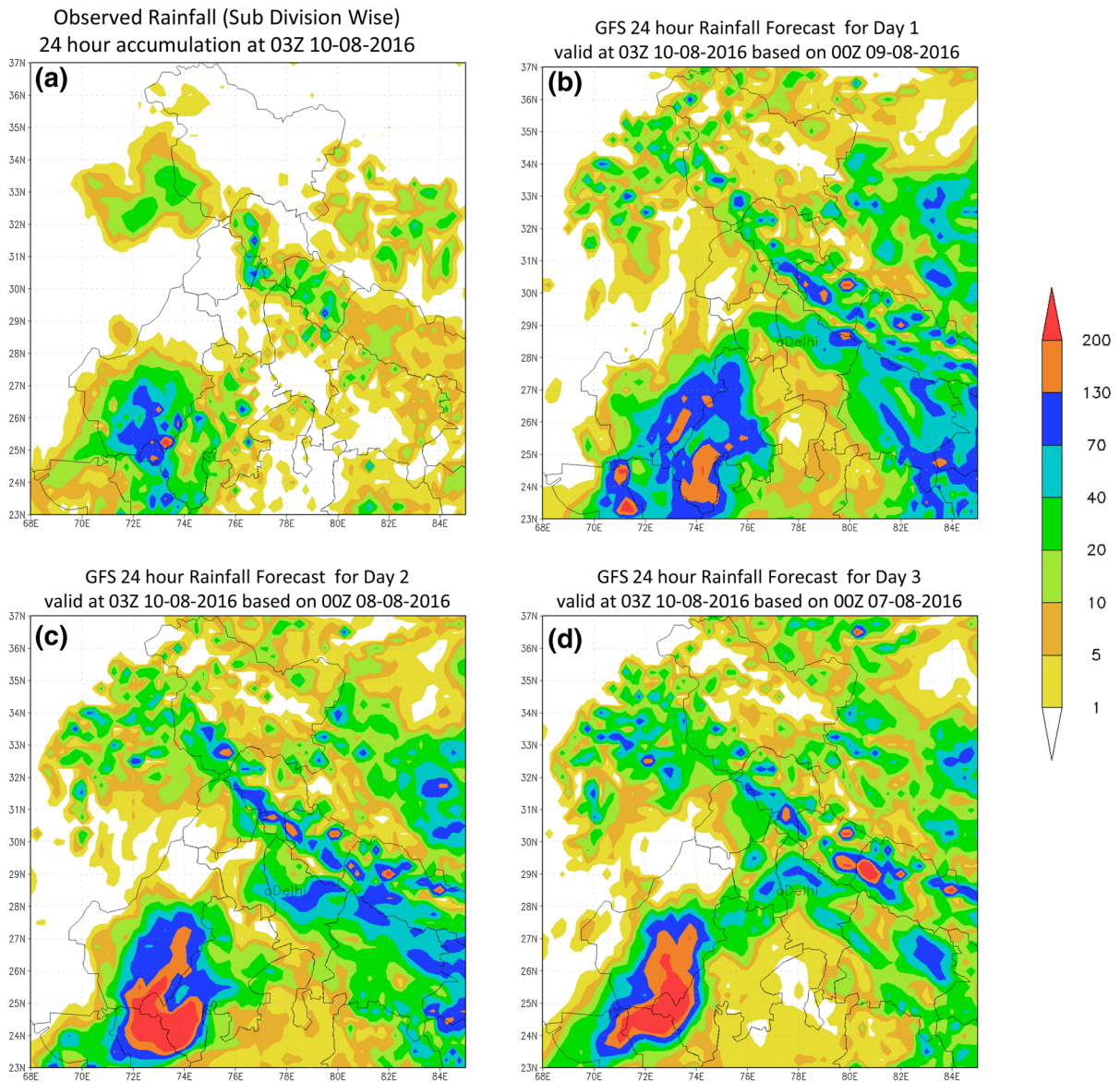


Figure 8

Spatial variations of **a** observed gridded rainfall and forecast rainfall for **b** day 1, **c** day 2 and **d** day 3 valid at 03 UTC of 10 August 2016

the districts of west Rajasthan received HR. Even though heavy rainfall (HR) warning is issued for east Rajasthan but it is under warning, as both the model predicted and observed warning is scattered HR (with isolated EHR) for D1 and D2.

Figure 9b depicts the stationwise actual rainfall received at all districts of east Rajasthan on 7 August 2016 (03 UTC of 08 August 2016). Out of 23 districts of east Rajasthan, two districts of east Rajasthan,

namely Chittorgarh and Kota, received EHR amounts of 21.2 and 21.9 cm, respectively (more than 20.4 cm); three districts Bundi Ajmer and Baran received very heavy rainfall amounts of 11.6, 14.4 and 16.1 cm, respectively, and five districts, namely Tonk, Banswara, Dungarpur, Bhilwara and Jhalawar, heavy rainfall amounts of 6.8, 7.6, 7.8, 8.8 and 8.8 cm (between 6.4 and 11.4 cm), respectively. 44% districts of east Rajasthan received heavy rainfall or

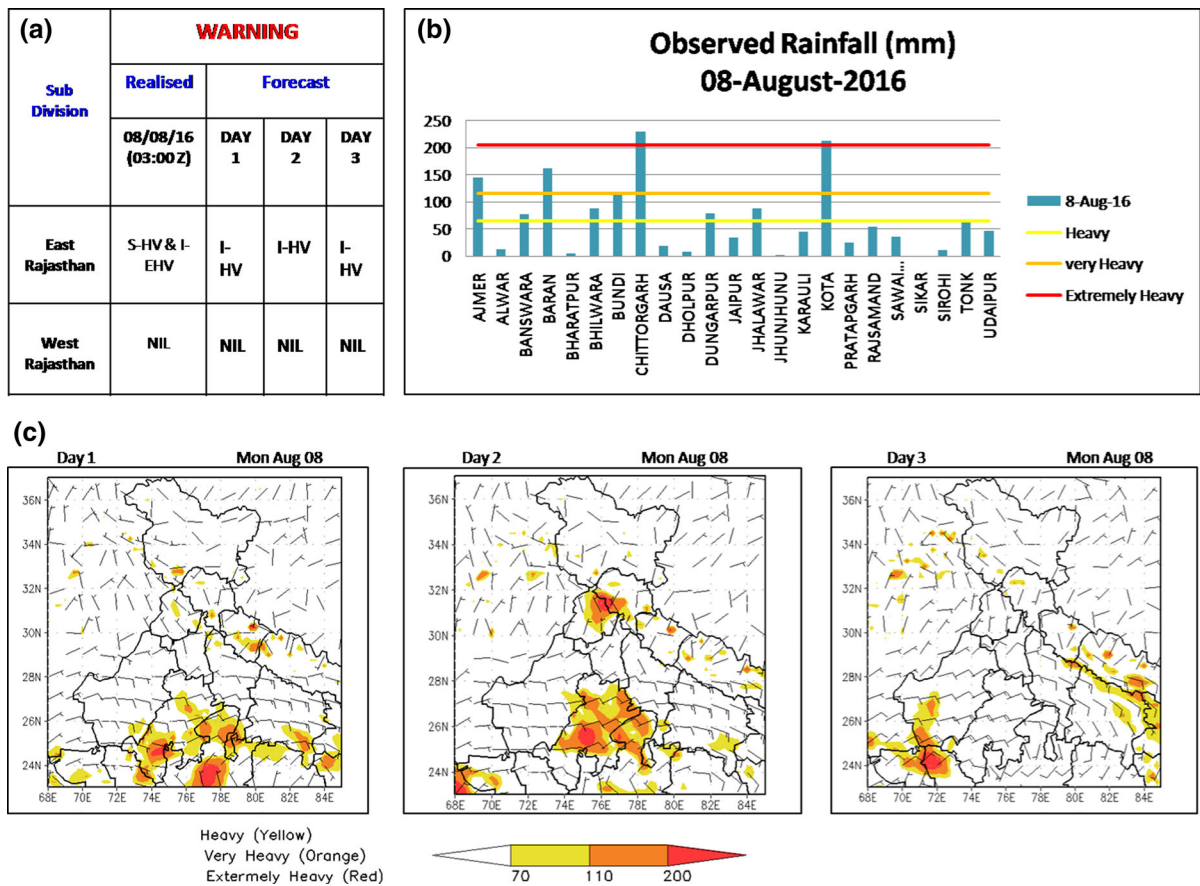


Figure 9

a Warning issued and actual realized warnings for east and west Rajasthan. **b** Stationwise actual recorded rainfall. **c** Wind pattern with overlaid heavy rainfall warnings valid at 03 UTC of 08 August 2016. (S-HV, I-EHV and I-HV indicate scattered heavy rainfall, isolated extremely heavy rainfall and isolated heavy rainfall, respectively)

more on 7 August 2016, and scattered heavy rainfall with isolated EHR occurred over east Rajasthan.

Figure 9c illustrates D1, D2 and D3 wind pattern at 850 hPa for 03 UTC of 07 August and overlaid heavy rainfall warnings between 03 UTC of 07 August and 03 UTC of 08 August 2016 as predicted by the NCEP GFS model. In the figure, heavy rainfall (HR), very heavy rainfall (VHR) and EHR amounts are plotted in yellow, orange and red colors, respectively. The model predicted EHR warning for Chittorgarh and neighboring districts and VHR and HR warnings for south of east Rajasthan and some pockets of north of east Rajasthan for D1. The D2 model predicted EHR warning for Chittorgarh and neighboring districts, VHR warnings for central and northern parts of east Rajasthan and HR warning for

the entire east Rajasthan except some parts of north and south. The D3 forecast of the model did not predict any warning for east Rajasthan; however, it has predicted EHR, VHR and HR warning for the adjoining areas of the southwestern boundary of east Rajasthan. Overall, NCEP model has predicted scattered HR with isolated EHR warning for D1 and D2 over east Rajasthan and no warning for west Rajasthan for D1, D2 and D3 (Fig. 9c).

4.1.4.2 EHR Warning for 8 August 2016 The model predicted mostly a northeasterly wind pattern over east Rajasthan in the D1, D2 and D3 forecast, which is similar to the analyzed/observed wind at 850 hPa shown in Fig. 10c. The model predicted scattered VHR (with isolated EHR warning) for D1

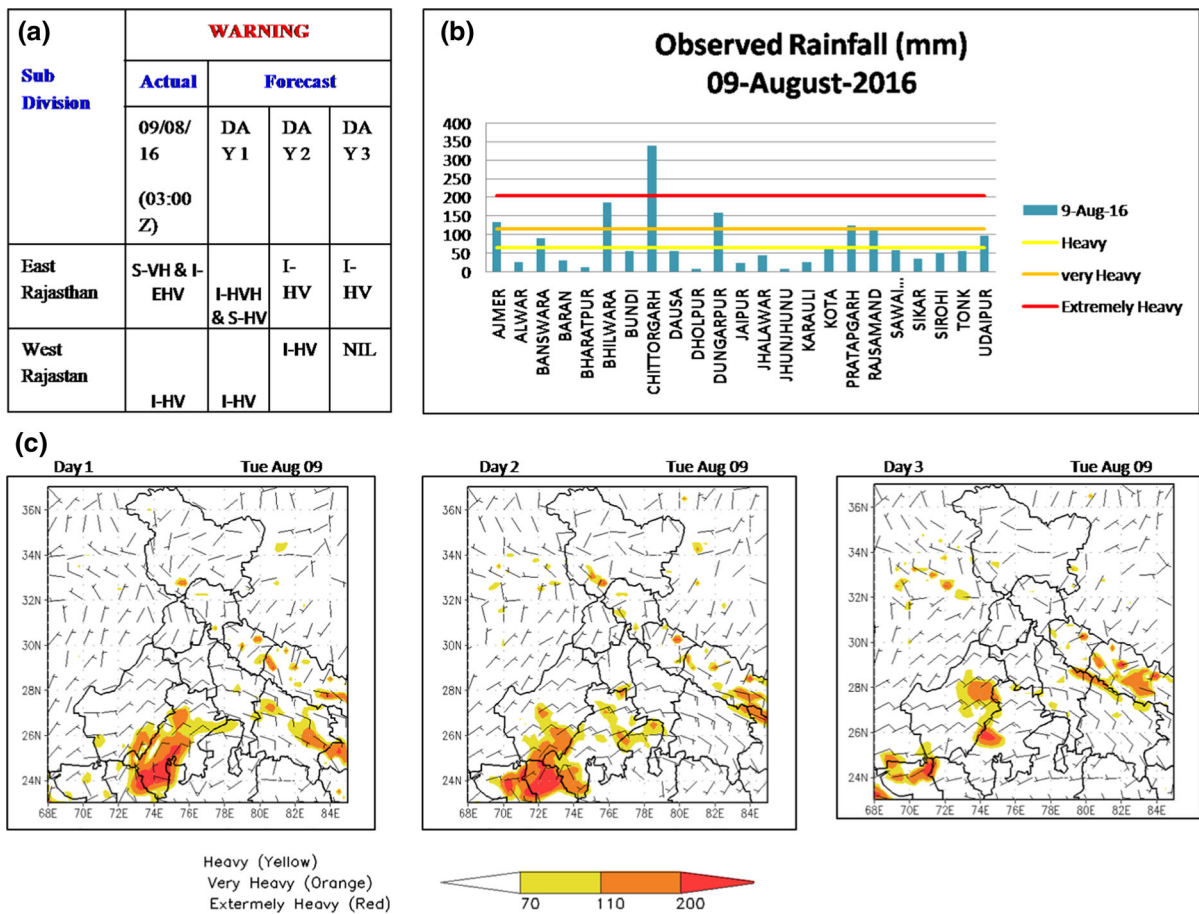


Figure 10

a Warning issued and actual realized warnings for east and west Rajasthan. **b** Stationwise actual recorded rainfall. **c** Wind pattern with overlaid heavy rainfall warnings valid at 03 UTC of 09 August 2016. (S-HV, I-EHV, I-HVH and I-HV indicate scattered heavy rainfall, isolated extremely heavy rainfall, isolated heavy to very heavy rainfall and isolated heavy rainfall, respectively)

and isolated HR warning for east Rajasthan in the D2 and D3 forecast. Real-time warning issued by RWFC for east Rajasthan in D1 bulletins was scattered HR (with isolated VHR); in D2 and D3 bulletins, it was isolated HR warning. The actual weather for east Rajasthan was scattered VHR (with isolated EHR). Though the VHR/HR warning was issued for east Rajasthan, it was under warning. The model also predicted isolated VHR warning for some pockets of west Rajasthan for D1, D2 and D3. Real-time warning issued for west Rajasthan in the D1 and D2 bulletins was isolated HR and the actual weather was isolated HR rainfall, similar to the warning issued by RWFC.

Figure 10b depicts the stationwise actual rainfall received at all districts of east Rajasthan 03 UTC of 8 August to 03 UTC of 9 August 2016. Out of 23 districts of east Rajasthan, 1 district, Chittorgarh, received EHR of 33.8 cm; five districts, namely Bhilwara, Dungarpur, Ajmer, Pratapgrah and Rajasmand, received VHR amounts of 18.7, 16.0, 13.3, 12.6 and 12.0, respectively, and three districts, namely Udaipur, Banswara and Kota, received heavy rainfall amounts of 9.7, 9.0 and 7.0, respectively. 39% of the district of east Rajasthan received heavy rainfall or more on 08 August 2016, and scattered heavy rainfall with isolated EHR occurred over east Rajasthan.

Figure 10c depicts D1, D2 and D3 HR warnings predicted by the model between 03 UTC of 8 August to 03 UTC of 9 August 2016. The model provided EHR warnings for Udaipur, Chittorgarh, Pratapgarh and Bundi districts, and VHR and HR warnings for almost the entire south of east Rajasthan and some pockets of north of east Rajasthan for D1. The D2 model predicted VHR and HR warnings for some pockets of east Rajasthan and also predicted EHR warning for the adjoining area close to the southwest of east Rajasthan. The D3 forecast of the model predicted EHR and VHR warnings for a very small area of east Rajasthan covering Bhilwara and Rajsamand districts. The general model predicted scattered VHR (with isolated EHR warning for D1) and isolated HR warning for east Rajasthan for D2 and D3. The model also predicted isolated VHR warning for some pockets of west Rajasthan for D1, D2 and D3 (Fig. 10c).

4.1.4.3 EHR Warning for 9 August 2016 The model predicted mostly northeasterly wind pattern over east Rajasthan in the D1, D2 and D3 forecast, which is similar to the analyzed/observed wind at 850 hPa as shown in Fig. 11a. Warning up to the level of scattered VHR (with isolated EHR) was issued and that actually observed was scattered HR (with isolated VHR). The real-time warning issued by RWFC for west Rajasthan in D1 and D2 bulletins was scattered HR (with isolated VHR) and the actual observed weather for west Rajasthan was also scattered HR (with isolated VHR). In the D3 bulletin, no warning was issued for west Rajasthan.

Figure 11b depicts the stationwise actual rainfall received at all districts of east Rajasthan on Rajasthan 03 UTC of 9 August to 03 UTC of 10 August 2016. Out of 23 districts of east Rajasthan, 1 district, Sirohi, received very heavy rainfall amounts of 16.8 cm and 5 districts, namely Ajmer, Baran, Udaipur, Sawai Madhopur and Banswara, received heavy rainfall of 10.9, 9.8, 9.5, 7.1 and 6.6, respectively. 30% of the district of east Rajasthan received heavy rainfall or more on 09 August 2016, and scattered heavy rainfall with isolated extremely heavy rainfall occurred over east Rajasthan.

Figure 11c depicts D1, D2 and D3 heavy rainfall warnings predicted by NCEP GFS model for the

duration 03 UTC of 9 August to 03 UTC of 10 August 2016. The model predicted a VHR warning for Kota, Chittorgarh, Udaipur and Banswara districts, and HR warnings for some northern pockets of east Rajasthan and VHR warning for Pali district of west Rajasthan in D1. The D2 forecast model predicted EHR warnings for Chittorgarh, Udaipur and Banswara and Sirohi districts of the southern parts of east Rajasthan and EHR and VHR warning for Pali district of west Rajasthan close to the boundary of east and west Rajasthan. The D3 forecast model predicted EHR warnings for Udaipur and Sirohi districts of the southern parts of east Rajasthan and EHR and VHR warning for Pali district of west Rajasthan. The general model predicted scattered VHR (with isolated EHR) warning for D1 and scattered HR (with isolated VHR) warning for D2 and isolated HR warning for east Rajasthan for D3. The model also predicted isolated VHR warning for some pockets of west Rajasthan for D1, D2 and D3 (Fig. 11c). In D1, D2 and D3 forecast for 9 August 2016 the model predicted EHR and VHR warning for Pali district of west Rajasthan. The actual rainfall was 29.3 cm over Pali district (Bali Tehsel) with a realized warning of EHR level.

4.2. Event of 19–21 August 2016

In this section, the heavy to very heavy rainfall that occurred over east Rajasthan subdivision during 18–21 August 2016 has been discussed.

4.2.1 Analysis Based on Satellite Images

Figure 12 depicts the visible images of satellite at 09:00 UTC for 18 August to 21 August 2016. Satellite image shows that there are two main cloud patches, one over east Rajasthan and other over East Madhya Pradesh on 18 August. With the westward movement of deep depression over extreme south Uttar Pradesh, intense clouds associated with the system also moved westward and lay over Madhya Pradesh and east Rajasthan on 19 and 20 August. With the weakening and westward movement of the system, scattered clouds were seen over entire Rajasthan on 21 August 2016.

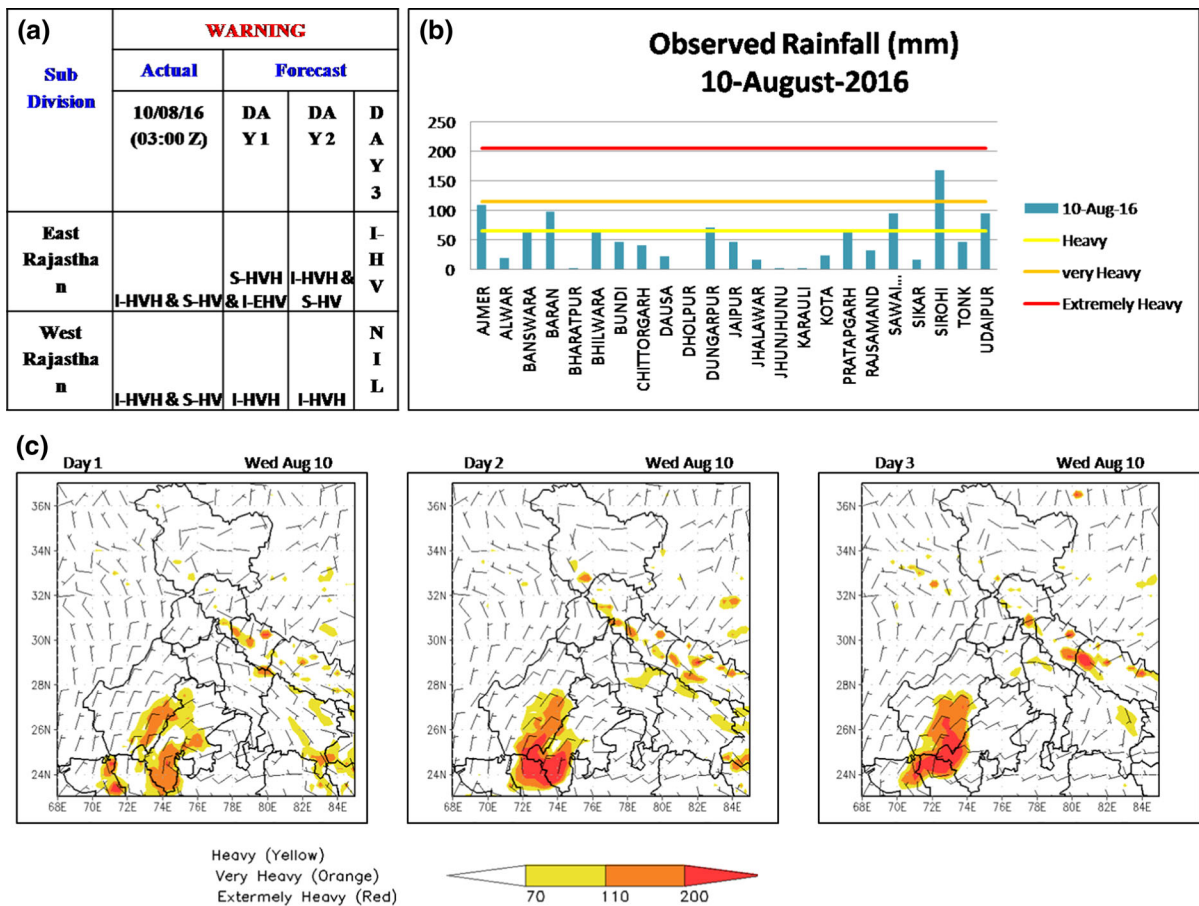


Figure 11

a Warning issued and actual realized warnings for east and west Rajasthan. **b** Stationwise actual recorded rainfall. **c** Wind pattern with overlaid heavy rainfall warnings valid at 03 UTC of 10 August 2016. (S-HV, I-EHV and I-HVH indicate scattered heavy rainfall, isolated extremely heavy rainfall and isolated heavy to very heavy rainfall, respectively)

4.2.2 Meteorological Analysis

Rainfall data show that the southwest monsoon was active over west Uttar Pradesh on 18 August 2016 and over east Rajasthan during 19 August to 21 August 2016. Analysis of wind pattern and observed gridded rainfall for day 1, day 2 and day 3 are shown in Figs. 13, 14, 15, 16, 17 and 18, respectively.

Analysis of wind pattern for the period 18 August to 21 August 2016 suggested that there was a deep depression over extreme south Uttar Pradesh and adjoining northeast Madhya Pradesh on 19 August 2016, which moved westward and gradually weakened into a depression on 20 August 2016. The system kept on moving westward and further

weakened into a low-pressure area and lay over east Rajasthan and adjoining area on 21 and 22 August 2016 along with associated upper air cyclonic circulation extending up to 7.6 km above mean sea level.

Figure 13 depicts that on 19 August 2016, the axis of the monsoon trough at mean sea level passed through Amritsar, Karnal, Aligarh, center of deep depression, Jamshedpur, Digha and thence eastward to Tripura. Figure 15 shows that on 20 August 2016, the axis of monsoon trough at mean sea level passed through Ganganagar, Narnaul, center of deep depression, Daltonganj, Bankura, and thence eastward to Mizoram. Figure 17 depicts that on 21 August 2016d the axis of monsoon trough at mean sea level continued to pass through Bikaner, center of low-

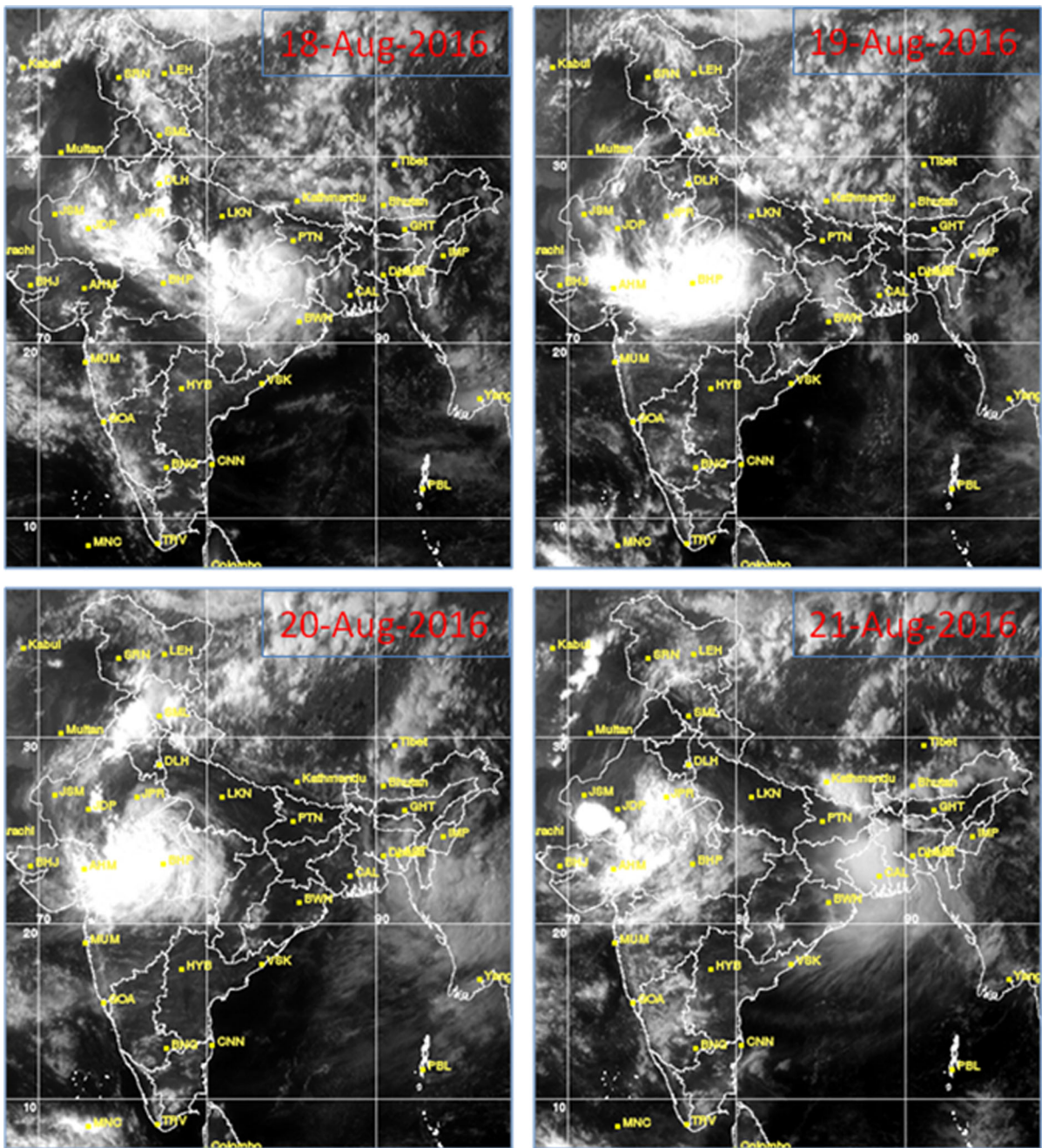


Figure 12
Satellite images during 18 August to 21 August 2016

pressure area over east Rajasthan and adjoining west Madhya Pradesh, Satna, Varanasi, Bhagalpur, center of low-pressure area over Bangladesh and neighborhood and thence southeastward to north Bay of Bengal.

4.2.3 Forecast of Rainfall Distribution and its Verification

4.2.3.1 Wind Pattern and Rainfall Distribution on 19 August 2016 Figure 13 depicts the model analyzed

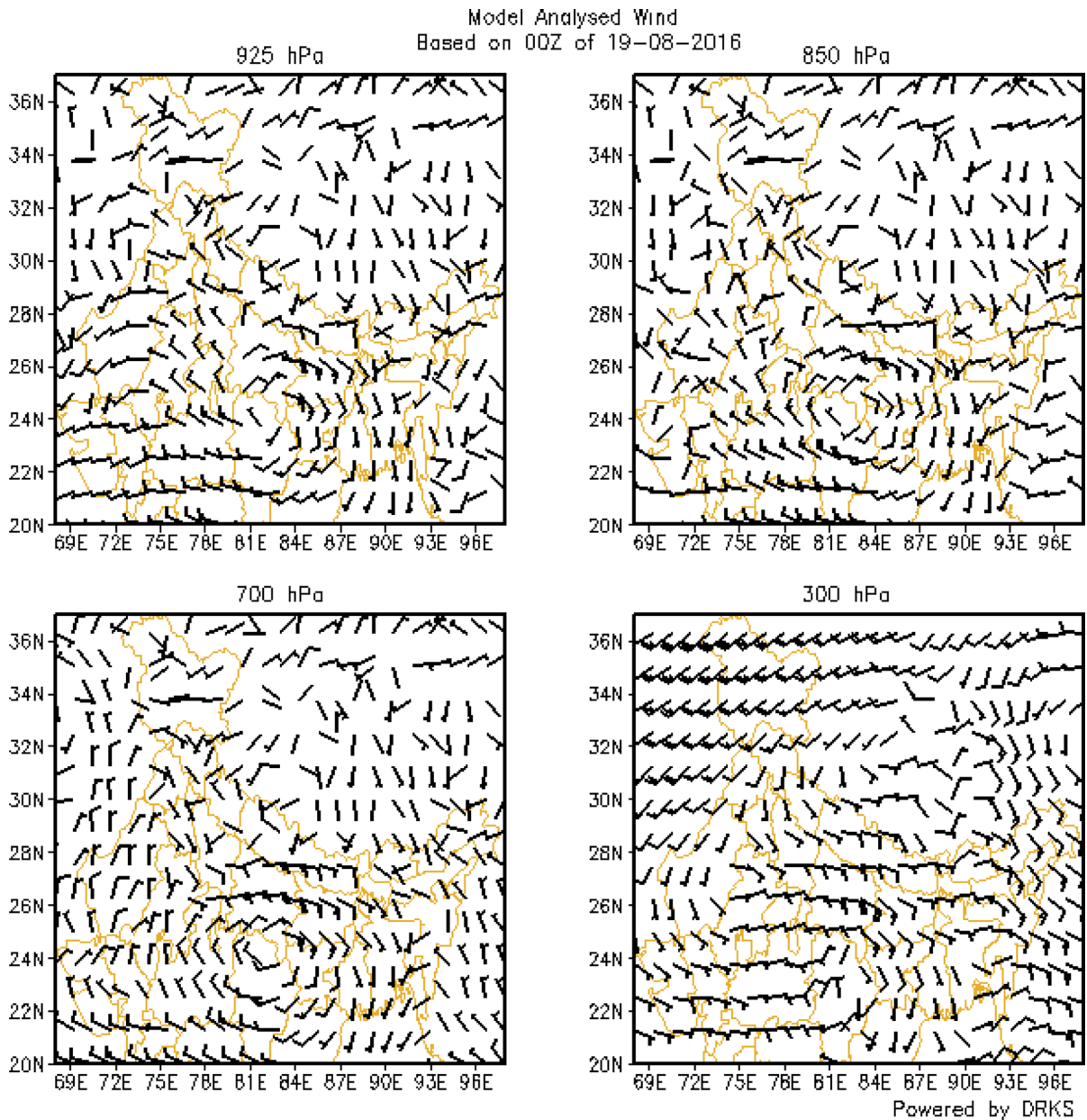


Figure 13
Model analyzed wind at 925, 850, 700 and 300 hPa at 00 UTC on 19 August 2016

wind at 925, 850, 700 and 300 hPa associated with deep depression over extreme south Uttar Pradesh and adjoining northeast Madhya Pradesh at 00UTC of 19 August 2016. At 925 hPa, cyclonic circulation associated with low-pressure area lay over northeast Madhya Pradesh. The deep depression has large

vertical extension up to 300 hPa. The system gets moisture supply from the Arabian Sea.

Figure 14a depicts the observed gridded rainfall and Fig. 14b–d depicts model rainfall forecast by NCEP GFS for D1 (24 h), D2 (48 h) and D3 (72 h) valid at 03 UTC of 20 August 2016. On comparing

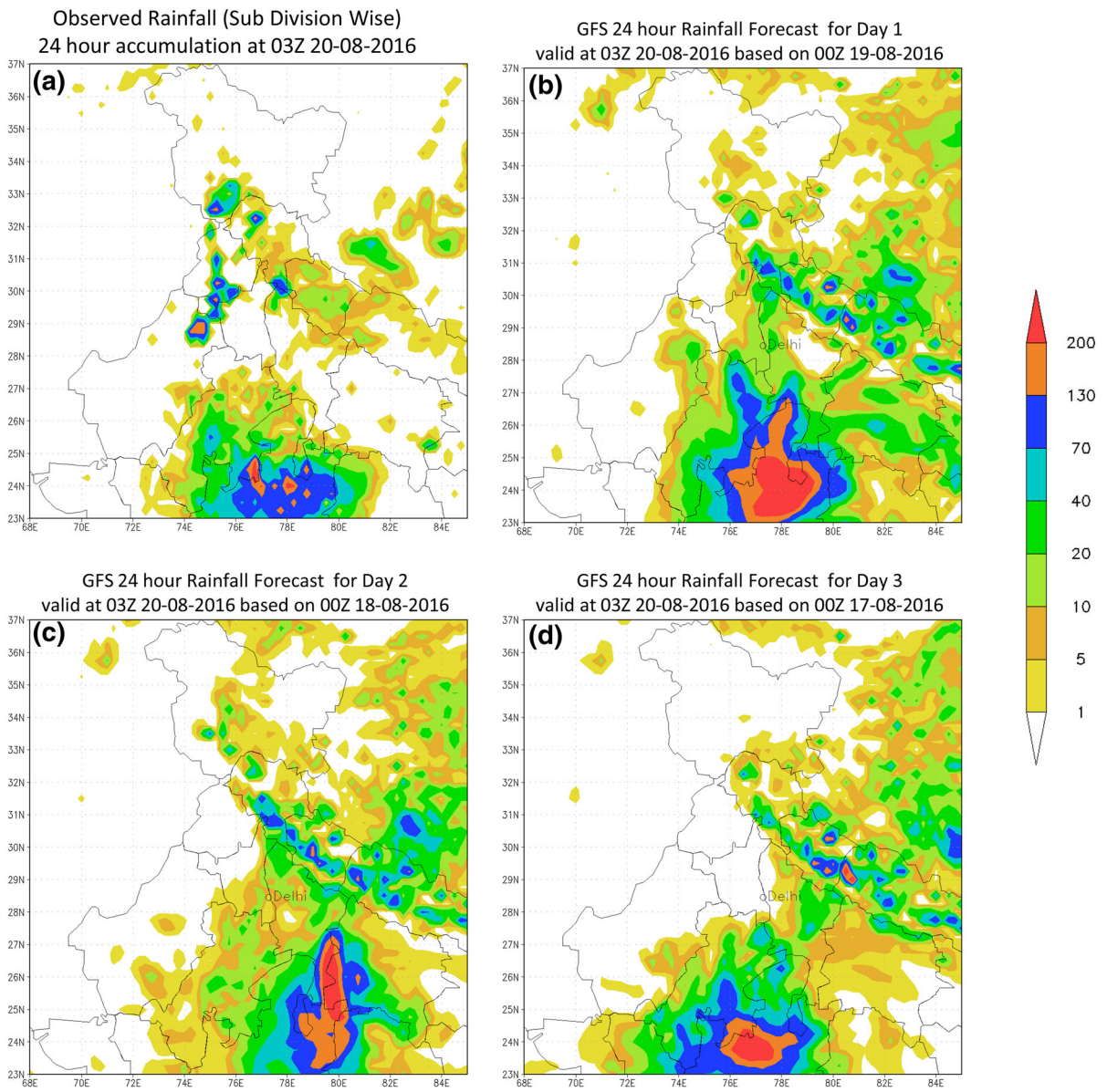


Figure 14

Spatial variations of **a** observed gridded rainfall and forecast rainfall for **b** day 1, **c** day 2 and **d** day 3 valid at 03 UTC of 20 August 2016

with gridded rainfall over east Rajasthan, the observed fairly widespread rainfall is very close to the model-predicted fairly widespread rainfall for D1, D2 and D3 and value-added forecast by RWFC is also fairly widespread for D1, D2 and D3. Model has also predicted rainfall more than 7.0 cm at most of the places (with one or two places more than 20.0 cm) at eastern part of east Rajasthan, which is

very close to the locations of actual rainfall occurred in D1 and D3 forecast, similar to gridded rainfall.

4.2.3.2 Wind Pattern and Rainfall Distribution on 20 August 2016 The deep depression over northwest Madhya Pradesh and neighborhood on 19 August moved westward and gradually weakened into a depression on 20 August 2016. Figure 15 shows that

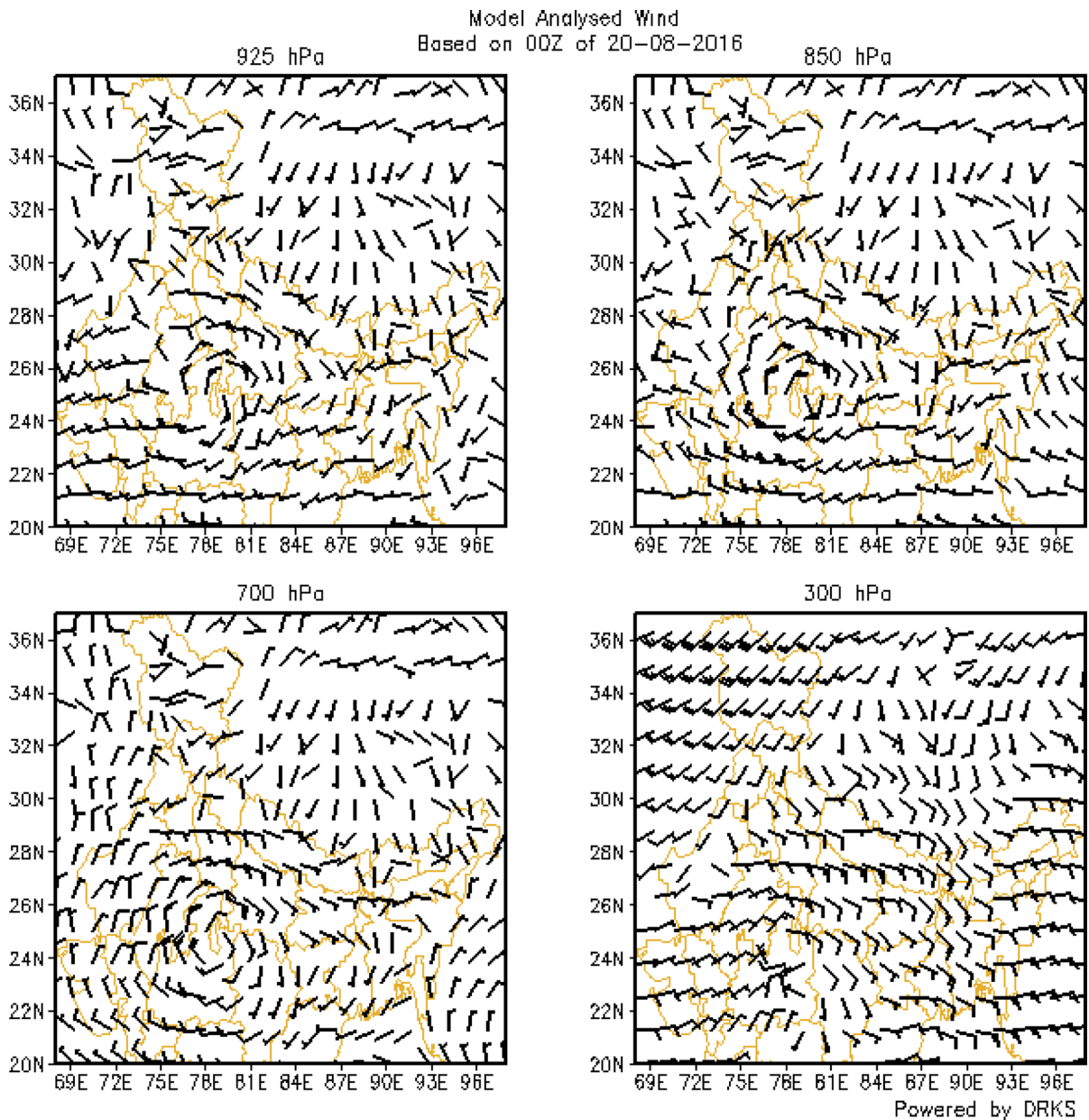


Figure 15
Model analyzed wind at 925, 850, 700 and 300 hPa at 00 UTC on 20 August 2016

cyclonic circulation associated with depression lies over northwest Madhya Pradesh and adjoining east Rajasthan at 925 hPa. The vertical extension of depression is up to 300 hPa. Similar to the previous day, with sufficient supply of moisture from Arabian Sea in the lower levels there is a possibility of heavy

rainfall over the western parts of Madhya Pradesh and the southern parts of east Rajasthan.

The observed gridded rainfall distribution shown in Fig. 16a depicts that fairly widespread rainfall occurred over east Rajasthan. Thus, the observed rainfall was similar to both the model-predicted and

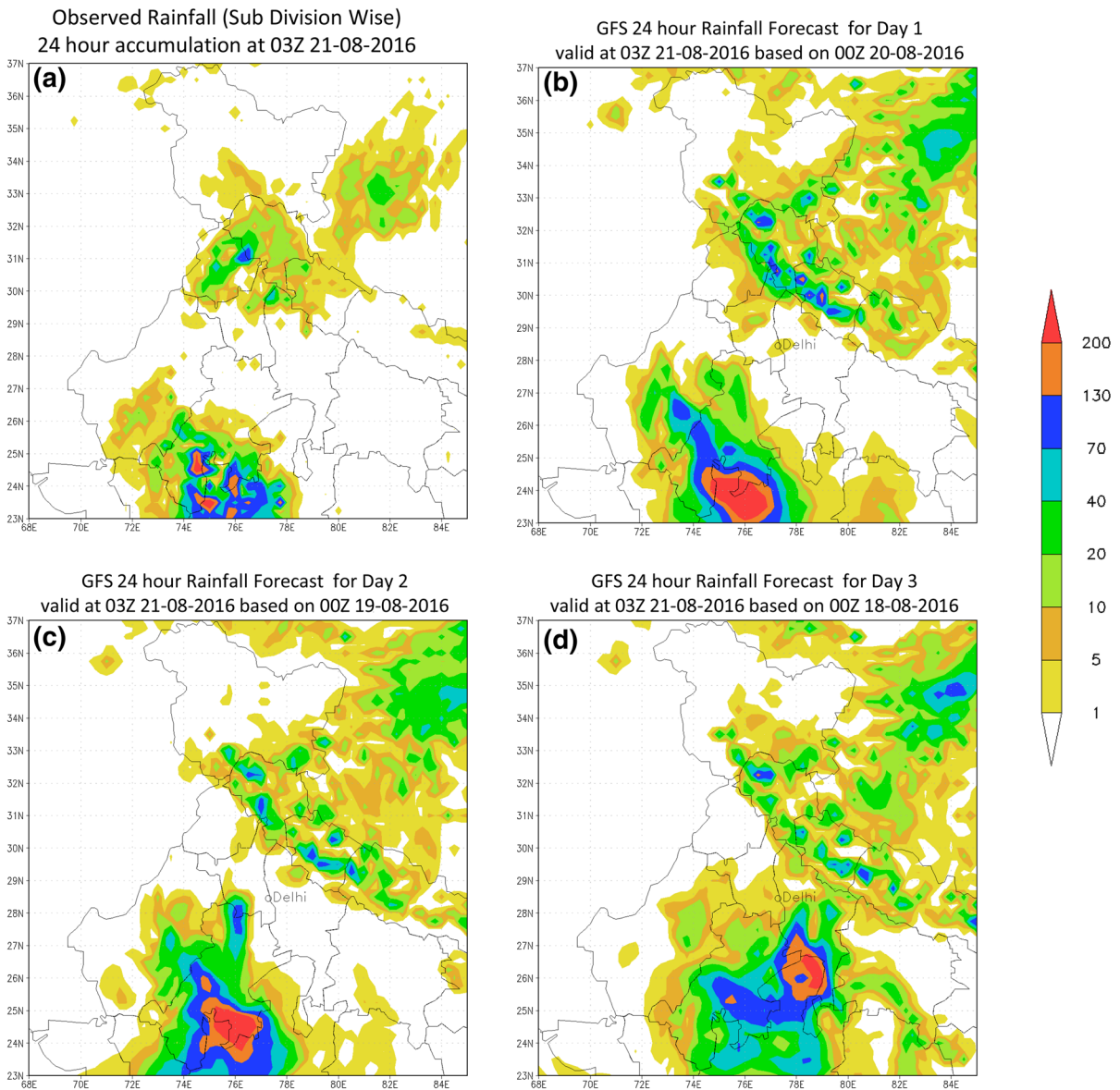


Figure 16

Spatial variations of **a** observed gridded rainfall and forecast rainfall for **b** day 1, **c** day 2 and **d** day 3 valid at 03 UTC of 21 August 2016

value-added forecast by RWFC for D1 and D2. The model also predicted rainfall more than 7.0 cm (some places more than 20.0 cm) at the southern part of east Rajasthan very close to the observed gridded rainfall locations in the D1 and D2 forecast.

4.2.3.3 Wind Pattern and Rainfall Distribution on 21 August 2016 The depression moved westward and weakened into a low-pressure area and lay over east

Rajasthan on 21 August 2016. Figure 17 shows that the cyclonic circulation associated with the low-pressure area now lay over east Rajasthan and adjoining west Madhya Pradesh with southwestward vertical tilting and vertical extension up to 300 hPa. The low-pressure system continues to get moisture supply from the Arabian Sea up to 700 hPa level. So, there is a good possibility of occurrence of heavy rainfall over the southern parts of east and west Rajasthan.

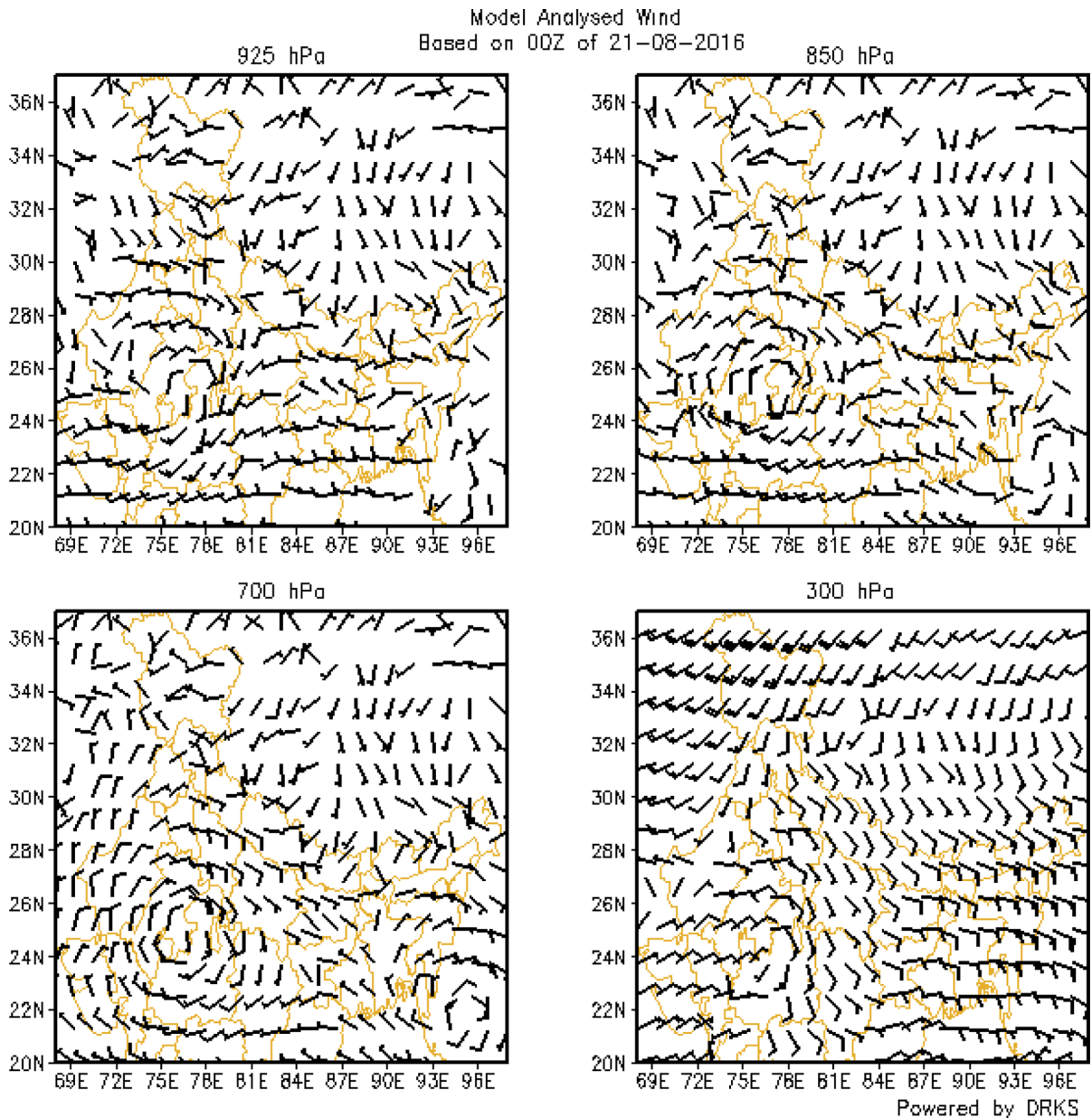


Figure 17
Model analyzed wind at 925, 850, 700 and 300 hPa at 00 UTC on 21 August 2016

The observed gridded rainfall distribution shown in Fig. 18 depicts that fairly widespread rainfall occurred over east Rajasthan. The observed fairly widespread rainfall was similar to both the model-predicted and value-added forecast by RWFC of fairly widespread rainfall for D1, D2 and D3. Gridded rainfall distribution shows that rainfall more than

7.0 cm occurred over the southern parts of both east and west Rajasthan. Figure 21b reveals that Pratapgarh and Udaipur districts of east Rajasthan received very heavy rainfall of 12.2 and 11.3 cm, respectively. The model has well predicted rainfall intensity up to 13.0 cm in the southern parts of east Rajasthan in the D1, D2 and D2 forecast. However, it predicted

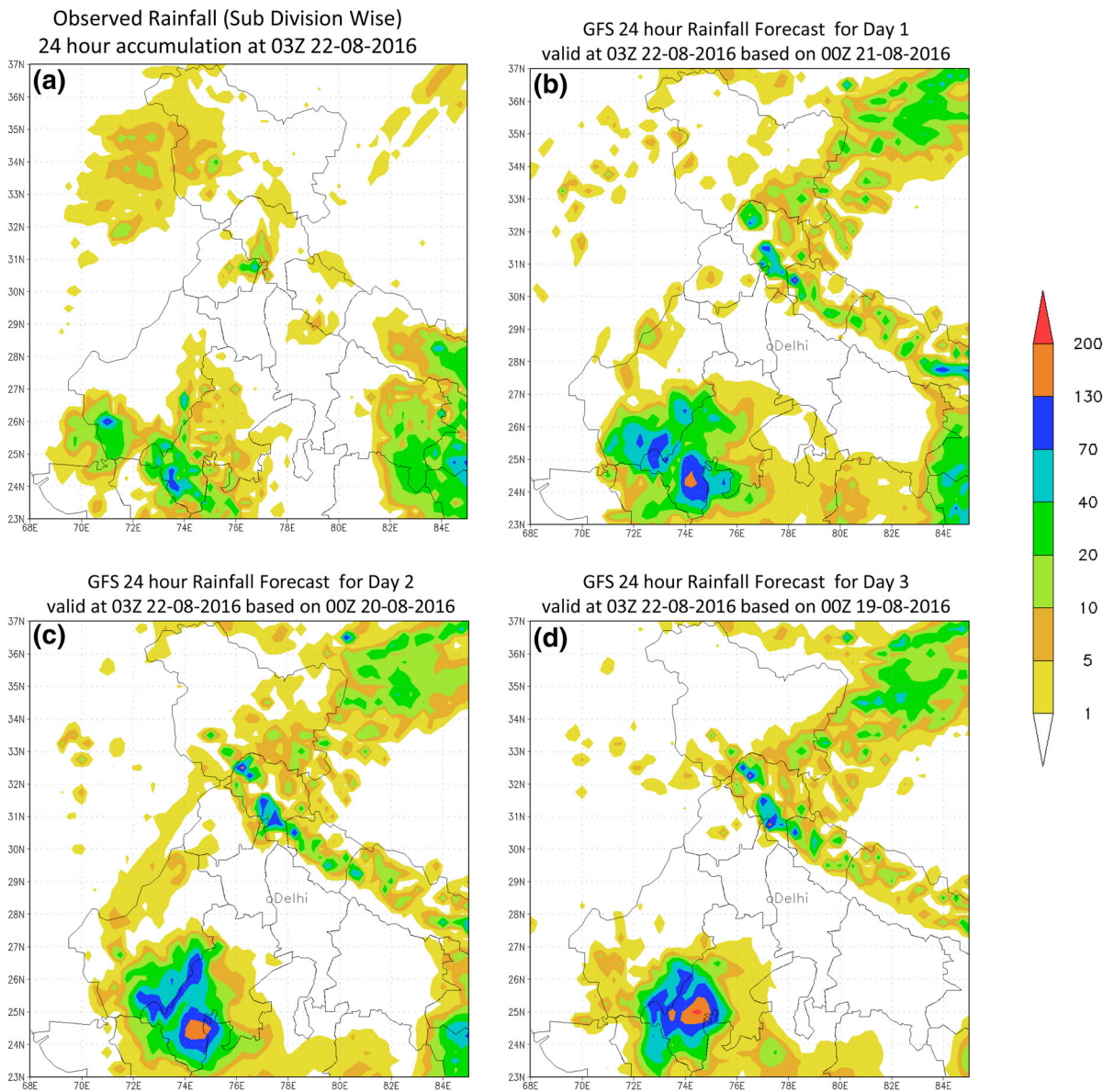


Figure 18

Spatial variations of **a** observed gridded rainfall and forecast rainfall for **b** day 1, **c** day 2 and **d** day 3 valid at 03 UTC of 22 August 2016

13.0–20.0 cm at some places in the D1, D2 and D2 forecast, which was not realized.

4.2.4 Real-Time Warning of EHR and its Verification

4.2.4.1 EHR Warning for 19 August 2016

The model has predicted easterly/east-northeasterly wind pattern over east Rajasthan in D1, D2 and D3 forecast

which is similar to the analyzed/observed wind. Real-time warning issued by RWFC shown in Fig. 19a in D1 and D3 bulletins was isolated heavy rainfall over east Rajasthan and the actual observed weather for east Rajasthan was also isolated HR (with isolated EHR). Based on the synoptic condition and model analyzed wind pattern, isolated VHR warning was issued for west Rajasthan for D2. Even though

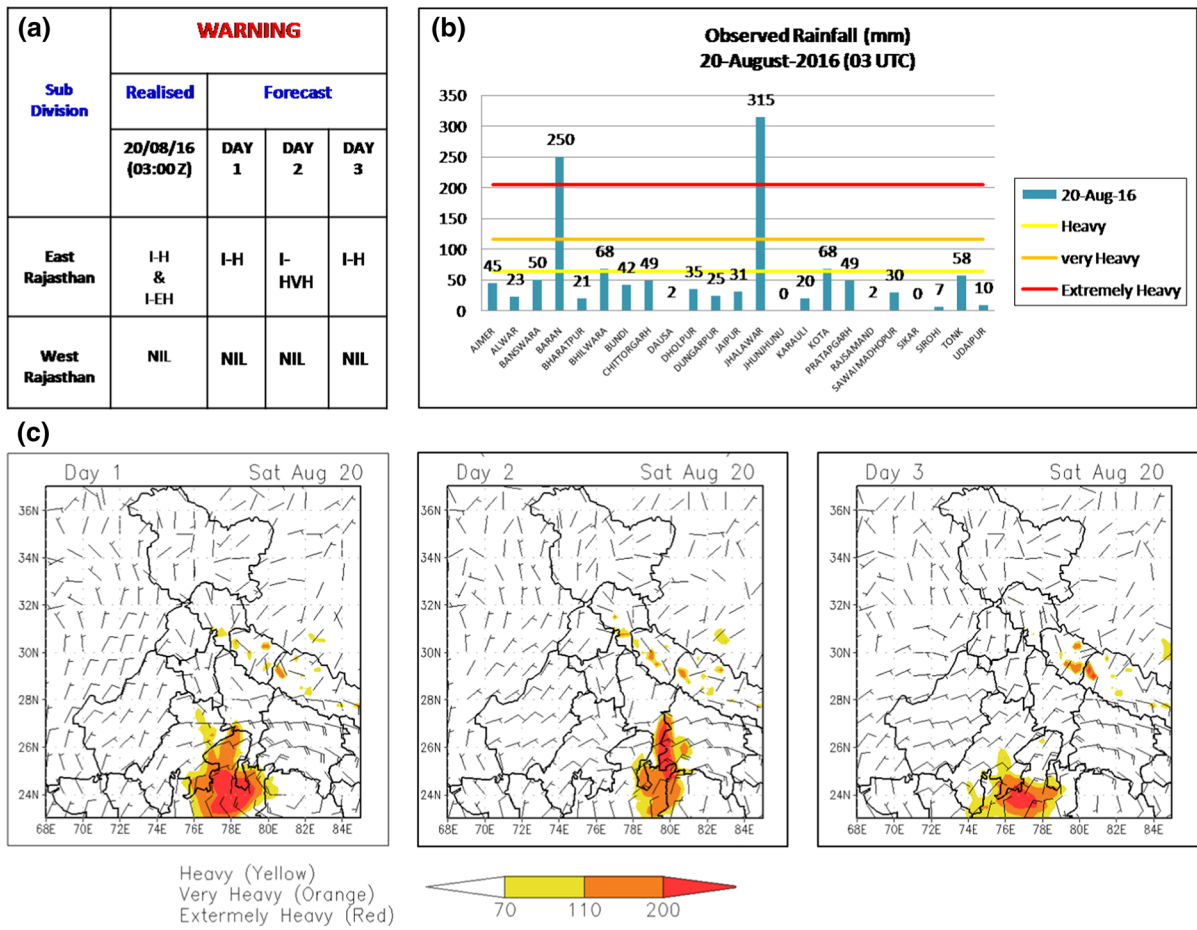


Figure 19

a Warning issued and actual realized warnings for east and west Rajasthan. **b** Stationwise actual recorded rainfall. **c** Wind pattern with overlaid heavy rainfall warnings valid at 03 UTC of 20 August 2016. (I-EH, I-HVH and I-H indicates isolated extremely heavy rainfall, isolated heavy to very heavy rainfall and isolated heavy rainfall, respectively)

isolated heavy rainfall (HR) warning is issued for east Rajasthan in D1, D2 and D3, but it is under warning as isolated places of east Rajasthan have received EHR amount of rainfall.

Figure 19b depicts the stationwise actual rainfall received at all districts of east Rajasthan on 19 August 2016. Out of 23 districts of east Rajasthan, 2 districts of east Rajasthan, namely Jhalawar and Baran, received HER amounts of 31.5 and 25.0 cm, respectively, and two districts namely Bhilwara and Kota received heavy rainfall of 6.8 cm. Less than 25% of the district of east Rajasthan received heavy rainfall or more on 19 August 2016, and isolated heavy rainfall with isolated extremely heavy rainfall occurred over east Rajasthan.

Figure 19c illustrates D1, D2 and D3 wind pattern at 850 hPa for 03 UTC of 19 August and overlaid heavy rainfall warnings between 03 UTC of 19 August to 03 UTC of 20 August 2016 as predicted by the NCEP GFS model. NCEP model has predicted isolated HR (with isolated EHR) warning for D1 and D3 for east Rajasthan and no warning for west Rajasthan for D1, D2 and D3. The model predicted EHR and VHR warning for Baran Jhalawar and neighboring areas in the D1 and D3 forecast. Overall, NCEP model has predicted isolated HR with isolated EHR warning for D1 and D3 over east Rajasthan and no warning for west Rajasthan for D1 and D3 (Fig. 19c).

4.2.4.2 EHR Warning for 20 August 2016 The model predicted mostly northeasterly wind pattern over east Rajasthan in the D1, D2 and D3 forecast, similar to the analyzed/observed wind at 850 hPa. As shown in Fig. 20a, real-time warning issued by RWFC for east Rajasthan in D1 bulletins is scattered VHR (with isolated VHR) warning; in D2 and D3 bulletins, the warning is isolated VHR. The actual realized weather for east Rajasthan was scattered VHR (with isolated EHR).

Figure 20b depicts the stationwise actual rainfall received at all districts of east Rajasthan 03 UTC of 20 August to 03 UTC of 21 August 2016. Out of 23 districts of east Rajasthan, 3 districts received more

than the HER amount of 20.4 cm, 1 district, Jhalawar, received very heavy rainfall of 16.8 cm and three districts, namely Bhilwara, Dungarpur and Kota, received heavy rainfall of 6.4 and 11.4 cm. 30% of the district of east Rajasthan received heavy rainfall or more on 20 August 2016, and scattered heavy rainfall with isolated extremely heavy rainfall occurred over east Rajasthan.

Figure 20c depicts D1, D2 and D3 heavy rainfall warnings predicted by the model between 03 UTC of 20 August and 03 UTC of 21 August 2016. The model predicted isolated VHR (with isolated EHR warning) for D1 and D2 and isolated HR warning for east Rajasthan in the D3 forecast. The model

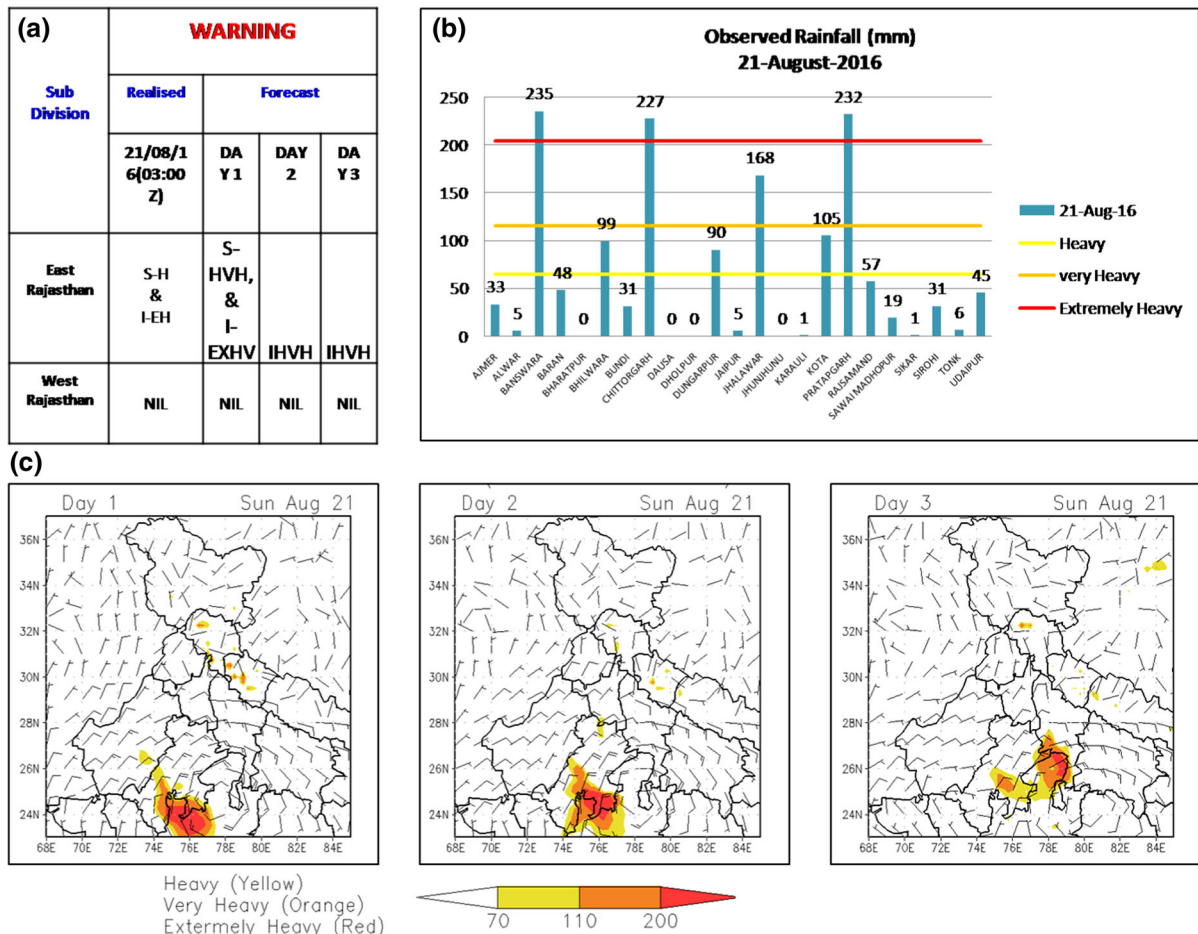


Figure 20

a Warning issued and actual realized warnings for east and west Rajasthan. b Stationwise actual recorded rainfall. c Wind pattern with overlaid heavy rainfall warnings valid at 03 UTC of 21 August 2016. (S-H, I-EXHV, S-HVH and I-HVH indicate scattered heavy rainfall, isolated extremely heavy rainfall, scattered heavy to very heavy rainfall and isolated heavy to very heavy rainfall, respectively)

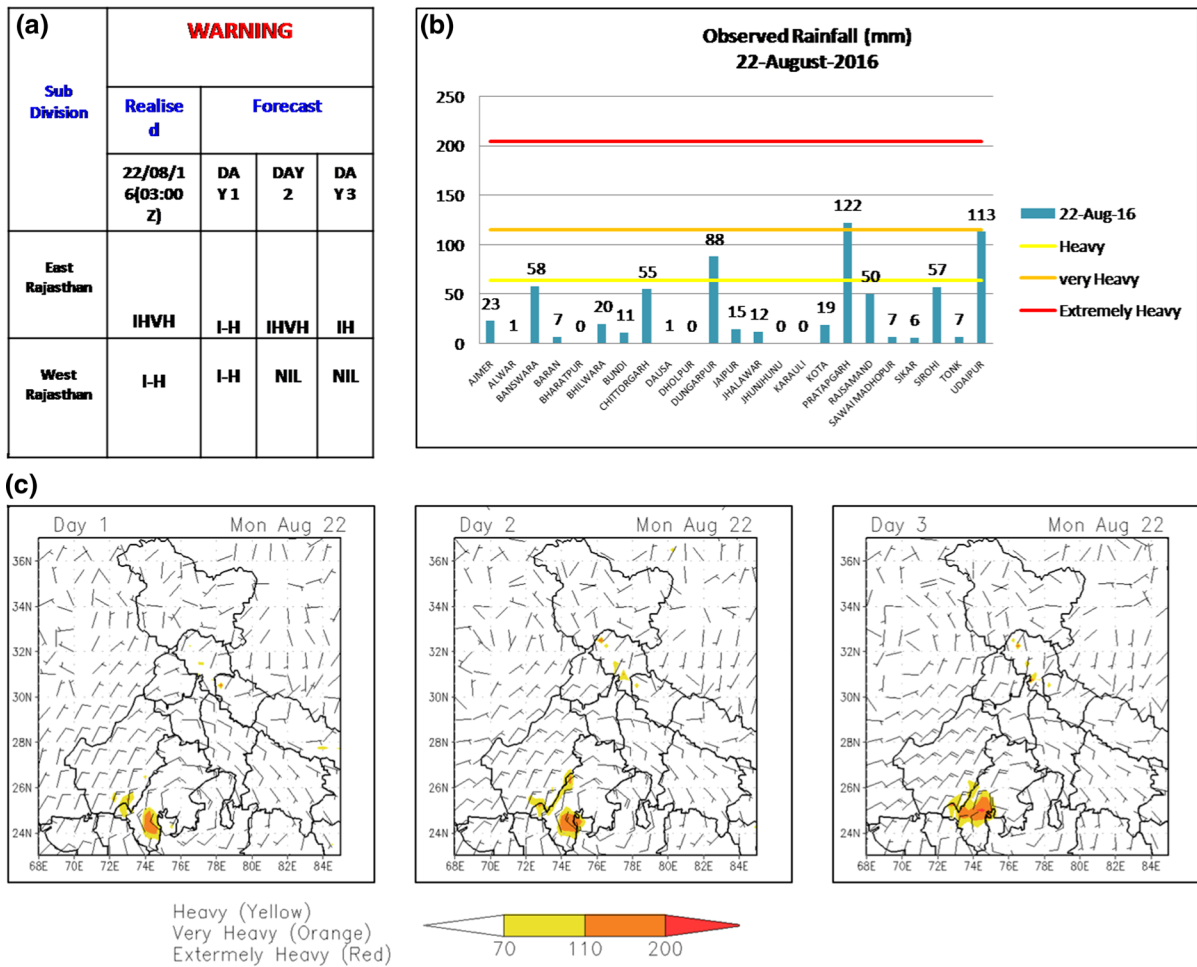


Figure 21

a Warning issued and actual realized warnings for east and west Rajasthan. **b** Stationwise actual recorded rainfall. **c** Wind pattern with overlaid heavy rainfall warnings valid at 03 UTC of 22 August 2016. (I-HVH and I-H indicates isolated heavy to very heavy rainfall and isolated heavy rainfall, respectively)

predicted EHR warning for Chittorgarh, Bundi, Kota and Jhalawar districts, and VHR and HR warnings for Rajsamand, Bhilwara, Pali and Jodhpur districts of east Rajasthan for D1 and D2. For D3, the model predicted VHR and HR warnings for Bundi, Bhilwara, Kota and Baran districts of east Rajasthan.

4.2.4.3 EHR Warning for 21 August 2016 The model predicted mostly northerly northeasterly wind pattern over east Rajasthan in the D1, D2 and D3 forecast, which is similar to the analyzed/observed wind shown at 850 hPa. As shown in the Fig. 21a, warning issued was up to the level of isolated HR in

D1 and D3 and isolated VHR in D2, while the realized warning was isolated VHR over east Rajasthan.

Figure 21b depicts the stationwise actual rainfall received at all districts of east Rajasthan on 21 August 2016. Out of 23 districts of east Rajasthan, only 1 district, Pratapgarh, received very heavy rainfall of 12.2 cm and two districts, namely Udaipur and Dungarpur, received heavy rainfall of 11.3 and 8.8 cm, respectively. Less than 25% of the districts of east Rajasthan received heavy rainfall or more on 21 August 2016, and isolated heavy rainfall with isolated very heavy rainfall occurred over east Rajasthan.

Figure 21c depicts D1, D2 and D3 heavy rainfall warnings predicted by the NCEP GFS model for the duration 03 UTC of 21 August to 03 UTC of 22 August 2016. The model predicted VHR and HR warning for Chittorgarh, Udaipur, Pratapgrah and Banswara districts of east Rajasthan in D1 and D2. The D3 forecast model predicted isolated VHR (with isolated EHR) warnings for Chittorgarh, Bhilwara, Rajsamand and Pali districts of southern parts of east Rajasthan.

5. Conclusions

Based on the predictions given by the NCEP GFS model for two cases (07–09 August and 19–21 August 2016) for heavy rainfall and with their application in real-time rainfall forecast and warning issued by the Regional Weather Forecasting Center (RWFC), the following conclusions can be drawn:

- (i) Heavy rainfall warning for day 1 and day 2 are issued well in advance by RWFC and all the warnings are realized for both the cases; however, the issued warnings were slightly underestimated by the model. The main reason for occurrence of such extremely heavy rainfall may be that south-east Rajasthan was under the southwest sector of low pressure/depression. After reaching a low pressure/depression over east Rajasthan, sufficient amount of moisture supply from the Arabian Sea is obtained. Apart from that, the Arawali Hills block/slow down further westward movement of the system and the maximum amount of rainfall occurs in east Rajasthan as compared to west Rajasthan.
- (ii) It may also be concluded that the model predicted wind pattern and extremely heavy rainfall (EHR) associated with the low-pressure system/deep depression in both the cases very accurately in the day 1 and day 2 forecasts and with slight error in intensity and space for day 3. The model also predicted the location of cyclonic circulation with a fair degree of accuracy.

Hence, NCEP GFS model forecast provides very good guidance to the weather forecaster for issuing

heavy rainfall warnings. However, more cases need to be investigated.

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