Influence of Initial Condition in global forecast system model (GFS T1534) for predicting Heavy and Extreme Rainfall over India

A project report submitted for the fulfillment of Summer Internship at

INDIAN INSTITUTE OF TROPICAL METEOROLOGY, PUNE

By

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DECLARATION

I hereby declare that the Summer Internship Report entitled "**Influence of Initial Condition in global forecast system model (GFS T1534) for predicting Heavy and Extreme Rainfall over India**" prepared by me under the guidance of **Dr. Malay Ganai, Scientist-D, Forecasting Research Division, Indian Institute of Tropical Meteorology, Pune**, is a bonafide work undertaken by me in time-span of summer internship and submitted to the Indian Institute of Tropical Meteorology, Pune in completion of the summer internship for the award of internship certificate. It has not been submitted to any other University or Institute for the award of any degree/diploma/certificate.

Arindam Ghosh

Place: IITM, Pune

CERTIFICATE

This is to certify that the Summer Internship Report entitled "**Influence of Initial Condition in global forecast system model (GFS T1534) for predicting Heavy and Extreme Rainfall over India**" is an authentic work carried out by **Mr. Arindam Ghosh**, Summer Intern, under my guidance at Indian Institute of Tropical Meteorology, Pune, from 21 May 2024 to 19 July 2024.

Dr. Malay Ganai

Scientist D

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ACKNOWLEDGEMENT

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I am grateful to Indian Institute of Tropical Meteorology, Pune for providing me with the opportunity to work in such a stimulating and enriching environment. I also would like to thank the community of scientists, research associates, scholars, fellow interns, and lab associates who generously shared their knowledge and experiences with me throughout my time in the lab. Once again thanks to all who have directly or indirectly played a part in making my summer internship experience so meaningful. Each interaction, whether it was a discussion or a shared experience, has indelibly contributed to my personal and professional growth.

Arindam Ghosh

Place: IITM, Pune

1. Introduction

Extreme rainfall events have profound social and economic implications, particularly in a country like India, where the monsoon season significantly influences agriculture, water resources, and overall livelihood. These heavy to extreme rainfall episodes often lead to devastating floods (Guhathakurta et al., 2011) , landslides, and other natural disasters, resulting in loss of life, displacement of populations, and extensive damage to infrastructure.

According to India Meteorological Department (IMD), Heavy rainfall is typically defined as rainfall that exceeds 64.5 mm in a 24-hour period, while extreme rainfall refers to precipitation that surpasses 204.5 mm in the same duration. These definitions help in categorizing the intensity of rainfall events and assessing their potential impacts on different regions.

The ability to predict such events accurately is crucial for early warning systems and disaster management, helping to mitigate their adverse effects on society. However, predicting extreme rainfall remains a formidable challenge for weather forecast models. The inherently chaotic nature of the atmosphere, coupled with the complex interactions between various meteorological variables, makes it difficult to achieve precise forecasts (Goswami et al., 2006). Traditional models often struggle with the spatial and temporal resolution required to accurately capture the intensity and distribution of extreme rainfall events (Sperber & Palmer, 1996). Additionally, the monsoon dynamics in the Indian subcontinent add another layer of complexity, further complicating prediction efforts. The increasing trend of extreme rain events over India in a warming environment further complicates prediction efforts, making it essential to refine and improve existing forecast models (Goswami et al., 2006).

Initial condition represents the state of the atmosphere at the beginning of the forecast period, and is a very important factor in determining the accuracy of weather predictions. Accurate and comprehensive initial conditions enable models to simulate the atmospheric processes more reliably, leading to better forecasts (Kalnay et al., 1996). Any inaccuracies or uncertainties in the initial conditions can propagate through the model, resulting in significant errors in the predicted outcomes (Saha et al., 2010). Therefore, understanding and improving the initial conditions is essential for enhancing the predictability of extreme rainfall events.

Additionally, different initialization times (such as 00Z, 06Z, and 12Z) for the same weather event can significantly impact the forecast. This is because atmospheric conditions can change rapidly, and slight variations in initial conditions at different times can lead to divergent predictions as the forecast progresses. Meteorological models often run multiple simulations with slightly varied initial conditions (ensemble forecasting) to capture this variability and provide a range of possible outcomes, aiding in more robust forecasting of extreme events.

This report aims to investigate how initial conditions play a crucial role in predicting heavy to extreme rainfall over India during the monsoon season. By examining different scenarios and analyzing the sensitivity of weather models to initial conditions, this study seeks to identify key factors that enhance forecast accuracy and contribute to more effective early warning systems.

2. Data, Model and Methodology

The National Centers for Environmental Prediction (NCEP) Global Forecast System (GFS T1534) is a weather forecasting model adopted for short to medium range weather forecast system in India under national Monsoon Mission. It is a global numerical weather prediction system that produces forecasts for up to 10 days in the future. GFS uses a global spectral model (GSM) with a resolution of approximately 12.5 kilometers (0.25 degrees) horizontally and 64 hybrid vertical levels (top layer around 0.27 hPa) in the atmosphere. It assimilates a wide range of observational data to initialize its forecasts, including satellite data, radiosonde observations, and surface observations. The model is being run at the Ministry of Earth Sciences high power-computer (HPC) facility 'Pratyush' at Indian Institute of Tropical Meteorology (IITM), Pune (Mukhopadhyay et al., 2019).

To validate the model forecast, the daily observed gridded rainfall data at 0.25°×0.25° resolution is utilized from India Meteorological Department (IMD) for JJA of 2020-2023. These data are merged product of gridded rain gauge observations and Global Precipitation Measurement (GPM) satellite-estimated rainfall data over the ISM region (Mitra et al., 2014). GPM is a joint mission between NASA and the Japan Aerospace Exploration Agency (JAXA), providing global precipitation estimates with high spatiotemporal resolution using satellite observations (Hou et al., 2014). In addition to rainfall data, various other satellite and reanalysis-based parameters are also used to further investigate model performance. ERA5 is the latest global atmospheric reanalysis produced by the European Centre for Medium-Range Weather Forecasts (ECMWF). ERA5 reanalysis based (Dee et al. 2011) wind, vertical velocity (omega) and relative humidity

(RH) are utilized to validate the corresponding model forecasts for the Indian summer monsoon of 2020 to 2023.

For this study, we conducted a comprehensive analysis using satellite and reanalysis data to investigate daily precipitation patterns and atmospheric dynamics over India during the monsoon season. Here is a detailed description of the methodology employed:

We utilized IMD-GPM merged data to create daily precipitation spatial plots and extracted ERA5 reanalysis data to calculate atmospheric parameters such as horizontal divergence (hdivg), moisture convergence (mconv), and omega. Vertical profiles of these atmospheric variables were plotted to examine their variations with altitude, providing insights into the vertical structure of weather systems contributing to heavy to extreme rainfall events over India. To calculate horizontal divergence (hdivg) and moisture convergence (mconv) from ERA5 data, we used the following formulas:

$$\text{hdivg} = -\frac{\partial u}{\partial x} - \frac{\partial v}{\partial y}$$

$$\text{mconv} = -\frac{\partial (q \cdot u)}{\partial x} - \frac{\partial (q \cdot v)}{\partial y}$$

where:

- u and v are the zonal (eastward) and meridional (northward) wind components, respectively.
- x and y are the longitude and latitude coordinates.
- q is specific humidity.

We utilized model predictions with multiple initial conditions (00Z, 06Z, 12Z) for the same event to compare forecast outcomes with observed GPM rainfall data. This approach allowed us to assess the variability and consistency of predictions across different initializations. Similarly, we conducted the same analysis for atmospheric parameters such as horizontal divergence (hdivg), moisture convergence (mconv), and vertical velocity (omega) in vertical profiles.

3. Result and Discussion

Daily precipitation spatial plots were created from GPM data to visualize and analyze the distribution and intensity of rainfall over the Indian subcontinent. Using these data, we have selected several heavy to extreme rainfall (RF) events over India for detailed analysis. The selected events are summarized in the table below:

Date	Location		Accumulated Precipitation (mm/day)
	Latitude (°N)	Longitude (°E)	
2 July 2020	26.25	89	305.29599
6 August 2020	12.25	75.5	385.6877747
	13	75.5	371.8261108
15 August 2020	20.75	86	328.4890137
	20.75	86.25	358.6130371
12 July 2021	18.25	73	386.4437866
13 July 2021	32.25	76.5	251.9676056
3 August 2021	25.25	77.5	317.0106201
31 August 2021	20.0	72.75	221.80039978027344
17 June 2022	25.25	90.75	441.0889893
	25.25	91	364.1610107
	25.25	91.75	965.8936768
5 July 2022	17.0	73.5	290.467529296875
9 July 2023	32.0	77.0	470.225006103515
27 July 2023	18.25	79.75	417.84976196289

Table 1. Selected Extreme rainfall events over India during 2020-23 JJA

From Table 1, we selected each event and plotted the rainfall spatial distribution, highlighting the high rainfall areas with a red box. We performed the same analysis for the Day-1 and Day-2 GFS forecast data with three initial conditions: 00Z, 06Z, and 12Z. Additionally, we calculated the area-averaged precipitation within the red box for all data sets and created a bar graph to visualize the results.

For the event on 2 July 2020:

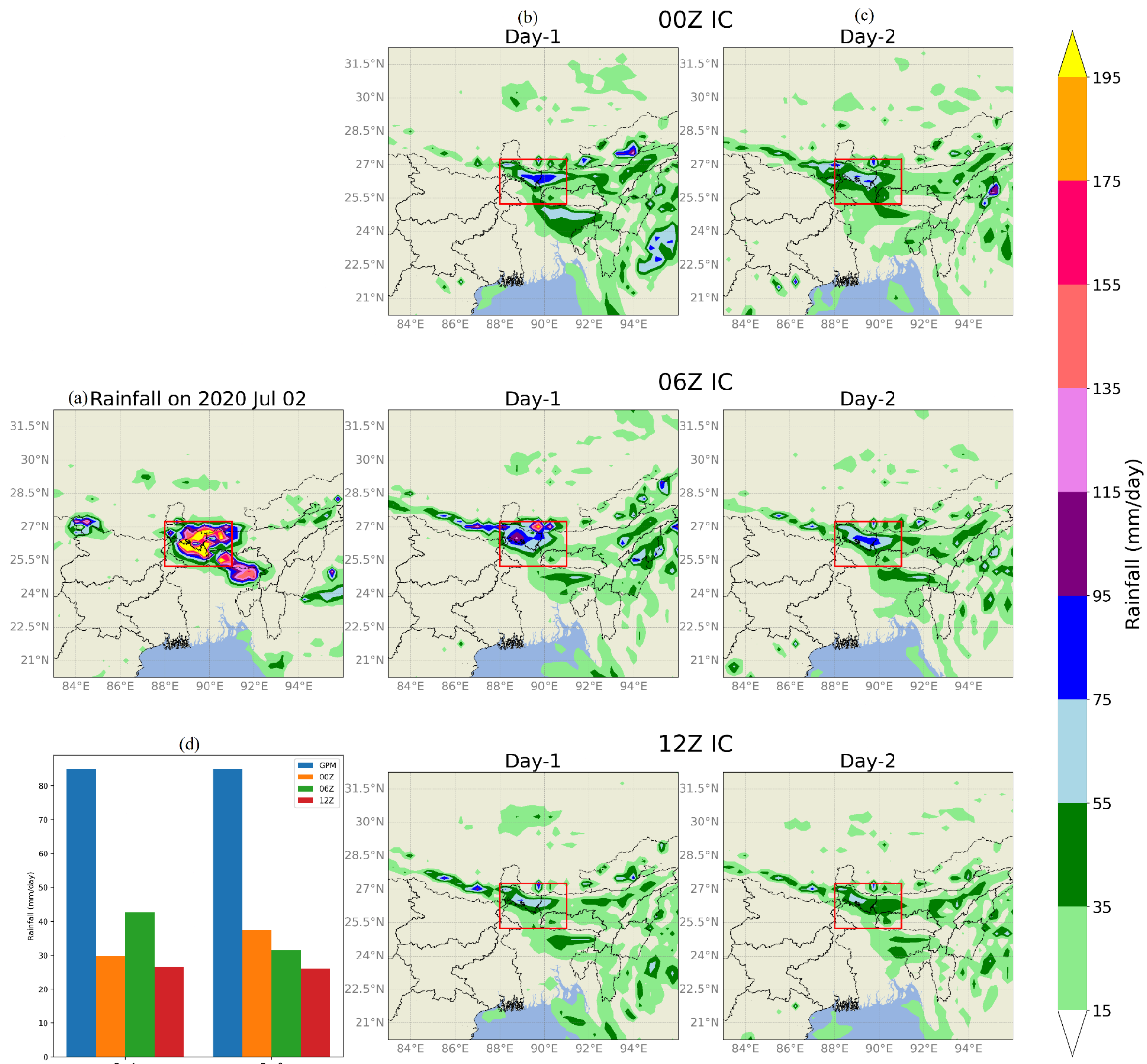

Figure 1. Spatial distribution of (a) Observed rainfall (mm/day) and GFS model forecast with (b) Day-1 and (c) Day-2 lead time with 3 different initial conditions (00Z, 06Z, 12Z) on 2 July, 2020 and (d) area-averaged precipitation within the red box.

In Figure 1a., the observed rainfall shows a concentrated area of heavy rainfall over North Bengal and some parts of Assam and Meghalaya, with rainfall intensities reaching more than 300 mm/day.

For all ICs and all days, the model captured the location of rainfall event reasonably well but the magnitude of rainfall was underestimated. But, for the 06Z initial condition, the Day-1 prediction captures the location and magnitude of rainfall slightly better than other ICs. Also in the bar graph (Fig 1d), the area-averaged precipitation within the red box shows, for Day-1, 06Z IC is closest to the observed value. Overall, all ICs underestimated the rainfall intensity.

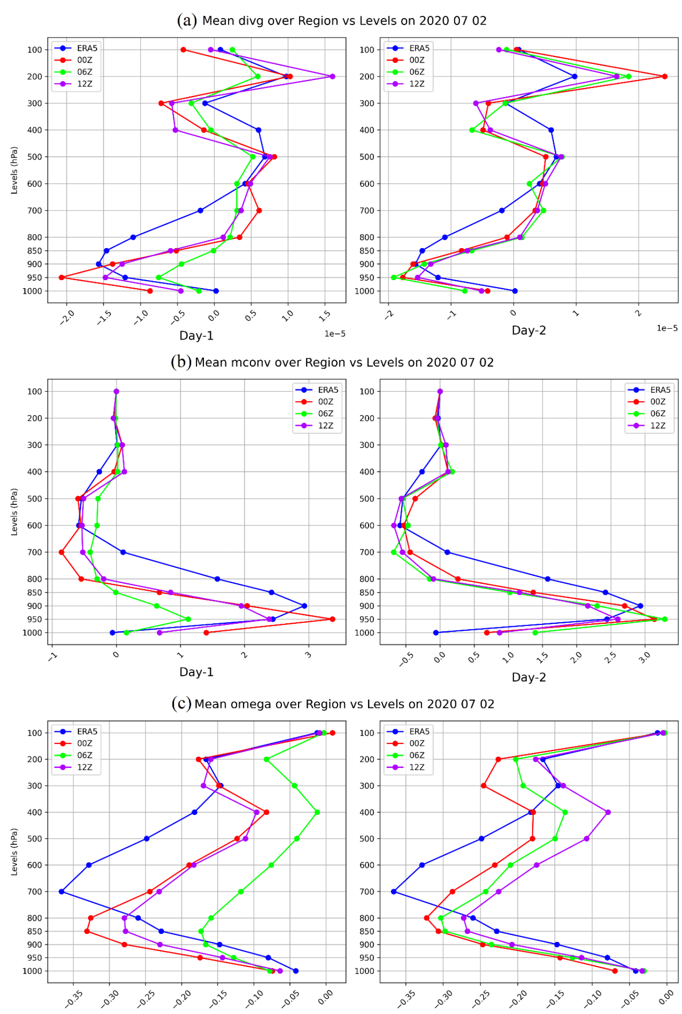

Figure 2. Vertical profiles of (a) divergence (divg, /s), (b) moisture convergence (mconv, /s), and (c) omega (hPa/s) over the red box (Fig 1) on July 2, 2020, derived from ERA5 reanalysis data (blue) and 00Z (red), 06Z (green), 12Z (purple) model forecast outputs.

In order to investigate the large-scale dynamical processes associated with the heavy rainfall event, various dynamical parameters namely divergence, moisture convergence and vertical velocity are shown in Figure 2. It is found that 00Z IC shows maximum lower level wind convergence (Fig. 2a) and moisture convergence (Fig. 2b) associated with strong ascending vertical motion (Fig. 2c) for Day-1 and Day-2 lead time. It is expected that the maximum convection and associated precipitation should be associated with stronger large-scale dynamical features. However, in this case, it is noted that the maximum rainfall from 06Z IC (Figure 1d) does not have the stronger dynamical processes (Fig. 2a-2c). Further investigation is required to ascertain the actual reason behind it. Nonetheless, it is noted that the precipitation (both intensity and location) is better captured with 06Z initial condition as compared to 00Z and 12Z IC.

For the event on 6 August, 2020:

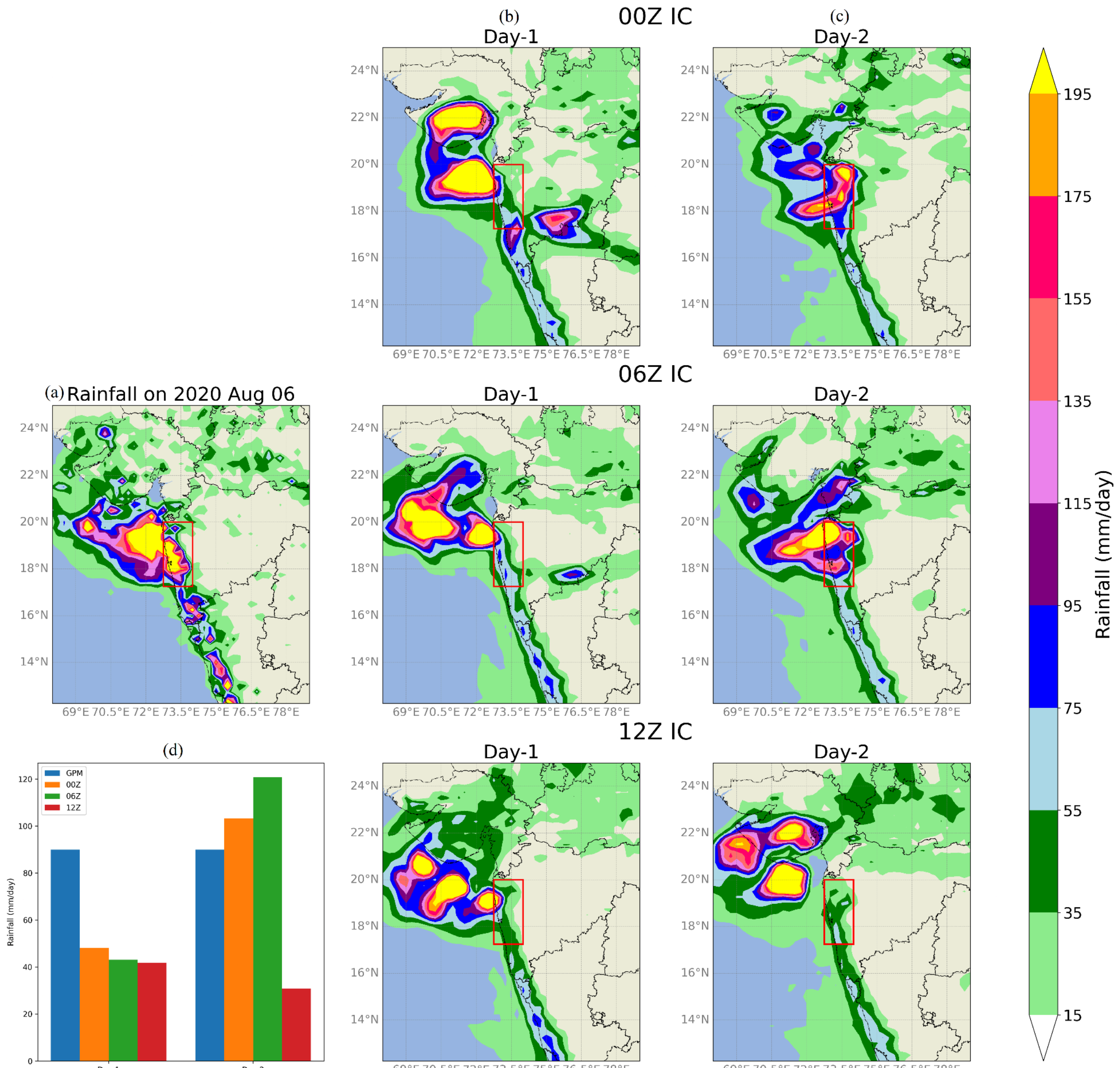

Figure 3. Spatial distribution of (a) Observed rainfall (mm/day) and GFS model forecast with (b) Day-1 and (c) Day-2 lead time with 3 different initial conditions (00Z, 06Z, 12Z) on 6 August, 2020 and (d) area-averaged precipitation within the red box.

In Figure 3a., the observed rainfall shows a highlighted area of heavy rainfall over Maharashtra and Arabian sea with rainfall intensities reaching more than 350 mm/day.

The model has captured the location of heavy rainfall event quite well in (Fig 3c) Day-2 with 00Z, 06Z ICs. But in Day-1 forecasts and Day-2 12Z forecast, the location is slightly shifted to north-west over Arabian sea and some parts of Gujrat. The bar graph (Fig 3d) shows Day-2 00Z and 06Z has slightly overestimated rainfall over the red box.

From Figure 4., we can see in Day-1, in the lower level all parameters are slightly underestimated in all ICs, but in higher levels well estimated. In Day-2, the model has overestimated vertical velocity at higher levels, which associates positively with rainfall intensity in Fig 3d. In Day-2, other parameters are quite well predicted across all the levels. Overall, the precipitation and other atmospheric parameters are better captured in Day-2 lead time with both 00Z and 06Z initial conditions.

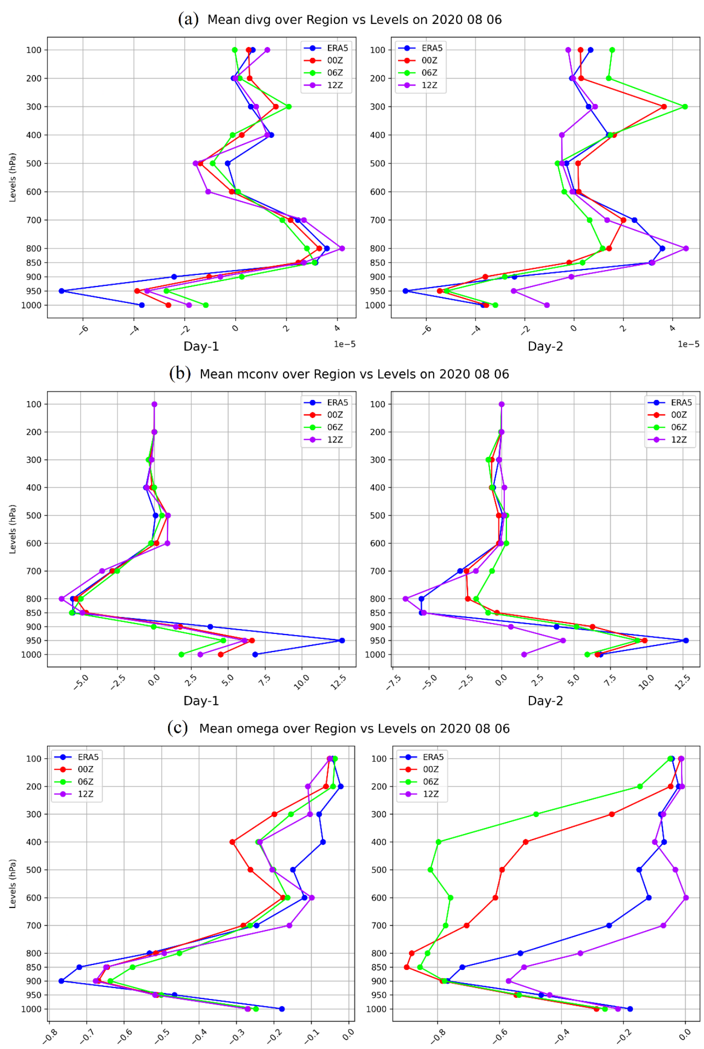

Figure 4. Vertical profiles of (a) divergence (divg, /s), (b) moisture convergence (mconv, /s), and (c) omega (hPa/s) over the red box (Fig 3) on August 6, 2020, derived from ERA5 reanalysis data (blue) and 00Z (red), 06Z (green), 12Z (purple) model forecast outputs.

For the event on 15 August, 2020:

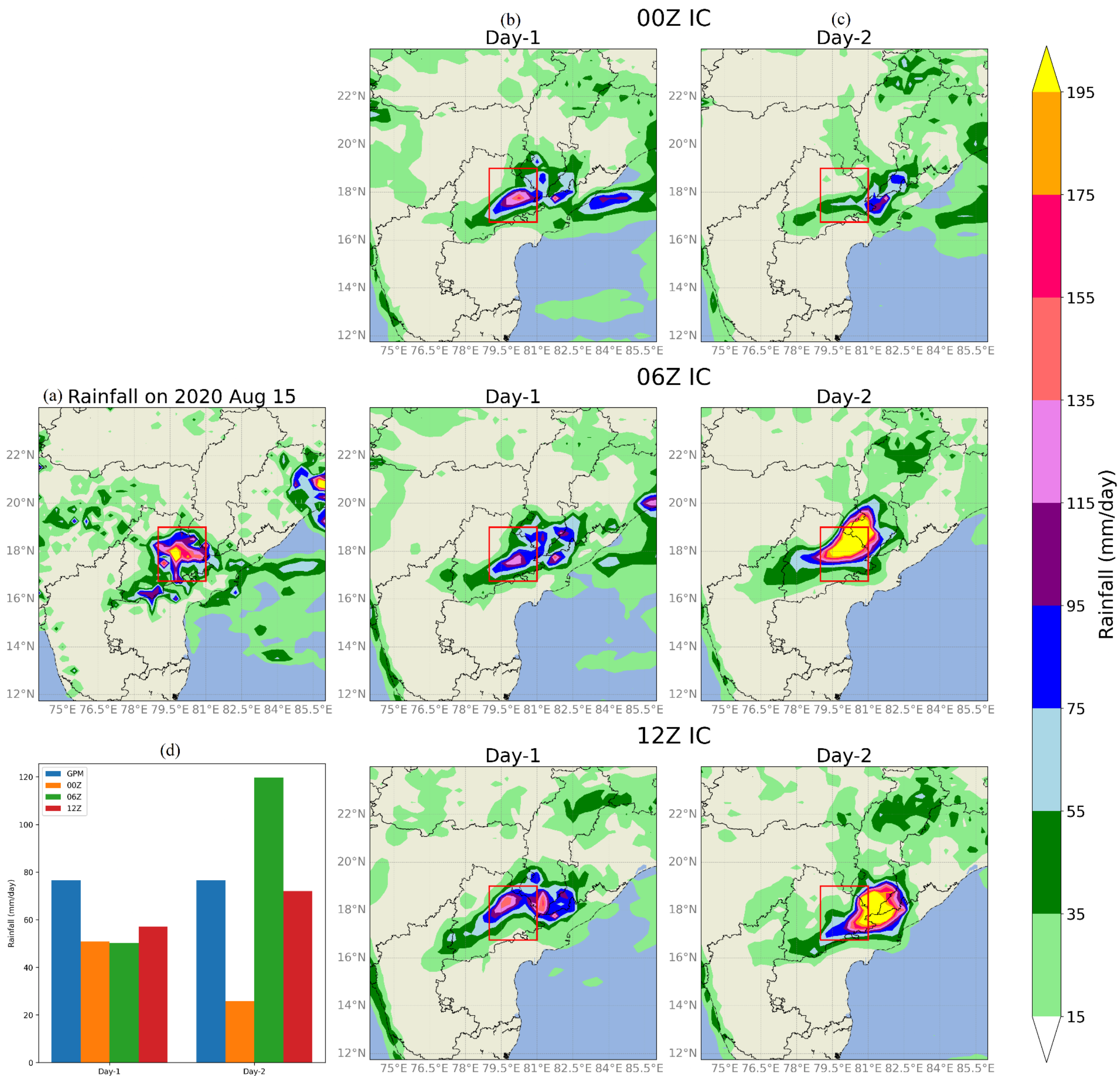

Figure 5. Spatial distribution of (a) Observed rainfall (mm/day) and GFS model forecast with (b) Day-1 and (c) Day-2 lead time with 3 different initial conditions (00Z, 06Z, 12Z) on 15 August, 2020 and (d) area-averaged precipitation within the red box.

In Figure 1a, the observed rainfall indicates a concentrated zone of heavy precipitation over Telangana, with intensities exceeding 300 mm/day.

From Figure 5b, Day-1 forecasts have captured the location of precipitation very well but underestimated the magnitude of rainfall in all ICs. In Day-2 (Fig-5c), 00Z has significantly underestimated the magnitude, but 06Z and 12Z have overestimated the magnitude. The predicted location from Day-2 12Z forecast is slightly shifted eastward from the observed location. But coincidentally, within the red box, the area-averaged rainfall from observations and the forecast output for Day-2 12Z IC are very close (Fig. 5d).

From Figure 6., horizontal divergence in Day-1 is slightly underestimated in 700-800 hPa levels, for all ICs and moisture convergence is slightly overestimated for the same levels. In Day-2 forecast, 06Z IC shows maximum wind convergence in lower levels but also maximum wind divergence in higher levels, and it also has overestimated vertical velocity (Fig. 6c).

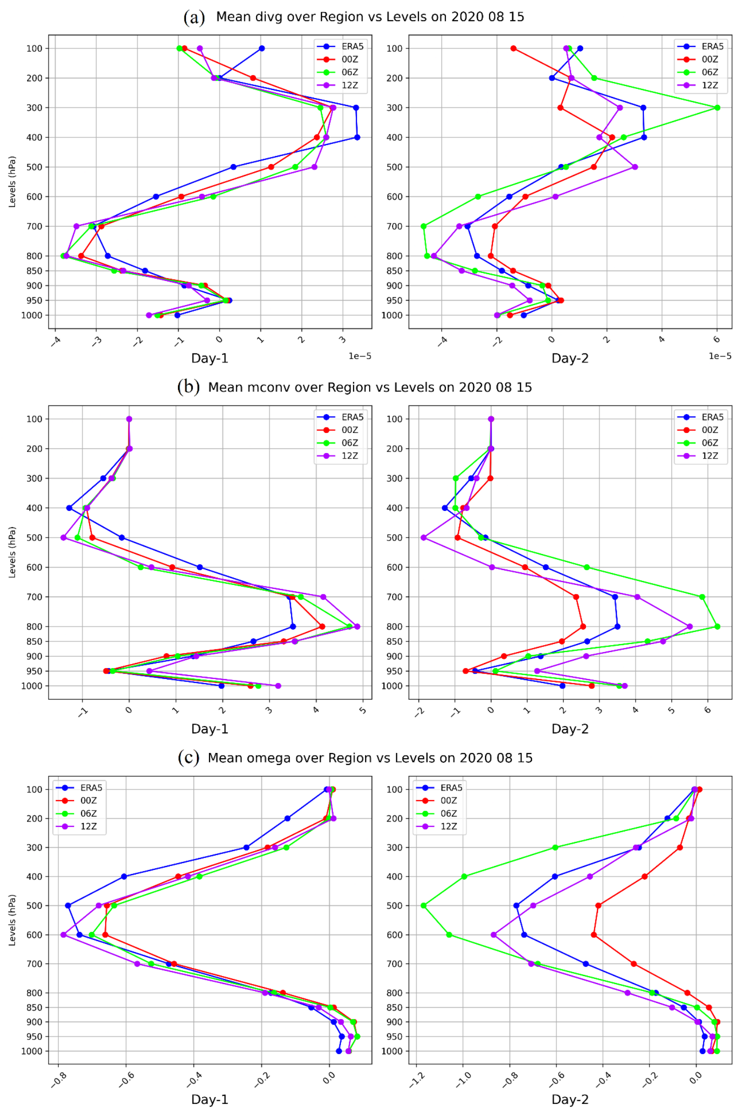

Figure 6. Vertical profiles of (a) divergence (divg, /s), (b) moisture convergence (mconv, /s), and (c) omega (hPa/s) over the red box (Fig 5) on August 15, 2020, derived from ERA5 reanalysis data (blue) and 00Z (red), 06Z (green), 12Z (purple) model forecast outputs.

Overall, though atmospheric parameters are well estimated in Day-1, precipitation (both intensity and location) is better captured with 12Z IC and Day-2 lead time.

For the event on 12 July, 2021:

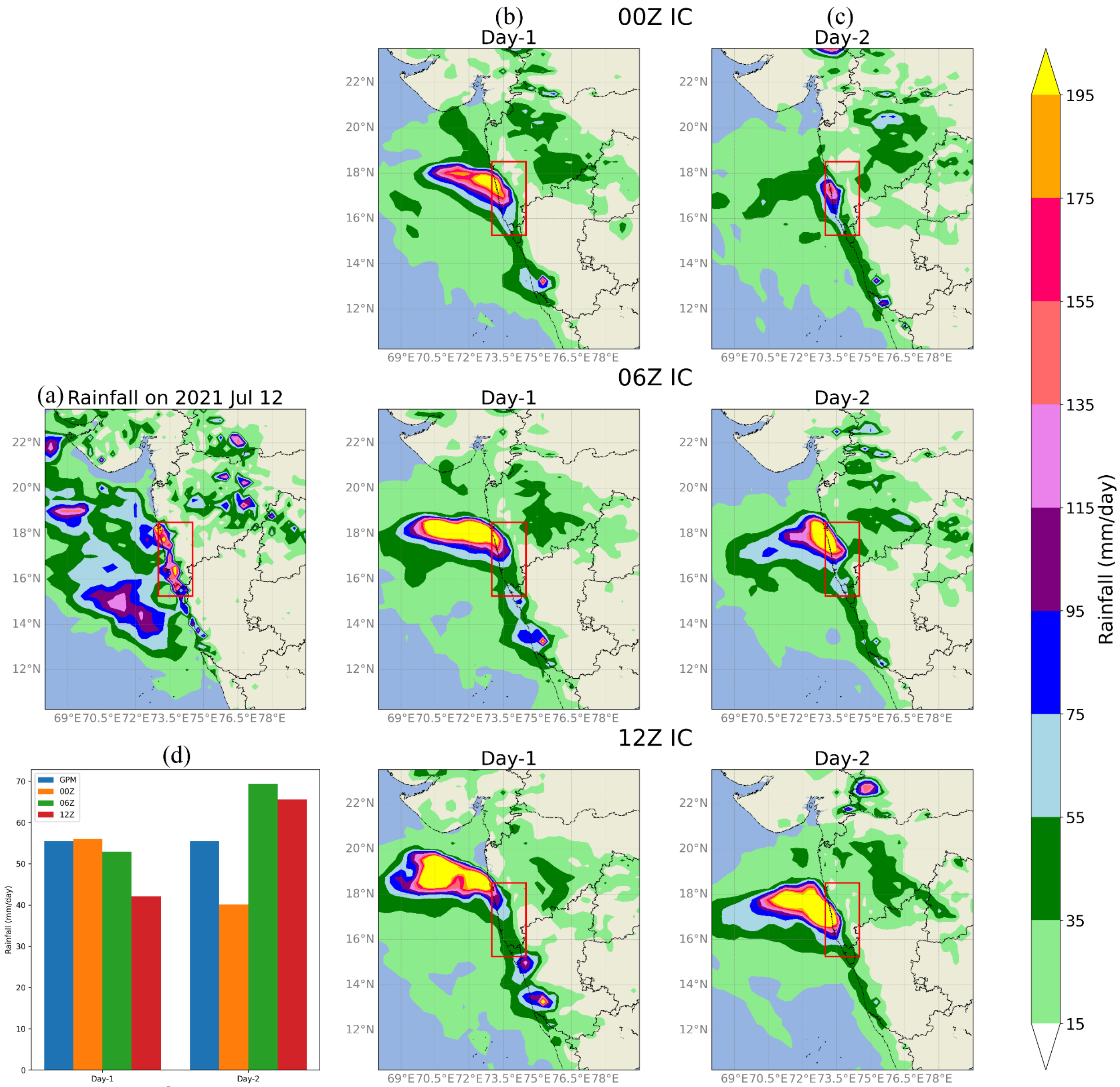

Figure 7. Spatial distribution of (a) Observed rainfall (mm/day) and GFS model forecast with (b) Day-1 and (c) Day-2 lead time with 3 different initial conditions (00Z, 06Z, 12Z) on 12 July, 2021 and (d) area-averaged precipitation within the red box.

In Figure 3a., the observed rainfall shows a concentrated area of heavy rainfall over Maharashtra with rainfall intensities reaching more than 350 mm/day.

In Day-1 forecasts, 00Z and 06Z IC have captured the location and magnitude both well, but in 12Z IC, the heavy rainfall area has shifted towards north-west. In Day-2 forecasts, 00Z IC has captured location good but underestimated magnitude. In 06Z and 12Z ICs, the model has overestimated rainfall magnitude (Fig 7d).

For both days, the model estimated less wind convergence in lower levels than observation (Fig 8a). Moisture convergence (Fig 8b) in both days is lesser than the observation in lower levels. Vertical velocity is underestimated in lower levels on both days. But in higher levels, on Day-2, 06Z and 12Z forecasts have overestimated omega, which associates with overestimated precipitation. Overall Day-1 forecasts with 00Z and 06Z IC have captured the heavy rainfall event well.

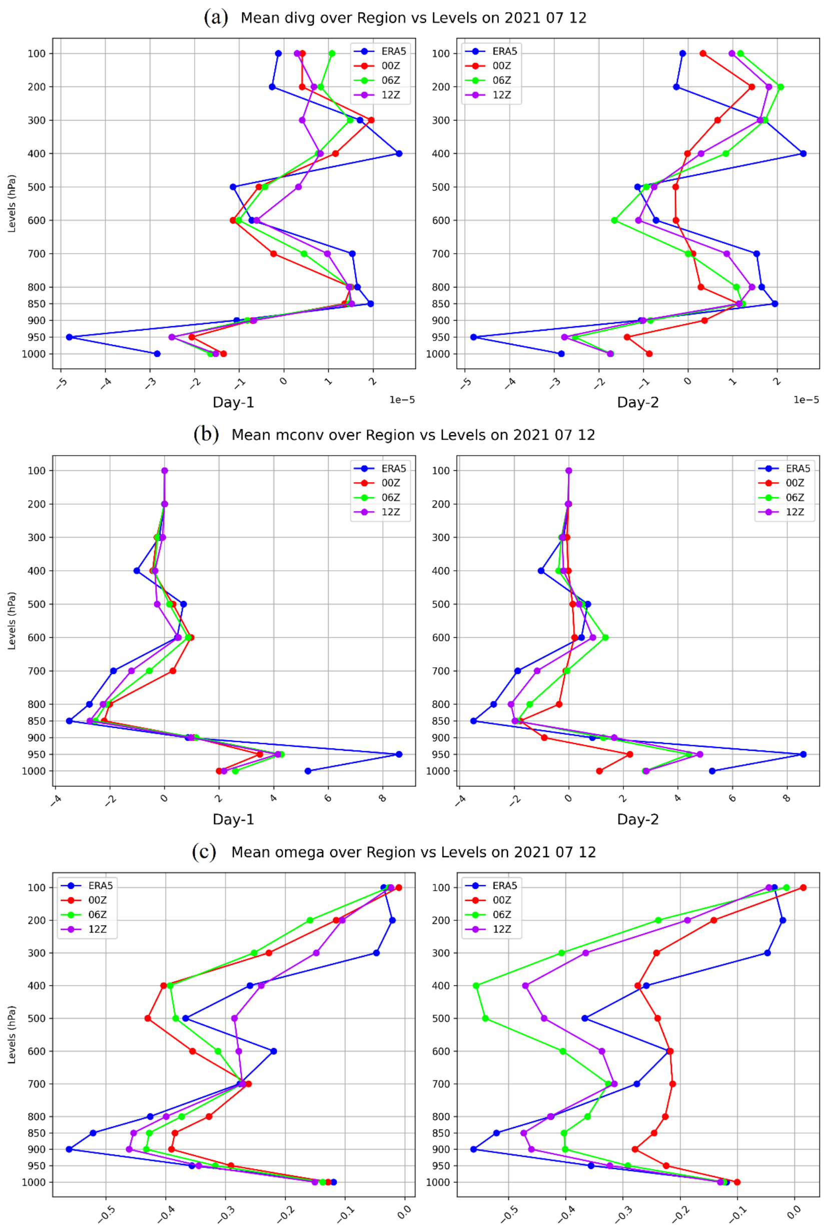

Figure 8. Vertical profiles of (a) divergence (divg, /s), (b) moisture convergence (mconv, /s), and (c) omega (hPa/s) over the red box (Fig 7) on 12 July, 2021, derived from ERA5 reanalysis data (blue) and 00Z (red), 06Z (green), 12Z (purple) model forecast outputs.

For the event on 13 July 2021:

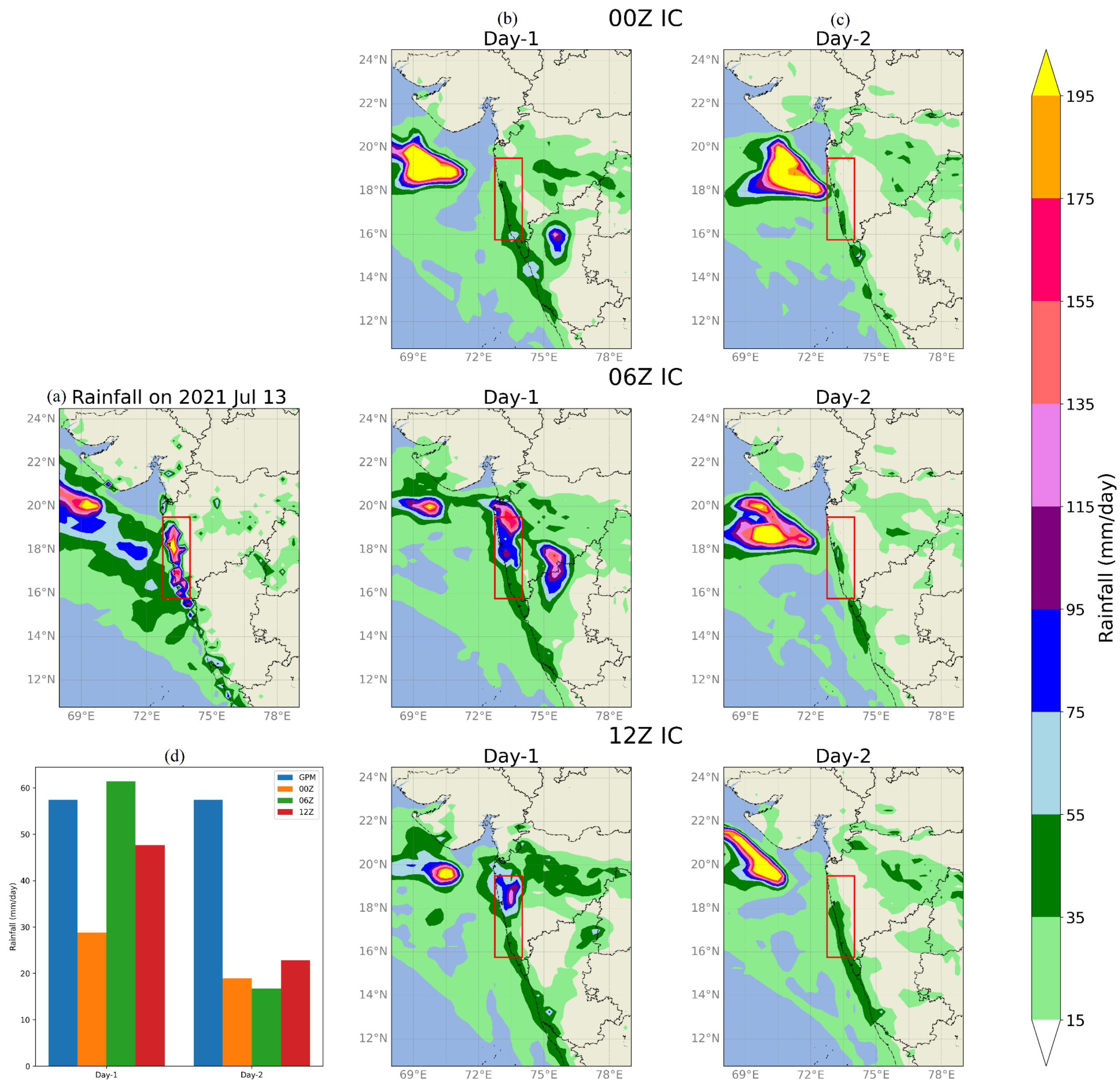

Figure 9. Spatial distribution of (a) Observed rainfall (mm/day) and GFS model forecast with (b) Day-1 and (c) Day-2 lead time with 3 different initial conditions (00Z, 06Z, 12Z) on 13 July, 2021 and (d) area-averaged precipitation within the red box.

Figure 9a. shows observed rainfall on 13 July, 2021 and we can see a heavy rainfall area over Maharashtra with maximum rainfall reaching 250 mm/day.

From Figure 9c., we can see that Day-2 forecasts could not at all capture the heavy rainfall event, but only a lighter rainfall. In Day-1 forecasts (Fig 9b), 06Z and 12Z IC have captured the location of the event with a little north-ward shift. From the bar graph (Fig 9d), Day-1 forecast with 06Z IC has captured event better than other forecasts.

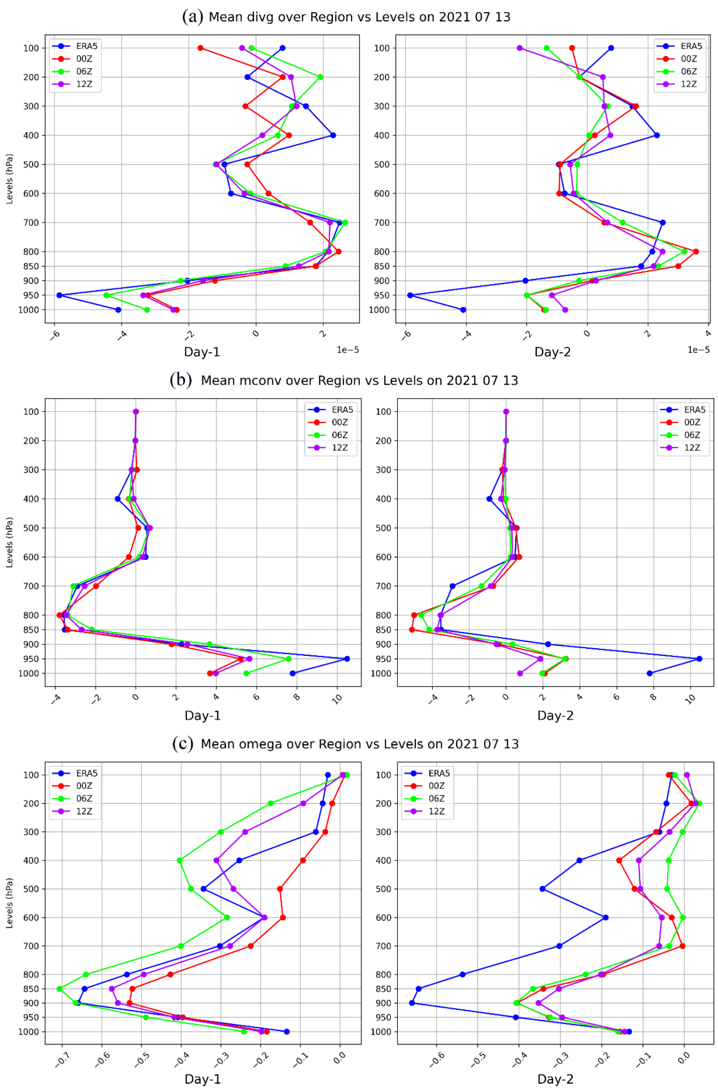

Figure 10. Vertical profiles of (a) divergence (divg, /s), (b) moisture convergence (mconv, /s), and (c) omega (hPa/s) over the red box (Fig 9) on 13 July, 2021, derived from ERA5 reanalysis data (blue) and 00Z (red), 06Z (green), 12Z (purple) model forecast outputs.

It is found that for Day-2 lead time, model has underestimated lower level wind convergence (Fig 10a) and moisture convergence (Fig 10b) associated with strong ascending vertical wind (Fig 10c). On Day-1 06Z IC forecast, ascending vertical wind (Fig 10c) is overestimated in all levels. Overall, the dynamical features are well captured in Day-1 06Z and 12Z IC forecasts.

For the event on 3 August, 2021:

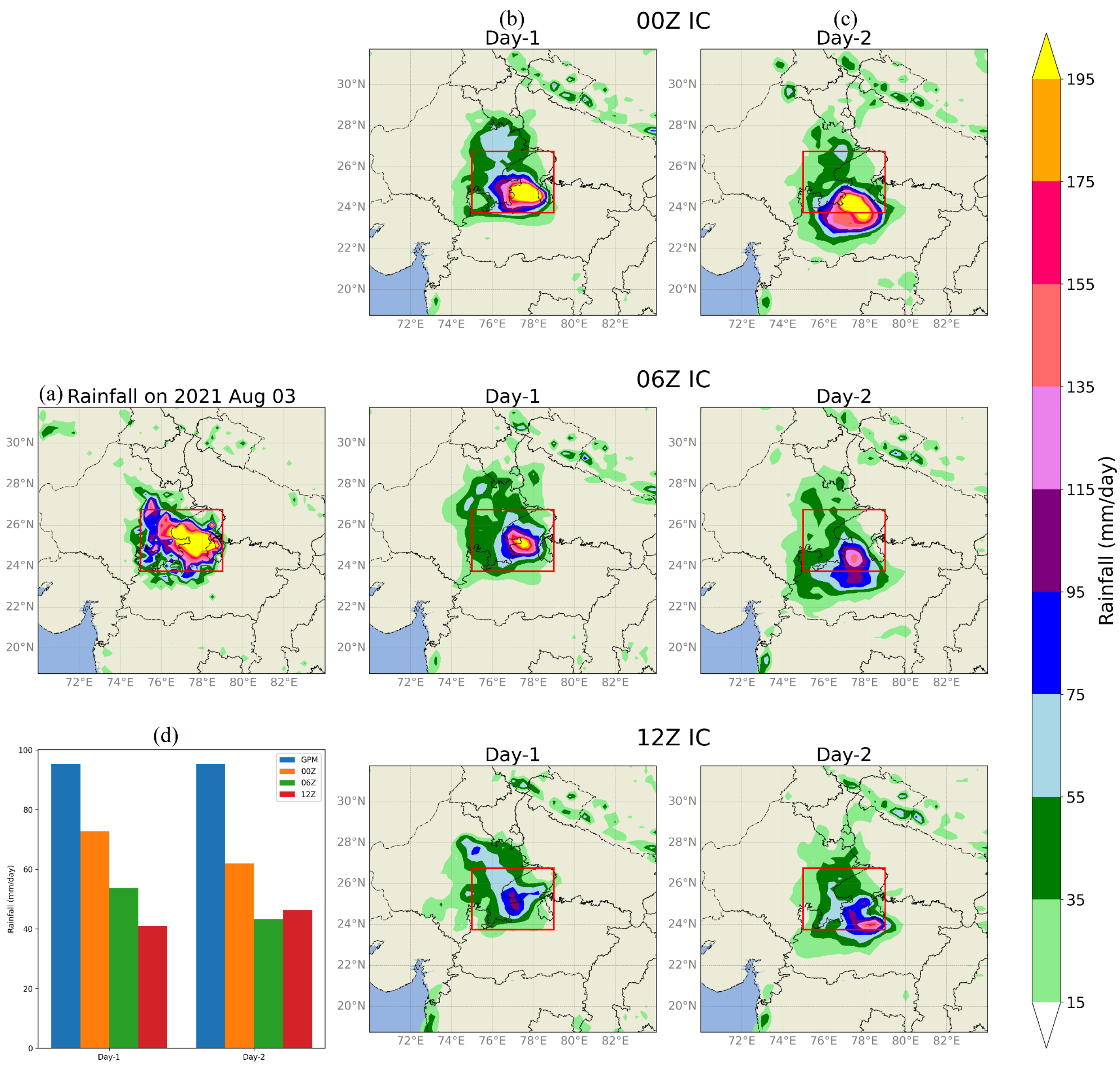

Figure 11. Spatial distribution of (a) Observed rainfall (mm/day) and GFS model forecast with (b) Day-1 and (c) Day-2 lead time with 3 different initial conditions (00Z, 06Z, 12Z) on 3 August, 2021 and (d) area-averaged precipitation within the red box.

In Figure 1a, the observed rainfall indicates a concentrated zone of heavy precipitation over Madhya Pradesh and some parts of Rajasthan, with intensities exceeding 300 mm/day.

All Day-1 forecasts have captured the location of heavy rainfall, but in Day-2 forecasts, the event was predicted a bit south from original location. Model has underestimated the magnitude of precipitation in all forecasts. From the bar graph (Fig. 11d), we can see that the Day-1 00Z IC forecast has the best magnitude inside the red box.

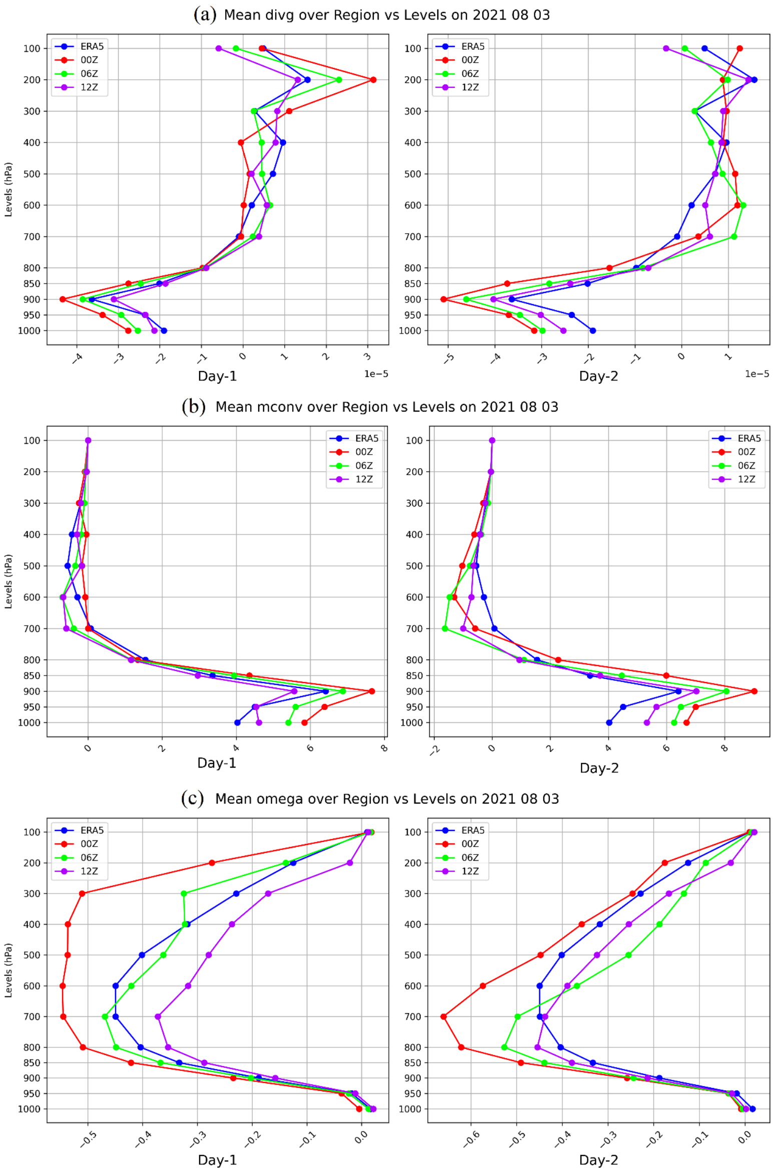

Figure 12. Vertical profiles of (a) divergence (divg, /s), (b) moisture convergence (mconv, /s), and (c) omega (hPa/s) over the red box (Fig 11) on 3 August, 2021, derived from ERA5 reanalysis data (blue) and 00Z (red), 06Z (green), 12Z (purple) model forecast outputs.

It is found that wind convergence (Fig. 12a) and moisture convergence is overestimated in lower levels in both Days 00Z forecast, which might be associated with precipitation forecasts being closest to observation data. Also, strong ascending vertical motion is overestimated in 00Z forecast on both days.

Overall, 00Z IC forecast with Day-1 lead time gave the best forecast of the event.

For the event on 31 August 2021:

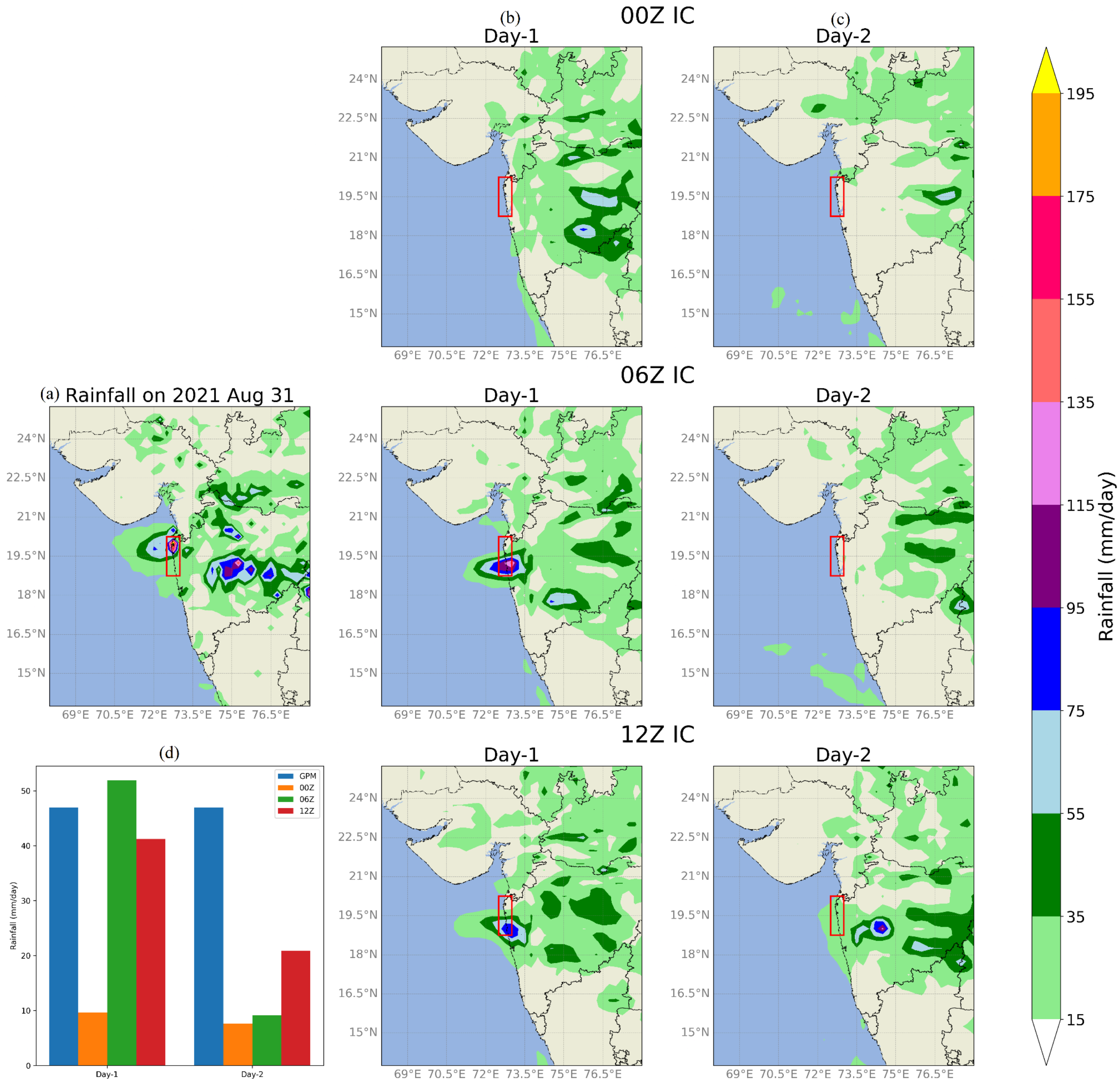

Figure 13. Spatial distribution of (a) Observed rainfall (mm/day) and GFS model forecast with (b) Day-1 and (c) Day-2 lead time with 3 different initial conditions (00Z, 06Z, 12Z) on 31 August, 2021 and (d) area-averaged precipitation within the red box.

Fig 13a. shows a small area of heavy rainfall over Maharashtra with maximum rainfall reaching 220 mm/day.

We can see, Day-2 forecasts couldn't estimate any heavy rainfall event, only light rainfall was predicted in 12Z IC forecast. Day-1 00Z forecast also couldn't capture any sign of heavy rainfall over the observed region. Day-1 forecast with 06Z IC captured the event with a slight southward shift of location, but the predicted magnitude is reasonably well.

Now in Figure 14. we have few dynamical parameters associated with the heavy rainfall event. In lower levels, wind convergence (Fig. 14a) and moisture convergence (Fig. 14b) both are underestimated in all forecasts. Similarly Fig 14c shows ascending vertical velocity is very underestimated in all forecasts. Further investigation is required to understand it. Overall, though the dynamical features weren't captured too well but Day-1 06Z IC captured rainfall event quite well.

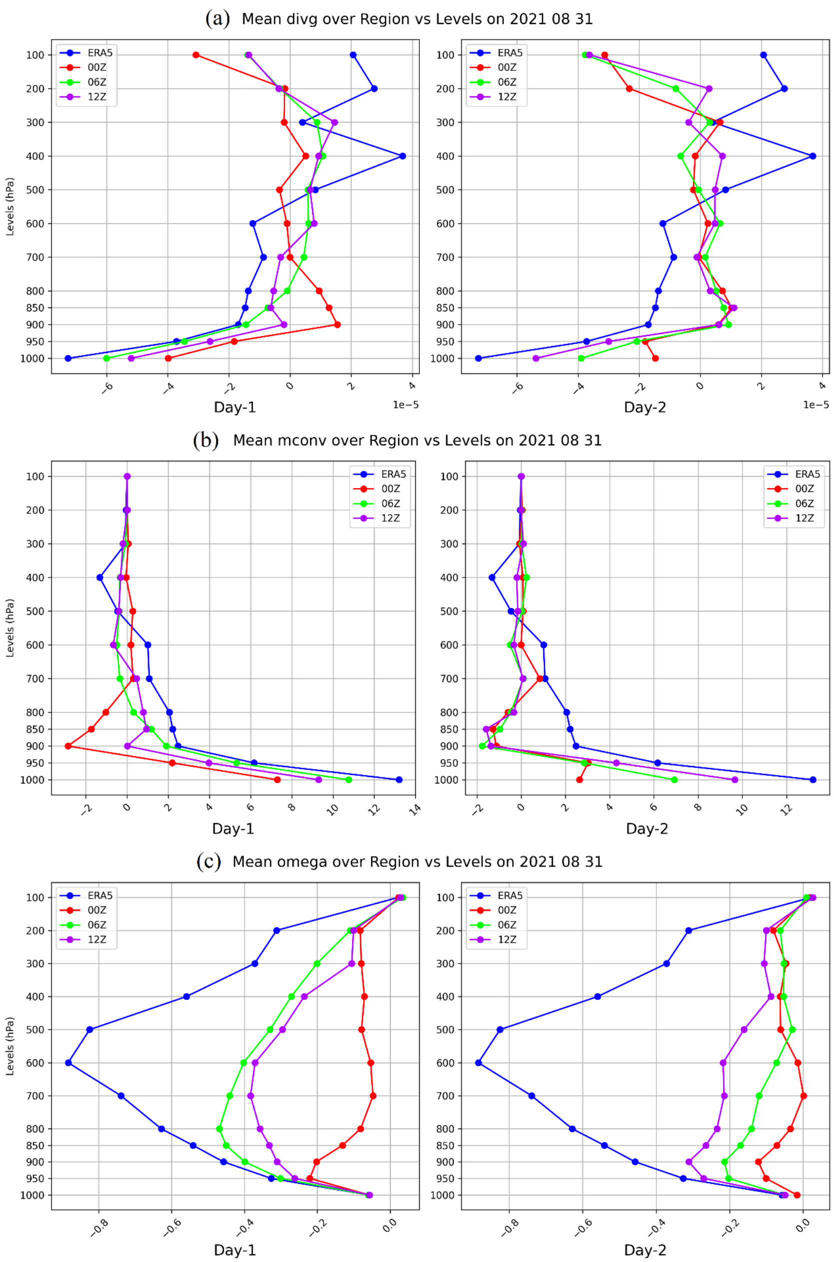

Figure 14. Vertical profiles of (a) divergence (divg, /s), (b) moisture convergence (mconv, /s), and (c) omega (hPa/s) over the red box (Fig 13) on 31 August, 2021, derived from ERA5 reanalysis data (blue) and 00Z (red), 06Z (green), 12Z (purple) model forecast outputs.

For the event on 17 June 2022:

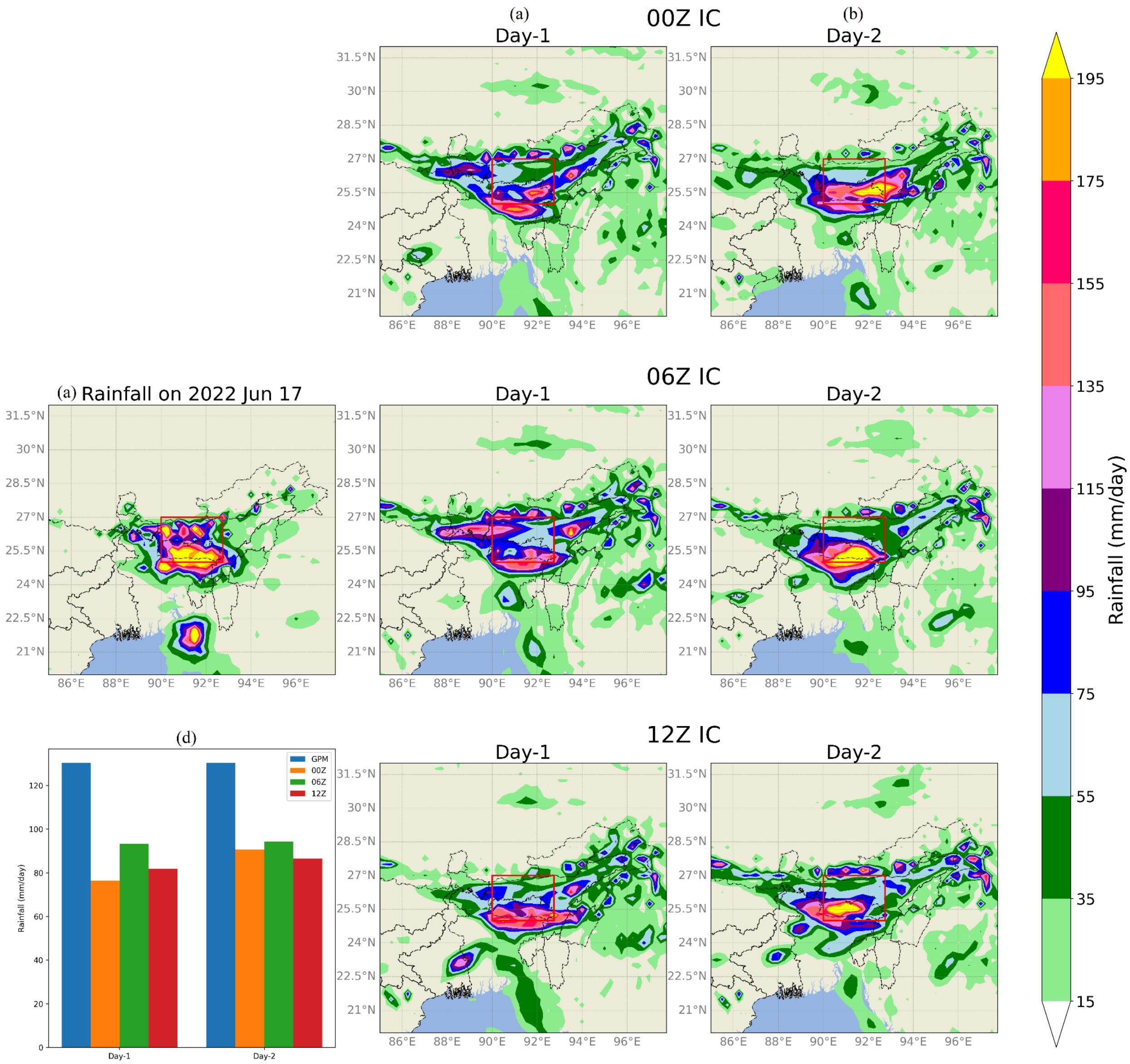

Figure 15. Spatial distribution of (a) Observed rainfall (mm/day) and GFS model forecast with (b) Day-1 and (c) Day-2 lead time with 3 different initial conditions (00Z, 06Z, 12Z) on 17 June, 2022 and (d) area-averaged precipitation within the red box.

In Figure 15a, the observed rainfall indicates a concentrated zone of heavy precipitation over Meghalaya and in some parts of Assam and Bangladesh, with intensities exceeding 900 mm/day.

Day-1 forecasts have somewhat captured the location of heavy rainfall event but slightly underestimated the magnitude. In Day-2 forecasts, we can see some improvement in the magnitude of rainfall. Though model only captured heavy rainfall over Meghalaya but failed to do so over Assam. That’s why it shows underestimation of rainfall inside the red box (Fig 15) in the bar graph (Fig 15d).

In vertical profiles (Fig 16a, 16b), we can see some good estimation of atmospheric features namely horizontal divergence and moisture convergence over the red box region. Ascending vertical winds were little underestimated in lower levels and overestimated in higher levels. Overall, Day-2 lead time gives better rainfall prediction with 00Z and 06Z ICs. But atmospheric features are captured slightly better in Day-1 lead time with 00Z IC.

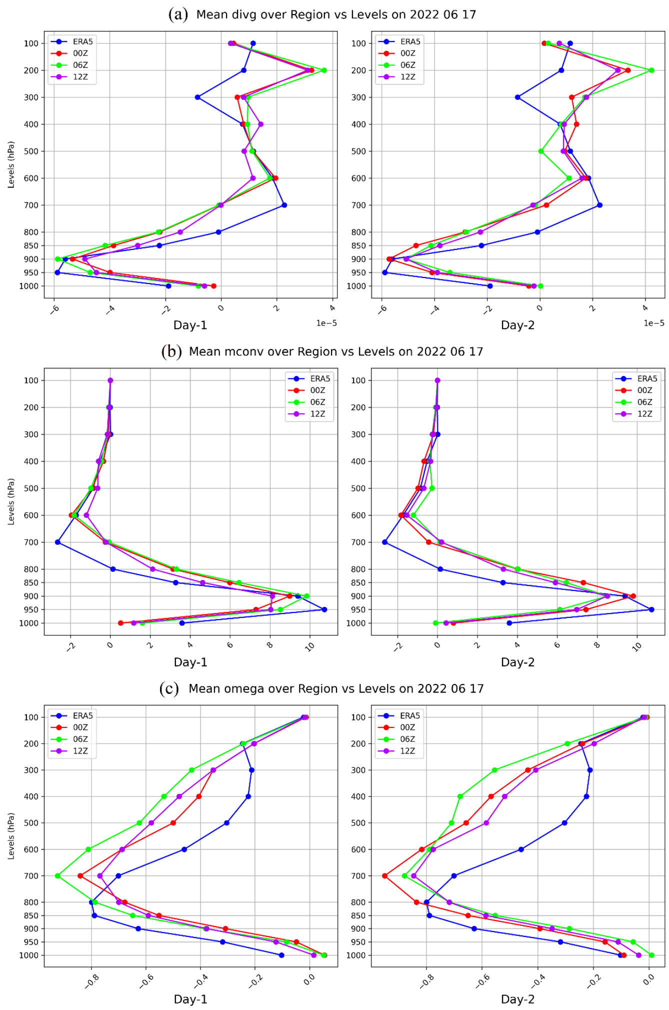

Figure 16. Vertical profiles of (a) divergence (divg, /s), (b) moisture convergence (mconv, /s), and (c) omega (hPa/s) over the red box (Fig 15) on 17 June, 2022, derived from ERA5 reanalysis data (blue) and 00Z (red), 06Z (green), 12Z (purple) model forecast outputs.

For the event on 5 July 2022:

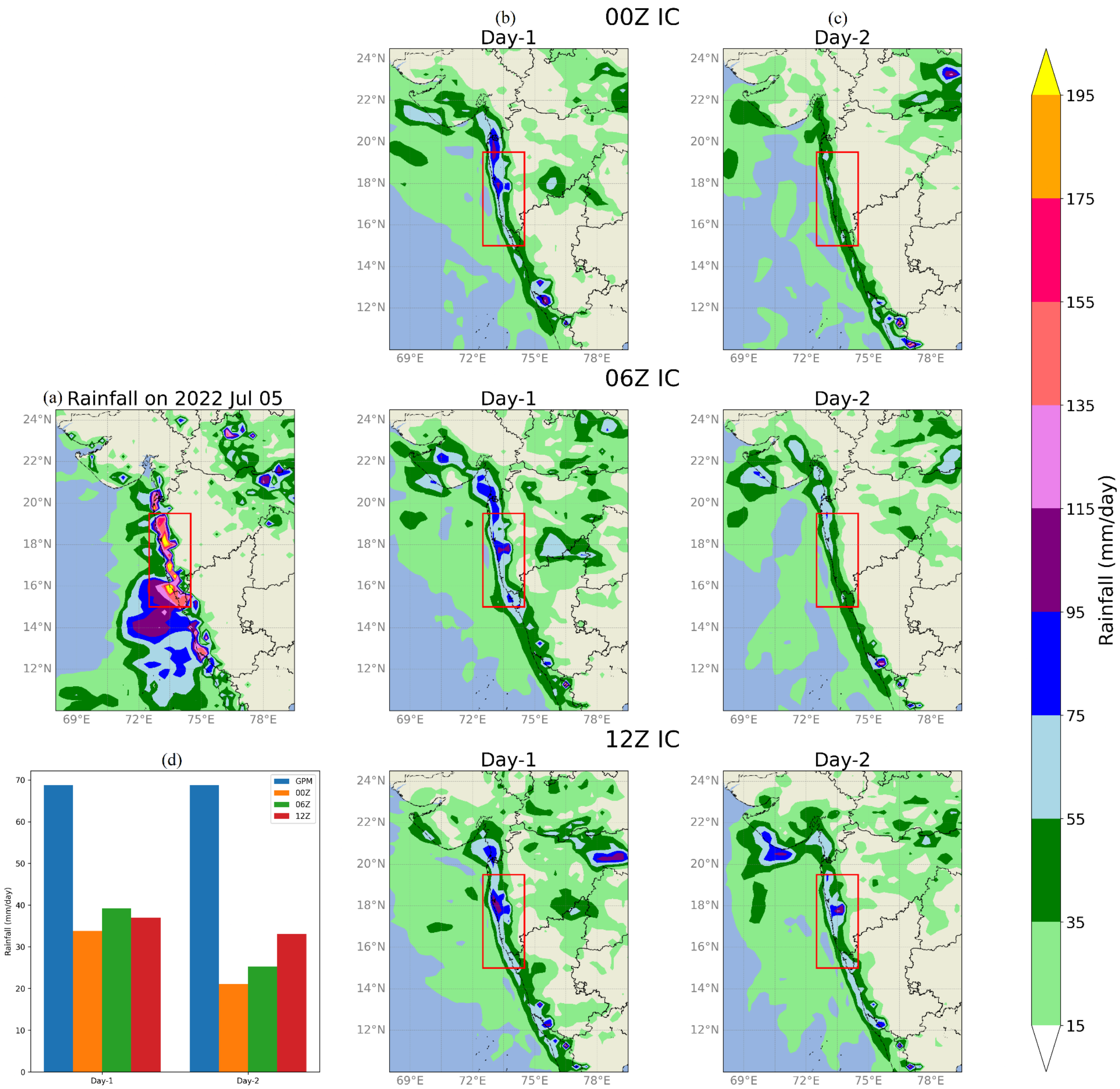

Figure 17. Spatial distribution of (a) Observed rainfall (mm/day) and GFS model forecast with (b) Day-1 and (c) Day-2 lead time with 3 different initial conditions (00Z, 06Z, 12Z) on 5 July, 2022 and (d) area-averaged precipitation within the red box.

In Figure 17a., the observed rainfall shows a concentrated area of heavy rainfall over Maharashtra and Arabian sea, with rainfall intensities reaching nearly 300 mm/day.

As the forecast data plots (Fig 17b, c) shows, none of them could capture the intensity of rainfall, but the location. The bar graph (Fig. 17d) clearly shows the magnitude of rainfall inside the red box (Fig 17) is considerably underestimated in all ICs.

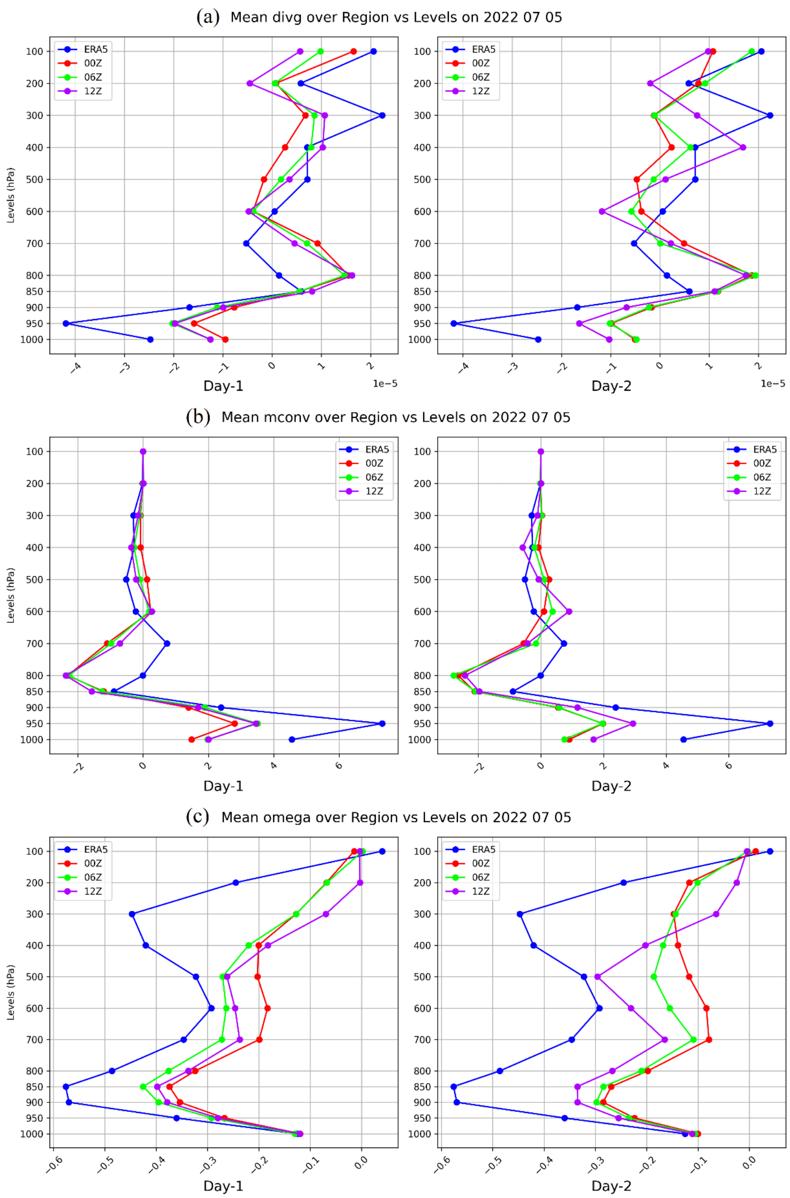

Figure 18. Vertical profiles of (a) divergence (divg, /s), (b) moisture convergence (mconv, /s), and (c) omega (hPa/s) over the red box (Fig 17) on 5 July, 2022, derived from ERA5 reanalysis data (blue) and 00Z (red), 06Z (green), 12Z (purple) model forecast outputs.

To further investigate the reason for such failure to capture magnitude, we have examined a few atmospheric parameters namely horizontal divergence, moisture convergence, vertical velocity. It is found that all forecasts have underestimated lower level wind convergence (Fig. 18a) and moisture convergence (Fig. 18b). In case of vertical velocity, strong ascending wind is underestimated across all levels in all forecasts. Further investigation and improvement in the model is required to avoid such failure.

For the event on 9 July 2023:

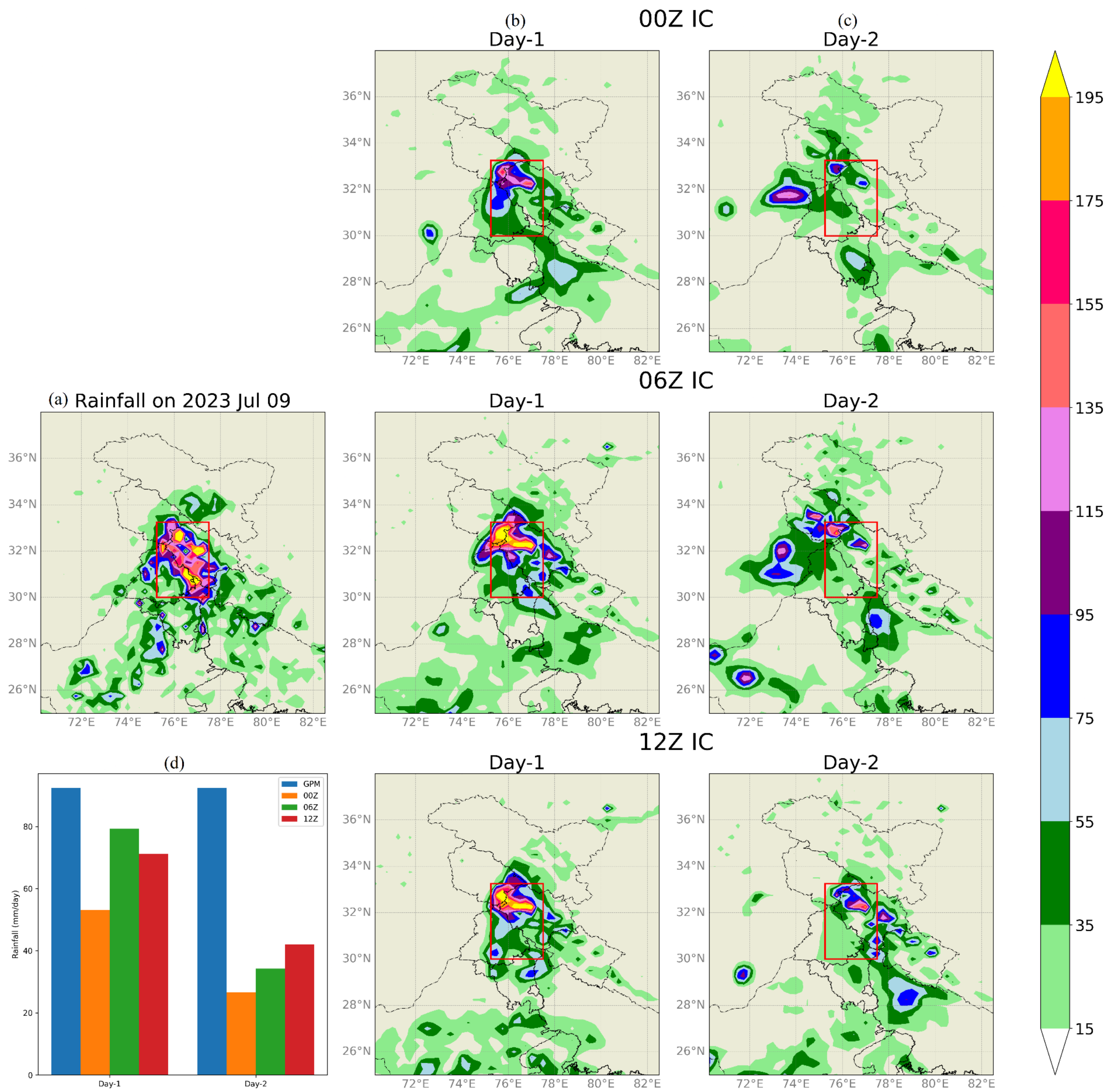

Figure 19. Spatial distribution of (a) Observed rainfall (mm/day) and GFS model forecast with (b) Day-1 and (c) Day-2 lead time with 3 different initial conditions (00Z, 06Z, 12Z) on 9 July, 2023 and (d) area-averaged precipitation within the red box.

In Figure 19a, the observed rainfall shows an area of heavy rainfall over Himachal Pradesh, in some parts of Punjab, Haryana, Jammu and Kashmir with rainfall intensities reaching 470 mm/day.

As we can see in Figure 19c, Day-2 forecasts have captured the location of heavy rainfall event with a little shift north-westward. Also the magnitudes were significantly underestimated in all ICs of Day-2 lead time. With Day-1 lead time, 06Z and 12Z ICs have captured the event over Jammu and Kashmir and northern part of Himachal Pradesh only. That's why in the bar graph (Fig. 19d) we can see, the area-averaged precipitation was slightly underestimated inside the red box.

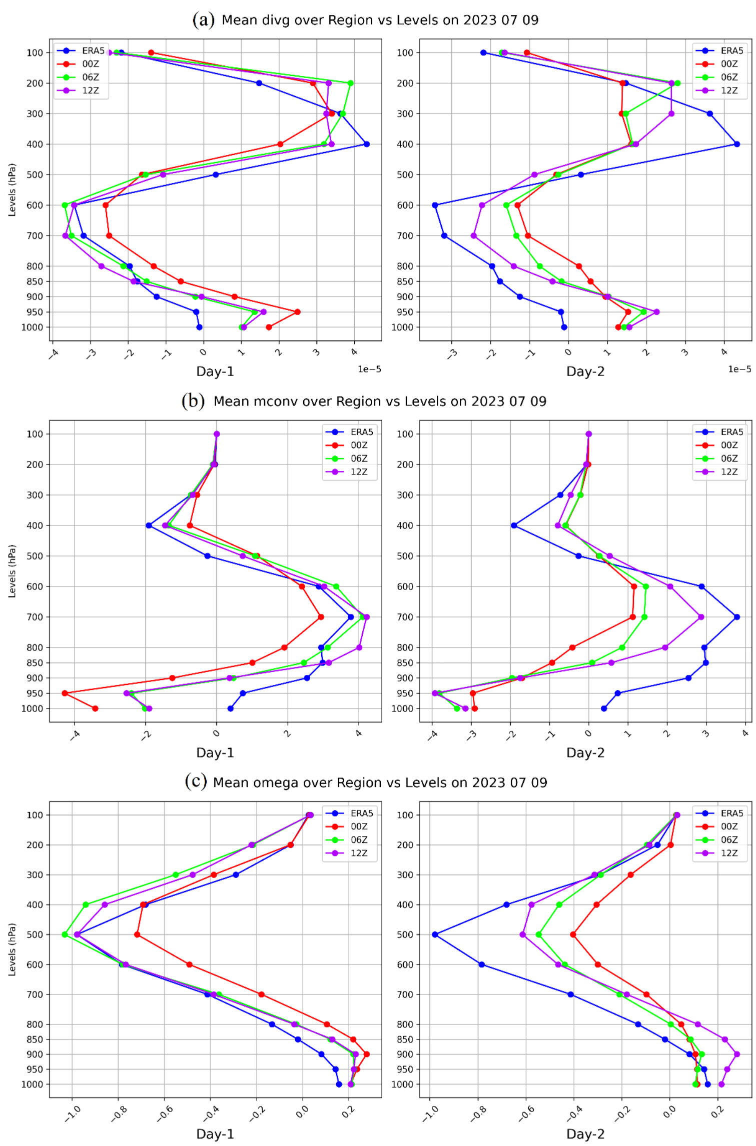

Figure 20. Vertical profiles of (a) divergence (divg, /s), (b) moisture convergence (mconv, /s), and (c) omega (hPa/s) over the red box (Fig 19) on 9 July, 2023, derived from ERA5 reanalysis data (blue) and 00Z (red), 06Z (green), 12Z (purple) model forecast outputs.

For Day-2 lead time, moisture convergence (Fig. 20b) is significantly underestimated in lower levels associated with weaker ascending motion than observation. This explains why the Day-2 forecasts couldn't capture the heavy rainfall. In Day-1 forecasts, moisture convergence was underestimated in lower levels, but the estimation for higher levels was good. 06Z and 12Z forecasts for vertical velocity are also reasonably well.

Overall, Day-1 lead time with 06Z IC has better captured the heavy rainfall event.

For the event on 27 July, 2023:

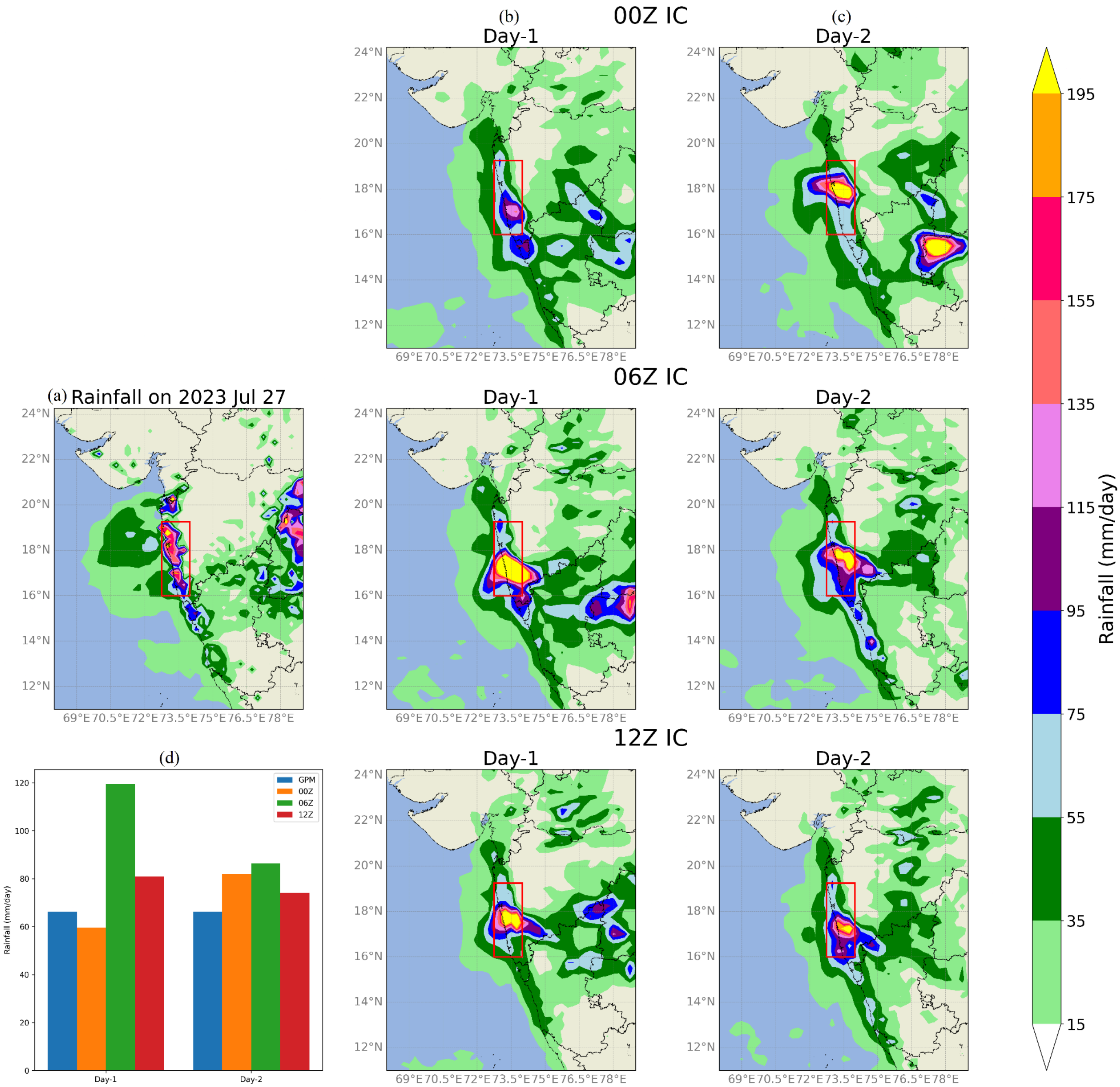

Figure 21. Spatial distribution of (a) Observed rainfall (mm/day) and GFS model forecast with (b) Day-1 and (c) Day-2 lead time with 3 different initial conditions (00Z, 06Z, 12Z) on 27 July, 2023 and (d) area-averaged precipitation within the red box.

In Figure 19a, an extreme rainfall event of up to 400 mm/day is observed over Maharashtra.

It is found that both Day-1 and Day-2 forecasts have captured the location and magnitude of the heavy rainfall well. Day-1 06Z IC has overestimated the rainfall almost 2 times that of observed (Fig. 21d).

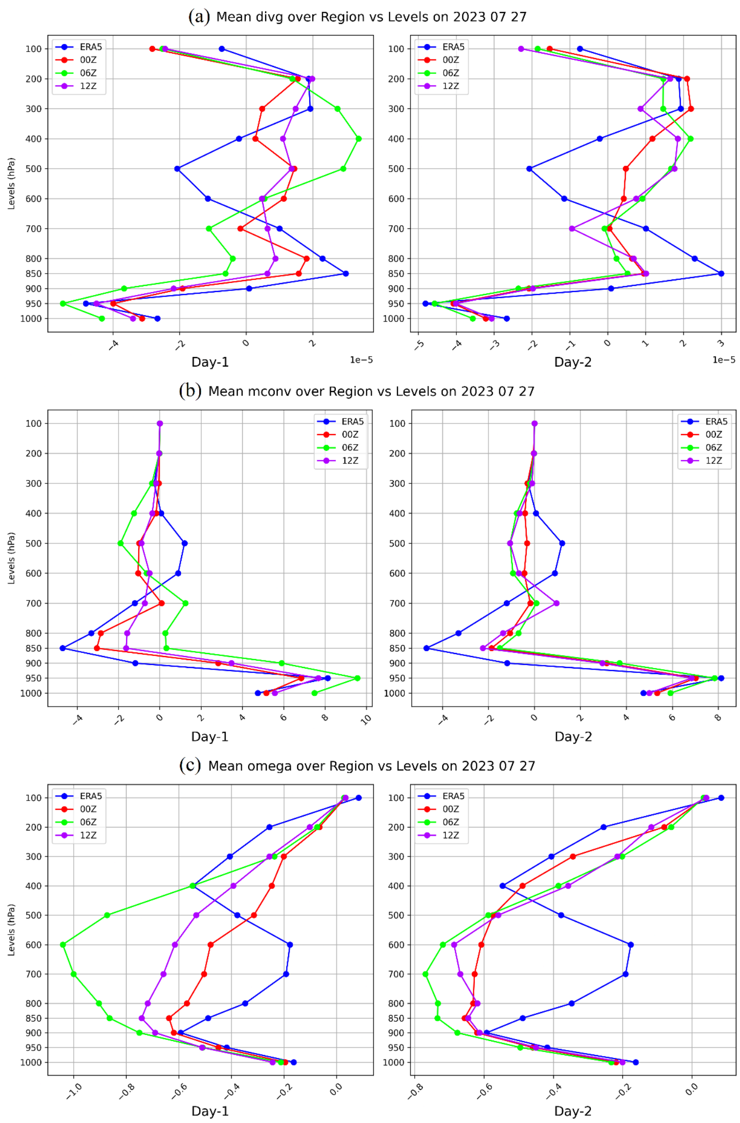

Figure 22. Vertical profiles of (a) divergence (divg, /s), (b) moisture convergence (mconv, /s), and (c) omega (hPa/s) over the red box (Fig 21) on 27 July, 2023, derived from ERA5 reanalysis data (blue) and 00Z (red), 06Z (green), 12Z (purple) model forecast outputs.

To understand the reasons behind those reasonably well forecasts, we compared horizontal divergence, moisture convergence and vertical velocity of observation and model data. The overestimation of strong ascending motion (Fig. 22c) in Day-1 06Z forecast associates with the overestimation of rainfall intensity (Fig. 21d). Moisture convergence and wind convergence is well estimated in Day-1 00Z IC.

Overall, except Day-1 06Z IC forecast, all forecasts have captured the heavy rainfall event with some precision.

4. Conclusions

From our above study and some previous study by (Mukhopadhyay et al., 2019), we have found the GFS model has a tendency to underestimate heavy rainfall. In the table below, we have listed the model's performance for our selected events.

Date	Day-1			Day-2		
	00Z	06Z	12Z	00Z	06Z	12Z
2 July 2020	U	U/B	U	U	U	U
6 August 2020	U	U	U	O/B	O	U
15 August 2020	U	U	U	U	O	O/B
12 July 2021	O/B	U	U	U	O	O
13 July 2021	U	O/B	U	U	U	U
3 August 2021	U/B	U	U	U	U	U
31 August 2021	U	O/B	U	U	U	U
17 June 2022	U	U	U	U	U/B	U
5 July 2022	U	U	U	U	U	U
9 July 2023	U	U/B	U	U	U	U
27 July 2023	U	O	O	O	O	O/B
U = underestimated O = overestimated B = better forecast for specified event						

Table 2. An overview of model forecast performance for selected rainfall events

Out of 66 forecasts, 52 were underestimations and 14 were overestimations. This clearly supports the model's tendency of underestimation.

In Table. 2, we have also mentioned the forecast which captured the event better among all ICs. For 5 July 2022, none of the forecasts were good enough to mention. Out of the ten events studied, forecasts initialized at 06Z provided the most accurate predictions for five events, indicating that this IC timing had the highest overall effectiveness. Forecasts initialized at 00Z accurately predicted three events, demonstrating significant reliability in certain scenarios. Meanwhile, forecasts initialized at 12Z accurately predicted two events.

These findings show that forecast accuracy for heavy rainfall events varies depending on the initial conditions (IC) timing-00Z, 06Z, and 12Z. It emphasizes the need to consider multiple IC timings to optimize forecasts. Evaluating forecasts from different ICs helps meteorologists better understand atmospheric dynamics, leading to improved predictions and informed decision-making in meteorology.

References

Guhathakurta, P., Menon, P., Mazumdar, A. B., & Sreejith, O. P. (2011). *Changes in extreme rainfall events and flood risk in India during the last century*. Journal of Earth System Science, 120(3), 359-373. DOI:10.1007/s12040-011-0082-0.

Goswami, B. N., Venugopal, V., Sengupta, D., Madhusoodanan, M. S., & Xavier, P. K. (2006). *Increasing trend of extreme rain events over India in a warming environment*. Science, 314(5804), 1442-1445. DOI:10.1126/science.1132027.

Sperber, K. R., & Palmer, T. N. (1996). *Interannual tropical rainfall variability in general circulation model simulations associated with the Atmospheric Model Intercomparison Project*. Journal of Climate, 9(10), 2727-2750. DOI:10.1175/1520-0442(1996)009<2727>2.0.CO;2.

Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., ... & Joseph, D. (1996). *The NCEP/NCAR 40-year reanalysis project*. Bulletin of the American Meteorological Society, 77(3), 437-472. DOI:10.1175/1520-0477(1996)077<0437>2.0.CO;2.

Saha, S., Moorthi, S., Pan, H. L., Wu, X., Wang, J., Nadiga, S., ... & Goldberg, M. (2010). *The NCEP climate forecast system reanalysis*. Bulletin of the American Meteorological Society, 91(8), 1015-1057. DOI:10.1175/2010BAMS3001.1.

Mukhopadhyay, P., et al., 2019. Performance of a very high-resolution global forecast system model (GFS T1534) at 12.5 km over the Indian region during the 2016–2017 monsoon seasons. J. Earth Syst. Sci 128, 1–18. https://doi.org/10.1007/s12040-019- 1186-6

M**itra, A.K., Prakash, S., Imranali, M.M., Pai, D.S., Srivastava, A.K., (2014).** Daily merged satellite gauge real-time rainfall dataset for Indian Region. Vayumandal 40 (1–4), 33–43.

Hou, A. Y., Kakar, R. K., Neeck, S., Azarbarzin, A. A., Kummerow, C. D., Kojima, M., ... & Iguchi, T. (2014). The Global Precipitation Measurement (GPM) mission. Bulletin of the American Meteorological Society, 95(5), 701-722. DOI:10.1175/BAMS-D-13-00164.1

Dee, D. P., Uppala, S. M., **Simmons, A. J.**, **Berrisford, P.**, **Poli, P.**, **Kobayashi, S.**, ... **Vitart, F.** (2011). The ERA-interim reanalysis: Configuration and performance of the data assimilation system. *Quarterly Journal of the Royal Meteorological Society*, 137(653), 553-597. https://doi.org/10.1002/qj.828