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RESEARCH REPORT

MoES Model Forecast Verification during JJAS2019: Verification of Rainfall Forecasts

S. Karunasagar, Kuldeep Sharma, Sushant Kumar, and Raghavendra Ashrit

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National Centre for Medium Range Weather Forecasting
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10	Abstract	This report provides a compilation rainfall forecast verification for the MoES models during monsoon season (JJAS) 2019. The verification results are focused on the rainfall forecasts since the India Meteorological Department (IMD) is using the NWP model precipitation forecast for day to day operational weather forecast in short to medium range. These are the two high resolution deterministic models namely (i) IMD's GFS and (ii) NCMRWF's NCUM generating real time NWP forecasts in the medium range time scale (up to 10 days) over Indian land regions during South West Monsoon (June-September) 2019. Both the deterministic models i.e., GFS and NCUM predict excessive rainfall over the mountains and neighboring seas areas. The Mean Error is seen to be more than 10 mm. The RMSE >15mm is evident over the wet regions like the west coast, eastern Indian and NE India. The dry regions of eastern peninsula and NW India have low RMSE. The RMSE is found to increase from Day-1 to Day-5 in both models. The overestimation is mainly due to prediction of higher (by over 20 to 49) number of rainy days (>1mm/day). For higher thresholds, i.e., moderate rain (>15.6mm/day) the both models indicate reasonable agreement with observations. For Heavy Rain (>65.5 mm/day) NCUM indicate comparable frequency over west coast while GFS indicates underestimation. During June and July both GFS and NCUM successfully predict the extended dry spell seen to the north of 20N. However, the dry spell seen to the south over peninsula (5-15N) is missed out in the forecasts. In GFS forecasts, the dry spells are not distinctly dry. The rainfall spells seem continuous without distinct gaps as in observations. Around 10-15°N, it is as though raining all the time in GFS. The Equitable Threat Score (ETS) values exceeding 0.3, are confined to a small region over NW India. NCUM Day-5 forecast has higher ETS than for GFS. ETS examined for different rainfall thresholds shows that both models have very similar forecast skill. GFS Day-1 forecast shows a higher PSS than NCUM for the rain/no rain case. NCUM exhibits a higher PSS for rainfall exceeding all the other thresholds.
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ABSTRACT

This report provides a compilation rainfall forecast verification for the MoES models during monsoon season (JJAS) 2019. The verification results are focused on the rainfall forecasts since the India Meteorological Department (IMD) is using the NWP model precipitation forecast for day to day operational weather forecast in short to medium range. These are the two high resolution deterministic models namely (i) IMD's GFS and (ii) NCMRWF's NCUM generating real time NWP forecasts in the medium range time scale (up to 10 days) over Indian land regions during South West Monsoon (June-September) 2019.

Both the deterministic models i.e., GFS and NCUM predict excessive rainfall over the mountains and neighboring seas areas. The Mean Error is seen to be more than 10 mm. The RMSE >15mm is evident over the wet regions like the west coast, eastern Indian and NE India. The dry regions of eastern peninsula and NW India have low RMSE. The RMSE is found to increase from Day-1 to Day-5 in both models. The overestimation is mainly due to prediction of higher (by over 20 to 49) number of rainy days (>1mm/day). For higher thresholds, i.e., moderate rain (>15.6mm/day) the both models indicate reasonable agreement with observations. For Heavy Rain (>65.5 mm/day) NCUM indicate comparable frequency over west coast while GFS indicates underestimation.

During June and July both GFS and NCUM successfully predict the extended dry spell seen to the north of 20N. However, the dry spell seen to the south over peninsula (5-15N) is missed out in the forecasts. In GFS forecasts, the dry spells are not distinctly dry. The rainfall spells seem continuous without distinct gaps as in observations. Around 10-15°N, it is as though raining all the time in GFS.

The Equitable Threat Score (ETS) values exceeding 0.3, are confined to a small region over NW India. NCUM Day-5 forecast has higher ETS than for GFS. ETS examined for different rainfall thresholds shows that both models have very similar forecast skill. GFS Day-1 forecast shows a higher PSS than NCUM for the rain/no rain case. NCUM exhibits a higher PSS for rainfall exceeding all the other thresholds.

Contents

1. Introduction

This report provides a compilation of the NWP model forecast verification for the MoES models during monsoon season (JJAS) 2019. The verification results are focused on the rainfall forecasts.

India Meteorological Department (IMD) is using the NWP model precipitation forecast for day to day operational weather forecast in short to medium range. So, it is very important to know the precipitation forecasts skill of the operational NWP models (under MoES) over India during rainy seasons (south west monsoon period). The main objective of this verification study is to document the precipitation forecast skill of MoES Global models. These are the two high resolution deterministic models namely (i) IMD's GFS and (ii) NCMRWF's NCUM generating real time NWP forecasts in the medium range time scale (up to 10 days) over Indian land regions during South West Monsoon (June-September) 2019.

1.1 Observed Rainfall during JJAS 2019

Detailed quantitative rainfall forecast verification presented here based on the IMD-NCMRWF daily high resolution (0.25°) rainfall analysis (Mitra et al. 2009, 2013). The rainfall analysis objectively analyses IMD daily rain gauge observations onto a 0.25° grid using a successive corrections technique with the GPM Satellite rainfall providing the first guess estimates. *The model forecasts are gridded to the 0.25° observed rainfall grids over Indian land regions* for 122 days from 1st June to 30th September 2019. As noted by Mitra et al. (2009), the merged analysis at 0.25° is appropriate for capturing the large scale rain features associated with the monsoon. The merging of the IMD gauge data into GPM estimates not only corrects the mean biases in the satellite estimates but also improves the large-scale spatial patterns in the satellite field, which is affected by temporal sampling errors (Mitra et al. 2009). Additionally, verification is also carried out against (i) IMD's gridded gauge data which is also grid resolution of 0.25° over Indian land regions and (ii) GPM IMERG data which is at 0.1° grid resolution.

1.2 MoES Global Forecast Models

(a) IMD GFS (T1534)

Global Forecasting System (GFS T1534L64 SL) model run operationally at India Meteorological Department (IMD) twice in a day (00 & 12 UTC) to give deterministic forecast in the short to medium range upto10 days. The forecast model has a resolution of approximately 12 km in horizontal and has 64 levels in the vertical. The initial conditions for this GFS model is generated from the four-dimensional (4D) ensemble–variation data assimilation (DA) system (4DEnsVar) building upon the grid point statistical interpolation (GSI)-based hybrid Global Data Assimilation System (GDAS) run on High Performance Computing Systems (HPCS) at National Center for Medium Range Weather Forecasting (NCMRWF). The real-time GFS T1534L64 model outputs are generated daily at IMD. This 4DEnsVar data assimilation system has capabilities to assimilate various conventional as well as satellite observations including radiances from different polar orbiting and geo-stationary satellites.

(b) NCUM (NCMRWF Unified Model)

The NCMRWF Unified model (NCUM) is a global model and has a horizontal grid resolution of ~12 km with 70 levels in the vertical reaching 80 km height. It uses “ENDGame” dynamical core, which provides improved the accuracy of the solution of primitive model equations and reduced damping. This helps in producing finer details in the simulations of synoptic features such as cyclones, fronts, troughs and jet stream winds. ENDGame also increases variability in the tropics, which leads to an improved representation of tropical cyclones and other tropical phenomena (Walters et al., 2017). An advanced data assimilation method of Hybrid 4D-Var is used for the creation of NCUM global analysis. The advantage of the Hybrid 4D-Var is that it uses a blended background error, blend of “climatological” background error and day-to-day varying flow dependent background error (derived from the 22–member ensemble forecasts). The hybrid approach is scientifically attractive because it elegantly combines the benefits of ensemble data assimilation (flow-dependent co-variances) with the known benefits of 4D-Var within a single data assimilation system (Barker, 2011). A brief description on the NCUM Hybrid 4D-Var system is given in Kumar et al. (2018).

2. Verification of Rainfall Forecasts

2.1 Observed and Predicted Mean Rainfall during JJAS 2019

Firstly, in Figure 1, the observed and forecast mean rainfall is presented for GFS and NCUM model forecasts during JJAS 2019. The panel in the top row (Figure 1a-c) shows the observed daily rainfall averaged from 1st June to 30th Sept 2019. The three panels provide a comparison among IMD-NCMRWF merged (Satellite+Gauge) rainfall analysis (Figure 1a), the rainfall analysis based on purely gridded gauge data (Figure7b) and GPM (Figure7c). The rainfall analysis based on gridded gage data (Figure7b) underestimates the rainfall over eastern parts of UP and Bihar and overestimates rainfall over parts of Assam and Arunachal Pradesh. The GPM (Figure7c) underestimates high rainfall amounts over west coast.

The panels in the middle (*and bottom*) row, Figure 1d-f (*Figure 1g-i*) show NCUM (*and GFS*) predicted daily rainfall averaged during the same period. The first, second and third columns correspond to Day-1, Day-3 and Day-5 forecasts respectively. The observed peak rainfall amounts (>15mm/day) along the Western Ghats and along the Arrakkan coast are predicted in both the models. However it is found that NCUM (*GFS*) overestimate (*underestimates*) this amount all over the west coast, NE India and over Himalayas. Both the model forecasts overestimate the isolated high rainfall amounts (>15mm/day) over eastern India. By and large, it can be concluded that both models have higher number of overestimation over the neighboring seas.

The reduced rainfall amounts (<6mm/day) over the eastern parts of the peninsula and the northwest India are predicted fairly well in both the models.

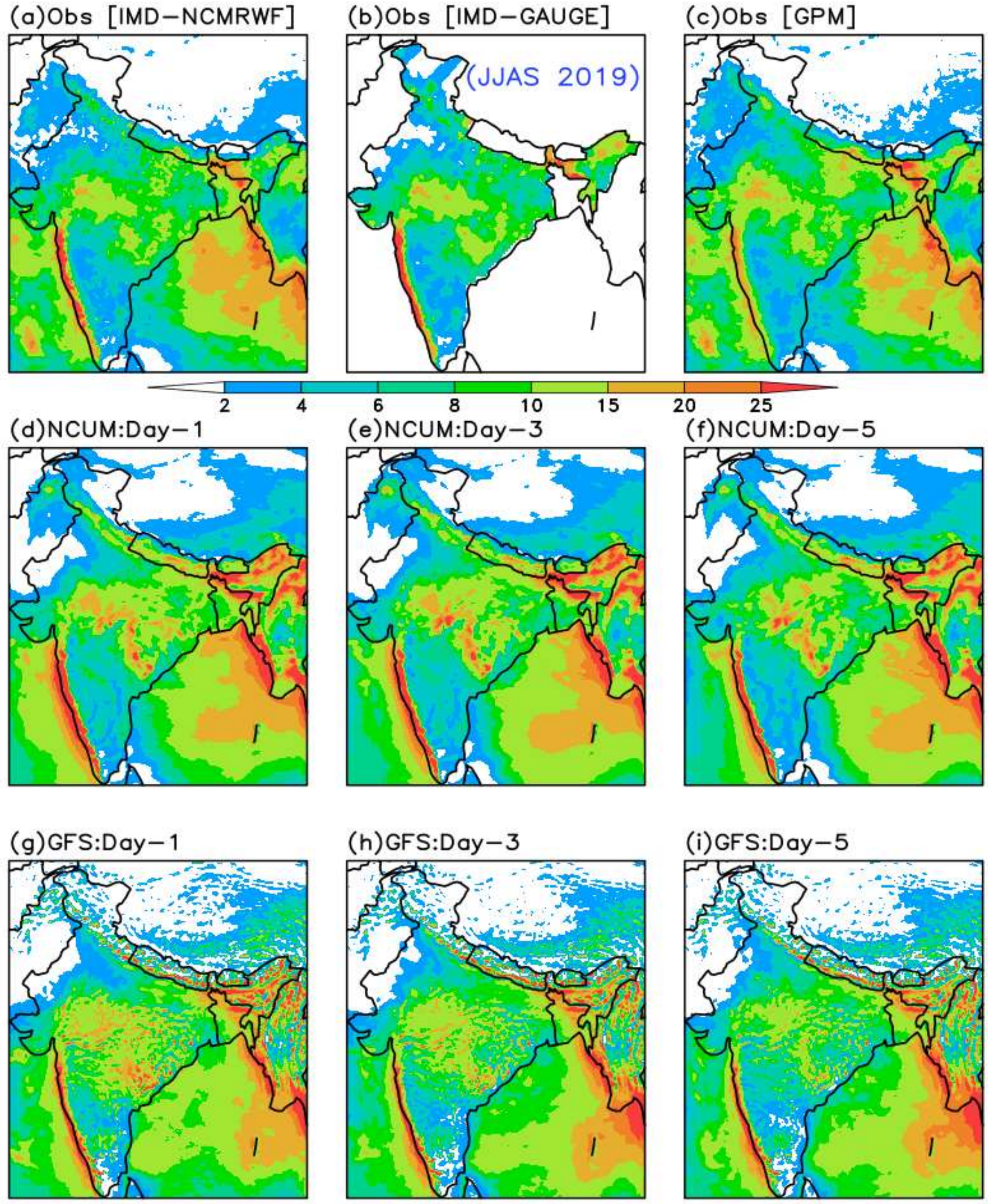

Figure 1. Observed model forecast rainfall (mm) averaged during Jun-Sept 2019. Panel (a) IMD-NCMRWF (b) gridded Gauge and (c) GPM show observed rainfall analysis. Panels (d), (e) and (f) correspond to Day-1, Day-3 and Day-5 forecast mean rainfall based on NCUM and panels (g), (h) and (i) correspond to Day-1, Day-3 and Day-5 forecast mean rainfall of GFS

2.2 Continuous Verification of Rainfall Forecasts during JJAS 2019.

Mean Error, Root Mean Square Error (RMSE) and Correlation Coefficient (CC) are some of the common verification scores categorized under continuous verification approach. Continuous verification scores can provide an overall measure of the forecast performance and assess a few of its attributes (e.g., bias or linear dependency). However, they are not very informative about the nature of the forecast errors.

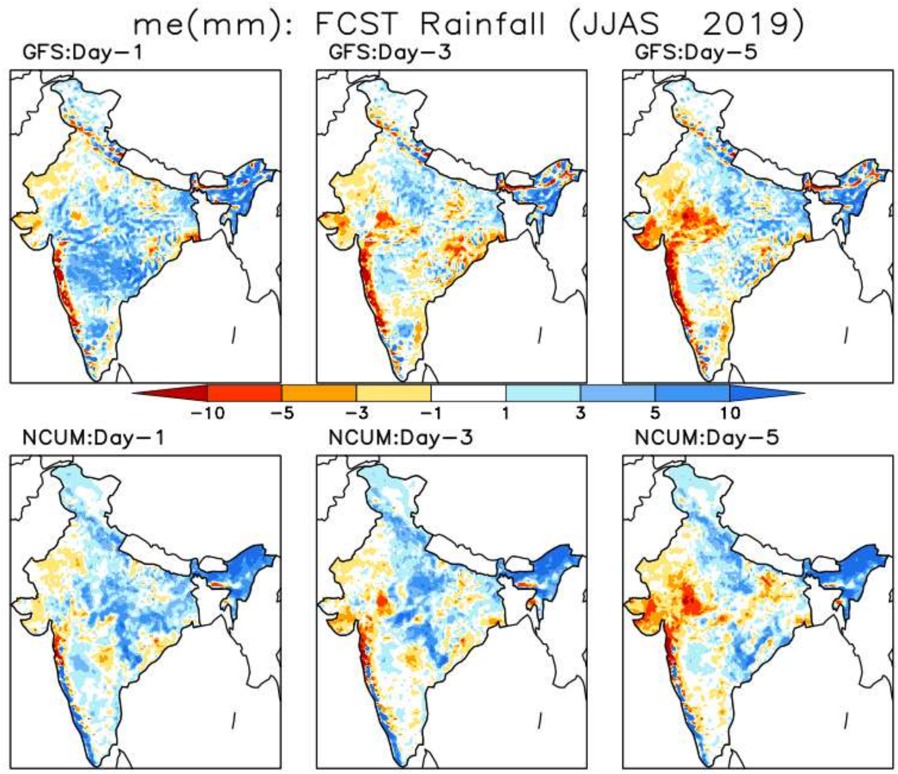

Figure 2. Mean Error in the forecast rainfall averaged during Jun-Sept 2019. Panels (a), (b) and (c) correspond to Day-1, Day-3 and Day-5 forecasts based on GFS and panels (d), (e) and (f) correspond to NCUM

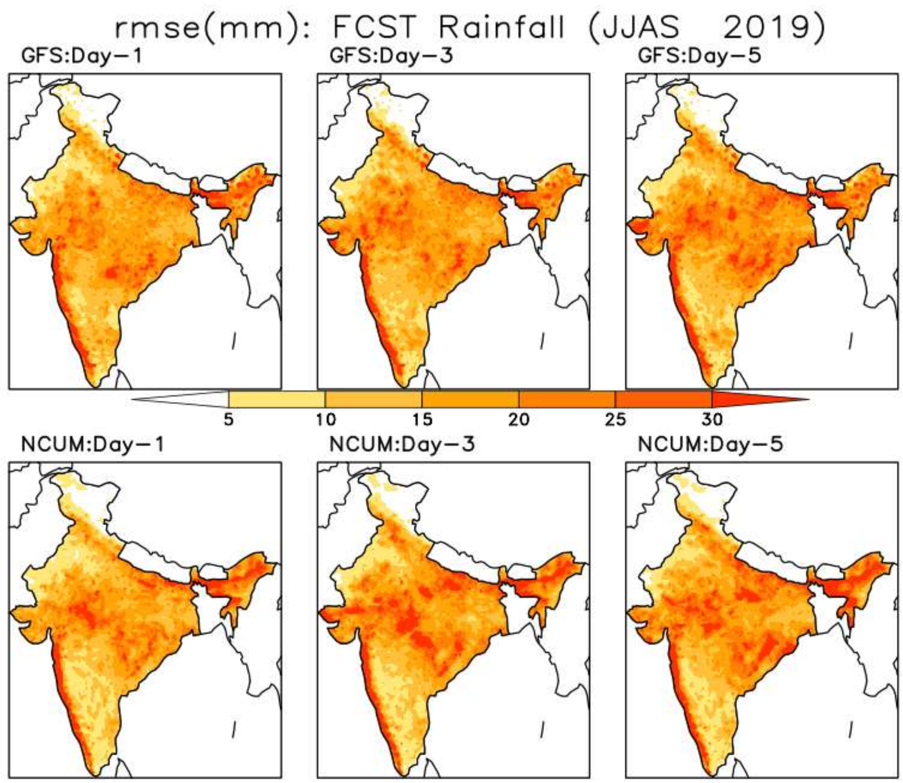

Figure 3. Root mean squared error (RMSE) in the forecast rainfall during Jun-Sept 2019. Panels (a), (b) and (c) correspond to Day-1, Day-3 and Day-5 forecasts based on GFS and panels (d), (e) and (f) correspond to NCUM

Additionally verification is provided by comparing observed and forecast Rainfall Hovemuller plots, number of rainy days (>1mm/day), rainy day counts for higher rainfall thresholds and time series of rainfall averaged over smaller regions.

To further isolate the forecast biases, mean error (ME), root mean squared error (RMSE) are presented in Figure 2-9 and the correlation coefficient (Figure 4) to map the association between the observed and forecast rainfall.

2.2.1. Mean Error (ME): Mean error gives the average forecast error. It is simple in interpretation since it gives *additive bias*. In other words, mean error allows one to identify the positive bias (*overforecasting*) and negative bias (*underforecasting*). The ME can vary in magnitude from -∞ to +∞, value of 0 being the perfect score. However, it does not indicate the magnitude of errors and describe the association between forecasts and observations.

$$ME = \frac{1}{N}\sum_{i=1}^{N}(F_i - O_i)$$

The ME computed for the rainfall forecasts is presented in Figure 2. The panels in three columns correspond to Day-1, Day-3 and Day-5 forecasts. Both GFS and NCUM show widespread errors (>3mm/day) over Indo-Gangetic Plain and Eastern India. In NCUM the ME values are much higher (>10mm/day) over Indo-Gangetic plains and NE India. Similarly in the IMD GFS forecasts also have high ME values (10mm/day) over eastern India. Pattern and magnitude of ME in NCUM and GFS seem very similar in Day-1 forecasts. Over the west coast GFS forecasts show underestimation, while NCUM forecasts show overestimation.

2.2.2. Root Mean Squared Error (RMSE): RMSE gives the average forecast error weighted according to squared error. While it does not indicate direction of the forecast errors, it gives greater emphasis on relatively larger errors.

$$RMSE = \sqrt{\frac{1}{N}\sum_{n=1}^{N}(F_i - O_i)^2}$$

Figure 3 shows the RMSE in rainfall forecasts. The panels show large RMSE (>15mm) over the wet regions like the west coast, eastern Indian and NE India. The dry regions of eastern peninsula and NW India have low RMSE. The RMSE is found to increase from Day-1 to Day-5 in both models.

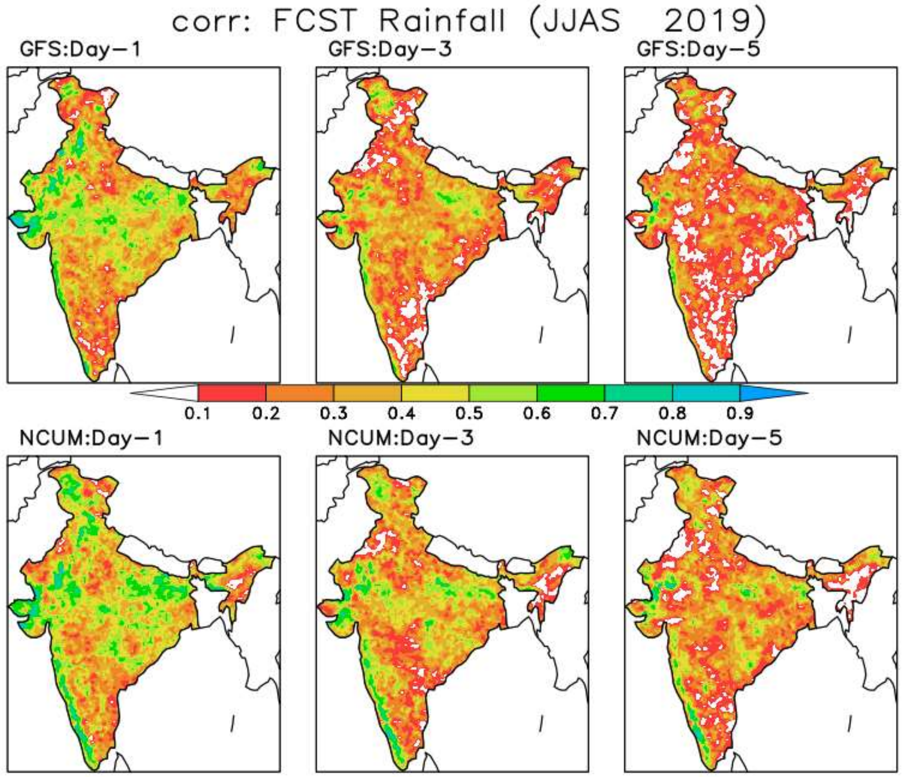

Figure 4. Temporal correlation (corr) in the forecast rainfall during Jun-Sept 2019. Panels (a), (b) and (c) correspond to Day-1, Day-3 and Day-5 forecasts based on GFS and panels (d), (e) and (f) correspond to Day-1, Day-3 and Day-5 forecasts of NCUM

<u>*2.3.3 Correlation Coefficient (CC):*</u> CC gives the measure of correspondence between the observations and forecasts. It is a good measure of association or phase error. It varied between -1 to +1; +1 being the perfect score. It must be noted that CC does not take forecast biases in to account. It is possible that forecasts with large biases to have good CC with observations.

$$CC = \frac{\Sigma(F - \bar{F})(O - \bar{O})}{\sqrt{(F - \bar{F})^2}\sqrt{(O - \bar{O})^2}}$$

The CC maps are shown in Figure 4 to show the association between observed and forecast rainfall in the models. Both the models show high values of CC over central and western India. Both the deterministic forecasts (NCUM and GFS) show die-off (decay in CC) from Day-1 to Day-5. Particularly GFS forecasts show faster reduction in CC.

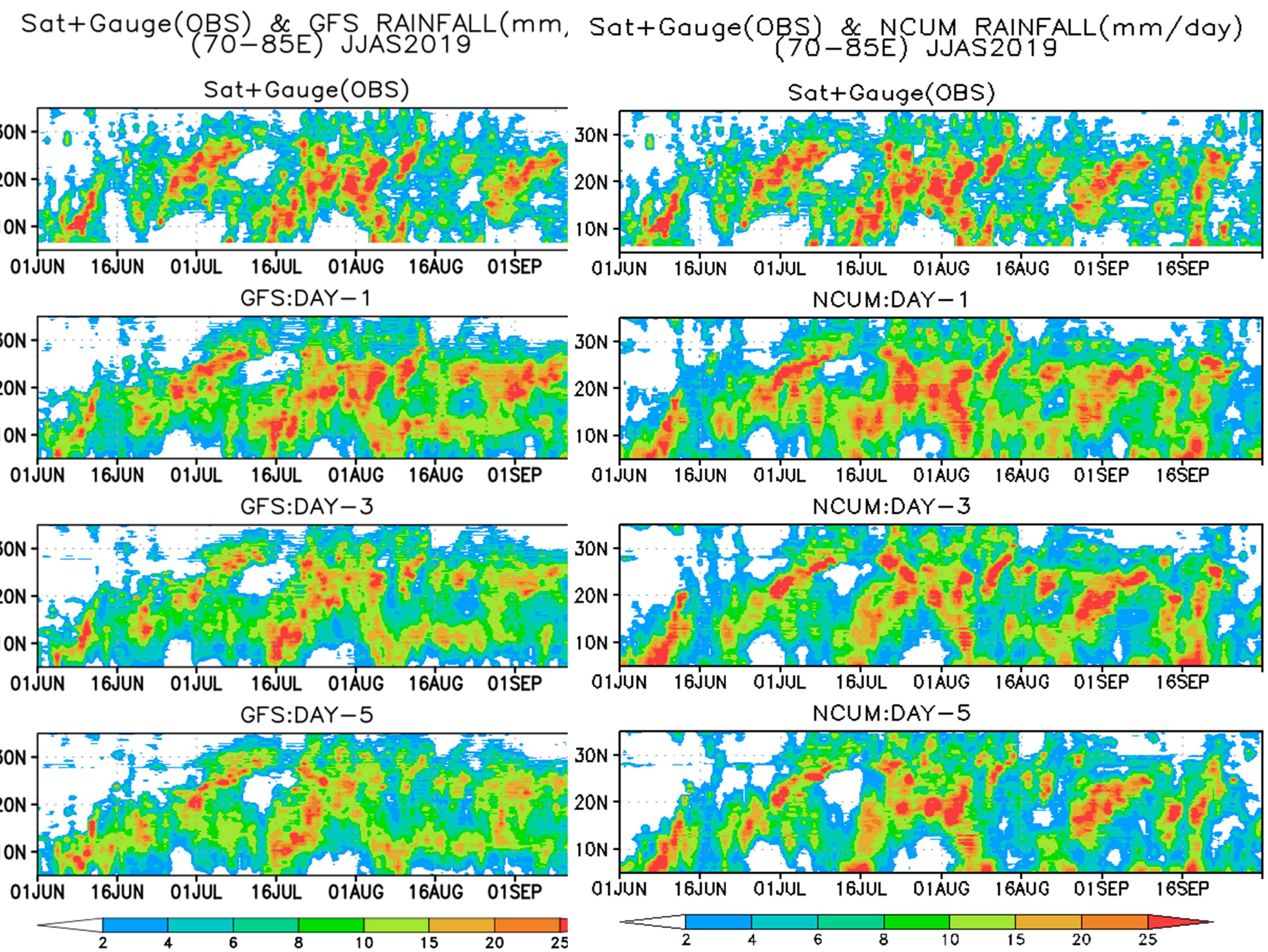

Figure 5. Observed and forecast rainfall in GFS (left) and NCUM (right) Hovemuller plots to show northward propagation of rainfall activity, averaged over the longitudes 70-85°E during JJAS 2019.

2.3 Observed and Predicted Active/Weak Rainfall Spells

The advance of the monsoon over Indian land regions manifested by active/weak rainfall spells and northward propagation of the rainfall bands. The Hovemuller plots of observed and model forecast rainfall averaged over longitudes 70-85°E is shown in Figure 5. The panels on the left correspond to GFS forecasts and panels on the right correspond to NCUM. The first impression would be that both models have excessive rain compared to the observations in top panel. This is evident in the Day-1 forecasts of both models.

Both GFS and NCUM have excessive rain compared to the observations. The active rainfall spells and northward propagation of rainfall bands during early and latter part of June, centered on mid-July, centered on mid-August and latter part of September are predicted very well in both GFS and NCUM.

The dry spell centered around 1st Aug is predicted relatively better in NCUM Day-3 and Day-5 forecasts. Similarly, the dry spell in the middle part of Sept is impressive in NCUM forecasts. In GFS forecasts, the dry spells are not distinctly dry. The rainfall spells seem continuous without distinct gaps as in observations. Around 10-15°N, it is as though raining all the time in GFS. During June and July both GFS and NCUM successfully predict the extended dry spell seen to the north of 20N. However, the dry spell seen to the south over peninsula (5-15N) is missed out in the forecasts. Prolonged dry spell from mid-July to mid-Aug is completely missed in GFS, while Day-3 and Day-5 forecasts of NCUM do a better job in predicting the dry spell. The dry spell extending from 1-15 Sept is predicted by both models.

2.4 Observed and Predicted number of rainy days, moderate and heavy rain days.

Total number of rainy days (rainfall > 1mm/day) is computed at each grid and spatial map of rainy day counts is shown for observations and forecasts in Figure 6. Observations indicate very high number of rainy days (>80) covering narrow area all along the west coast and parts of NE India. A small area over eastern India (E) has over 60 rainy days. A large part of central, western and peninsula has 40-60 days of rainfall >1mm/day. Both model forecasts overestimate the rainy day counts. Bias is particularly significant over peninsula and large parts of central and western India where the number of rainy days is 40-60 (also >60) while both the models gave 60-80 (also >80) rainy days.

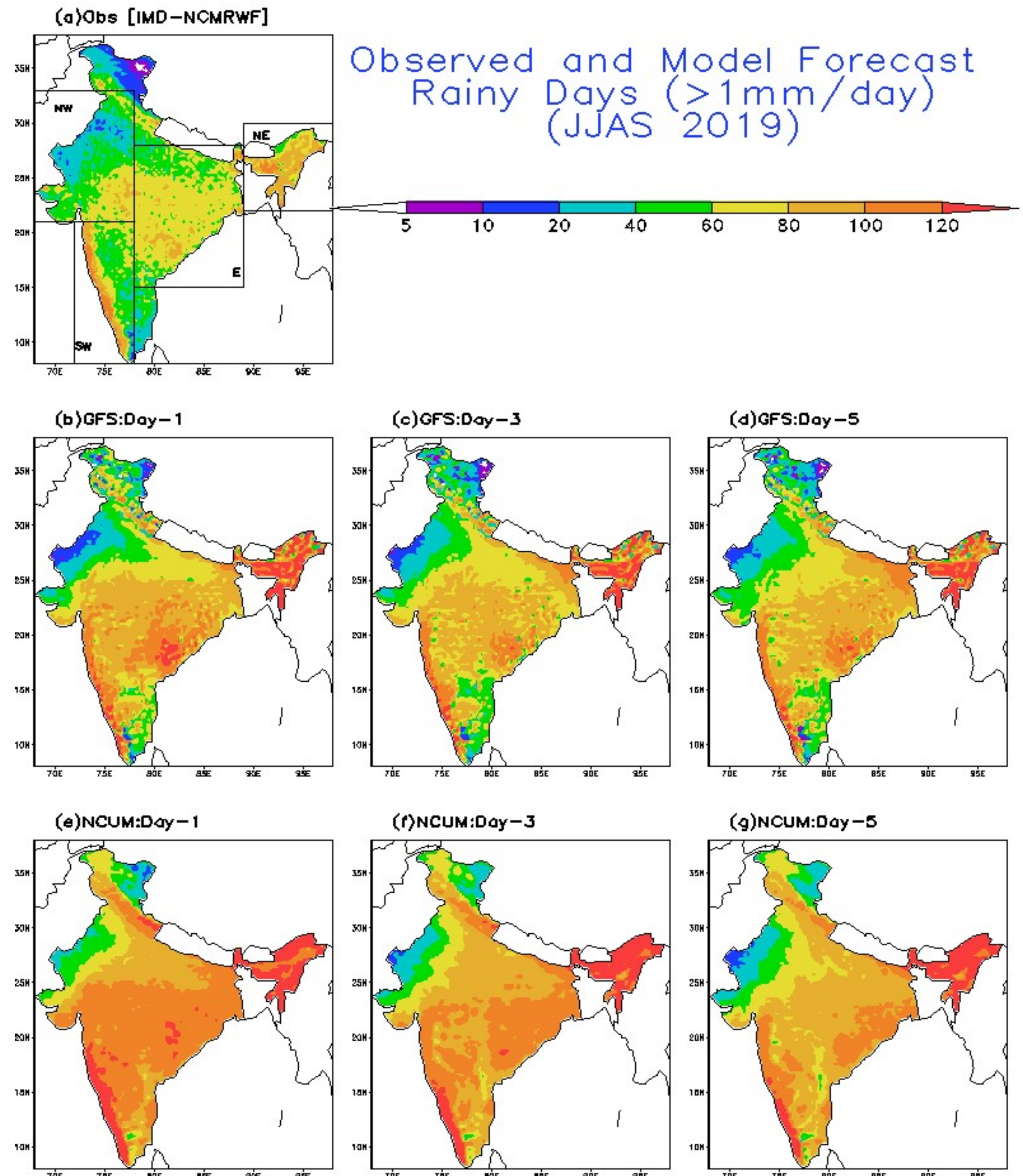

Figure 6. Observed model forecast number of rainy days during Jun-Sept 2019. Panel (a) Observed (IMD-NCMRWF) rainfall analysis. Panels (b), (c) and (d) correspond to Day-1, Day-3 and Day-5 forecasts based on GFS and panels (e), (f) and (g) correspond to Day-1, Day-3 and Day-5 forecasts of NCUM

Similar to the number of rainy day counts discussed in Figure 6, number of days with Moderate rain (>15.6mm/day) and Heavy rain (64.5 mm/day) are shown in Figure 7 and 14 for observations and the two model forecasts. Both GFS and NCUM overestimate the number of days with moderate rain over most parts of India. This is particularly evident over west coast, NE India and eastern India which the core monsoon zone. NCUM underestimates the counts over dry regions. GFS forecasts relatively seem to do better over dry regions.

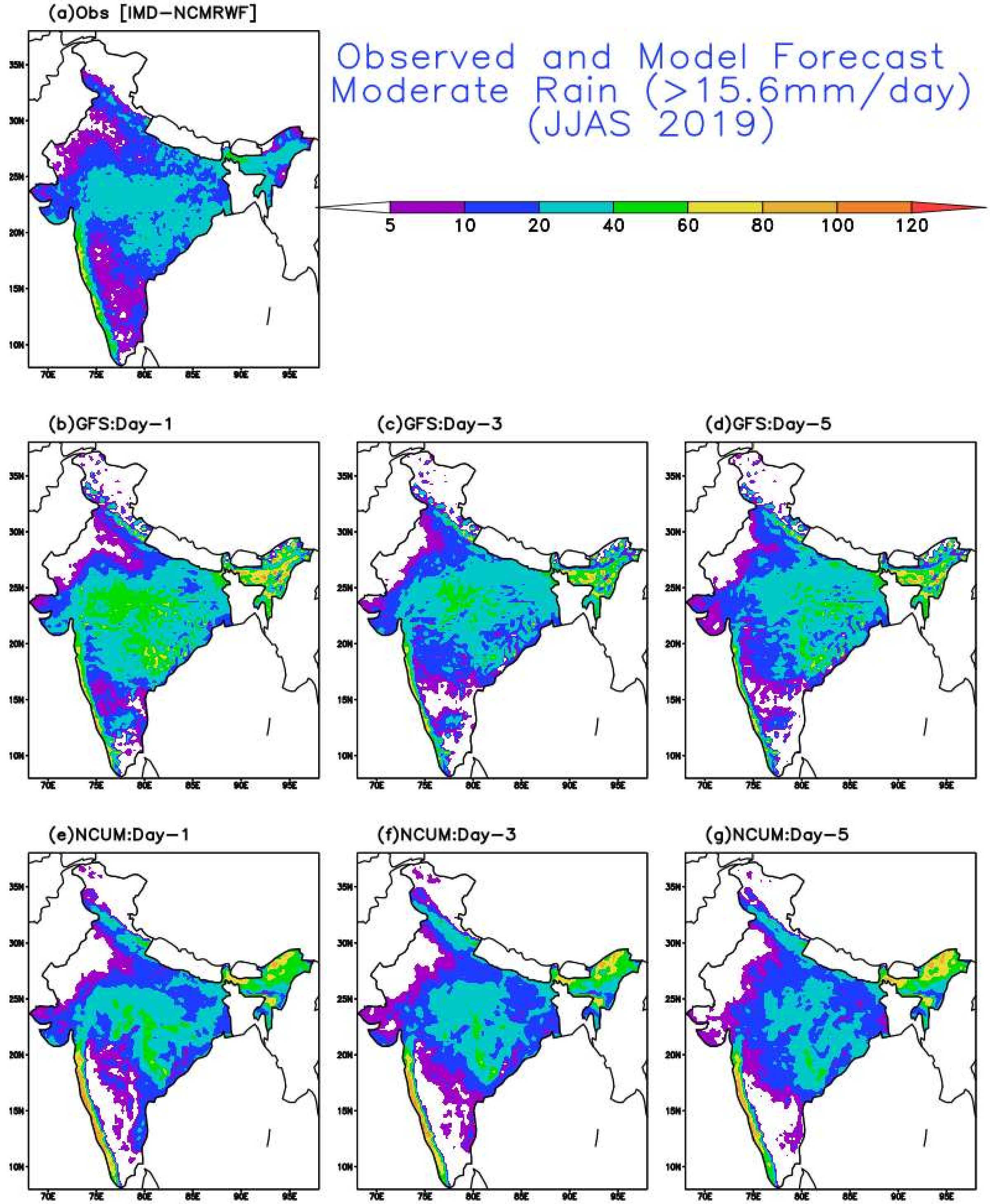

Figure 7. Observed model forecast number of days exceeding moderate rainfall (15.6mm/day) threshold during Jun-Sept 2019. Panel (a) Observed (IMD-NCMRWF) merged rainfall analysis. Panels (b), (c) and (d) correspond to Day-1, Day-3 and Day-5 forecasts based on GFS and panels (e), (f) and (g) correspond to Day-1, Day-3 and Day-5 forecasts of NCUM

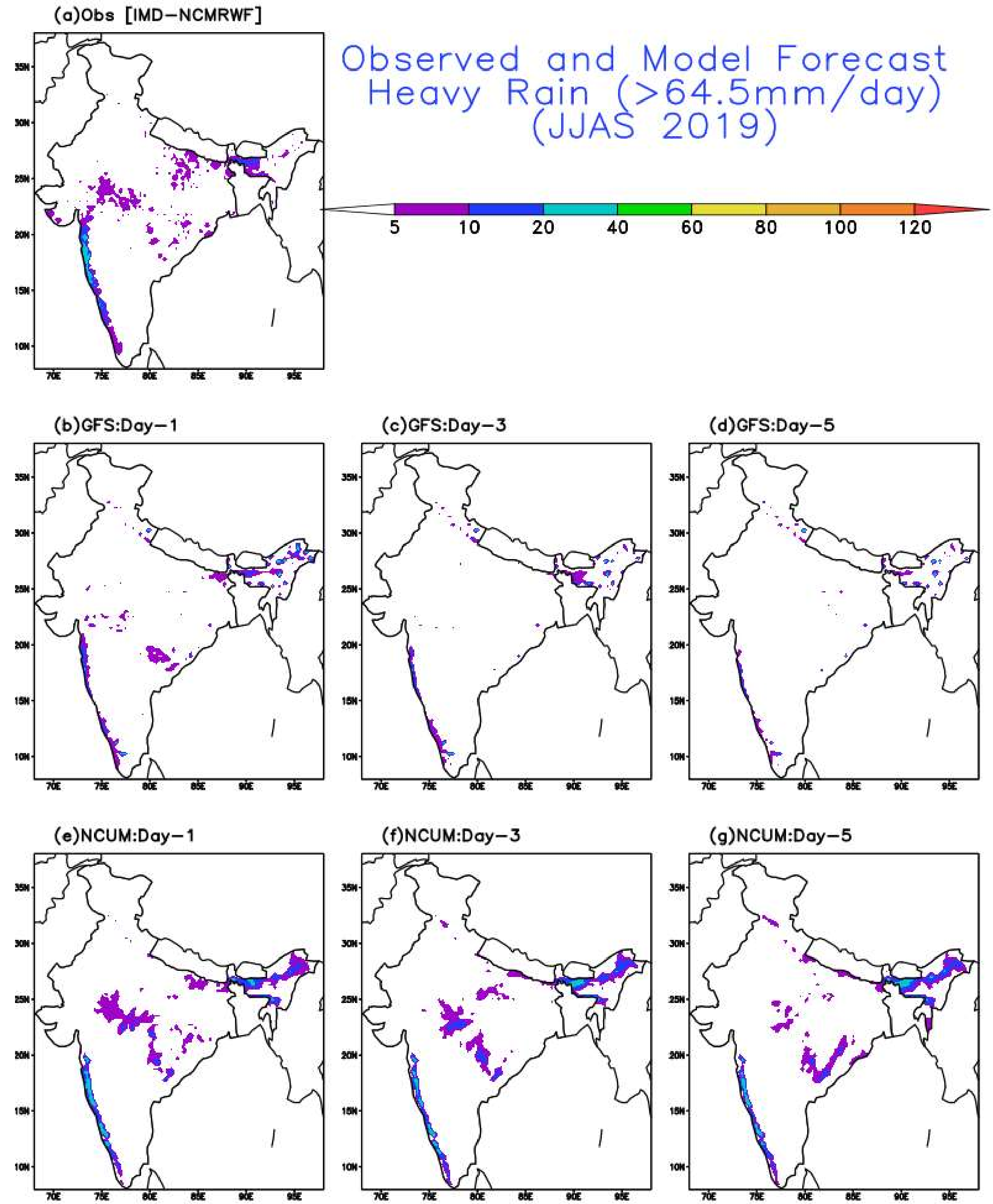

Figure 8. Observed model forecast number of days exceeding heavy rainfall (64.5mm/day) threshold during Jun-Sept 2019. Panel (a) Observed (IMD-NCMRWF) merged rainfall analysis. Panels (b), (c) and (d) correspond to Day-1, Day-3 and Day-5 forecasts based on GFS and panels (e), (f) and (g) correspond to Day-1, Day-3 and Day-5 forecasts of NCUM

3. Categorical Verification of Rainfall Forecasts.

The categorical approach of verifying QPF is generally based on the 2 x 2 contingency table which is evaluated for each threshold. We consider an event as a hit (a) when the prediction of an event matches with the observation on a grid point. On the other hand, an event on a grid point is predicted but it is not observed, we denote it as a false alarm (b). A miss (c) occurs when an event is not predicted but it is actually observed. Finally, correct rejection (d) is when an event does not occur and model does not predict. Based on these components of the contingency table, categorical skill scores are computed for different rainfall thresholds.

Table 5. Contingency table elements and verification scores used for categorical verification

		Observed		**Total**
		Yes	**No**	
Forecast	**Yes**	*Hits*	*False alarms*	*ForecastYes*
	No	*Miss*	*Correct Negative*	*ForecastNo*
Total		*Observed Yes*	*Observed No*	*Total*

1.	**POD Score or the Hit Rate (H):** POD tries to answer the question, "*What fraction of the observed "yes" events were correctly forecast?*"	$POD = \frac{hits}{hits + misses}$ Its value varies from 0 to 1, for perfectly forecasted events POD=1.
2.	**FAR (F)**: *What fraction of the predicted "yes" events actually did not occur?*	$FAR = \frac{false\ alarms}{hits + false\ alarms}$ Its value varies from 1 to 0, for perfectly forecasted events FAR=0
3.	**CSI:** *How well did the forecast "yes" events correspond to the observed "yes" events?* The CSI, also known as threat score.	$CSI = \frac{hits}{hits + misses + false\ alarms}$ Its value varies from 0 to 1, for perfectly forecasted events CSI=1
4.	**BIAS:** *How did the forecast frequency of "yes" events compare to the observed frequency of "yes" events?*	$BIAS = \frac{hits + false\ alarms}{hits + misses}$ Its value varies from 0 to ∞, for perfectly forecasted events BIAS=1 *(BIAS>1) => overforecast events* *(BIAS<1) => underforecast events*
5.	**ETS:** *How well did the forecast "yes" events correspond to the observed "yes" events (accounting for hits due to chance)?*	$ETS = \frac{hits - hits_{random}}{hits + misses + false\ alarm - hits_{random}}$ $hits_{random} = \frac{(hits + miss)(hits + false\ alarms)}{total}$ This score ranges between -1/3 to 1. '0' shows no skill and 1 denotes the perfect skill.
6.	**HK:** *How well did the forecast separate the "yes" events from the "no" events?* The expression is identical to ***HK = POD - POFD***, **(a.k.a true skill statistic, Peirce's skill score PSS)**	$HK = \left[\frac{hits}{hits + misses}\right] - \left[\frac{false\ alarms}{false\ alarms + correct\ negatives}\right]$ The value varies from -1 to 1; 0 indicates no skill and 1 denotes a perfect skill

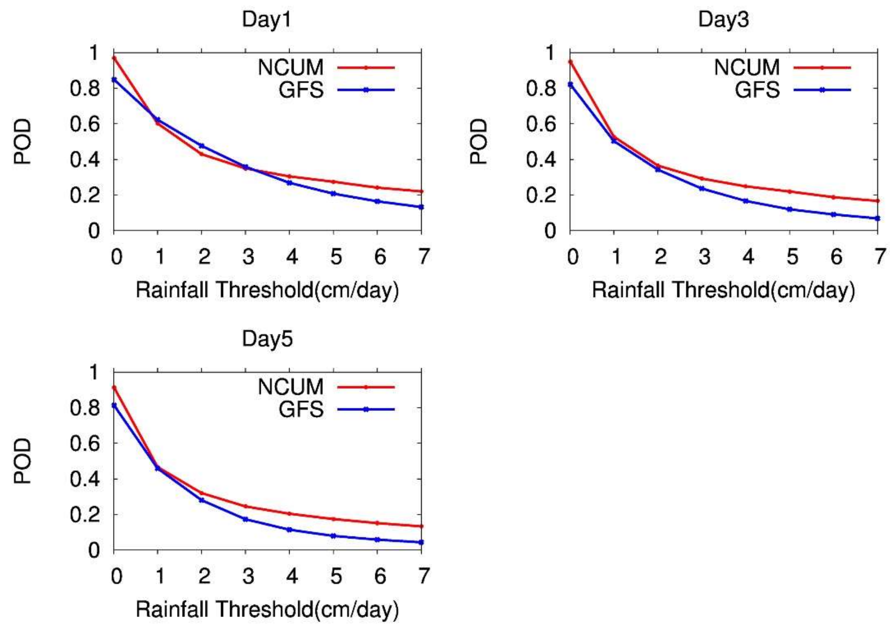

Figure 9. Probability of Detection (POD) for forecast rainfall exceeding different threshold during Jun-Sept 2019. Panels (a), (b) and (c) correspond to Day-1, Day-3 and Day-5 forecasts.

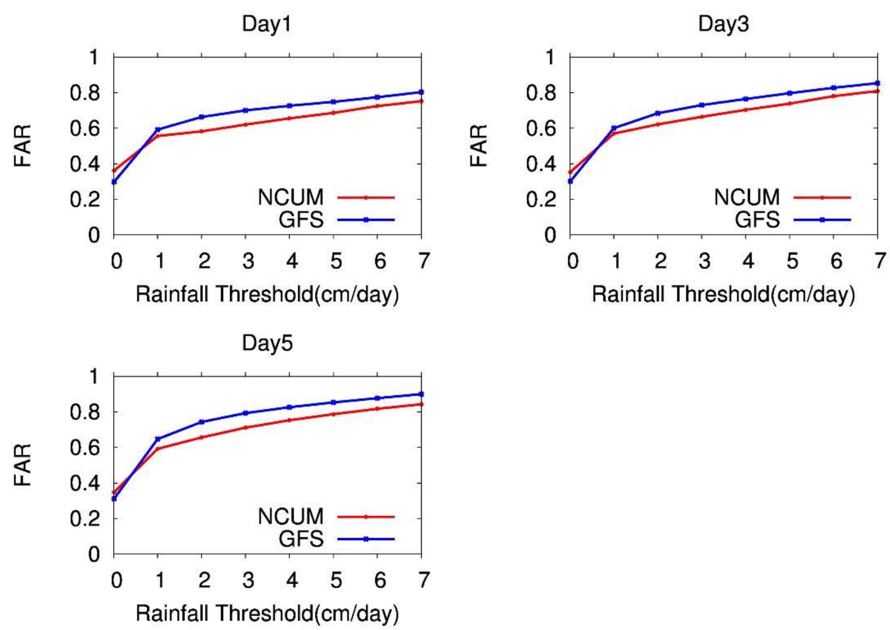

Figure 10. False Alarm Ratio (FAR) for forecast rainfall exceeding different threshold during Jun-Sept 2019. Panels (a), (b) and (c) correspond to Day-1, Day-3 and Day-5 forecasts.

3.1Probability of Detection (POD) & False Alarm ratio (FAR):

POD for different rainfall thresholds is shown in Figure 9. NCUM shows slightly higher POD than GFS for lower rainfall thresholds (<1cm/day) and for higher thresholds (>4cm/day) at all lead times. The FAR (Figure 10) for different rainfall thresholds suggest NCUM shows slightly lower FAR than GFS at all lead times and for all rainfall thresholds.

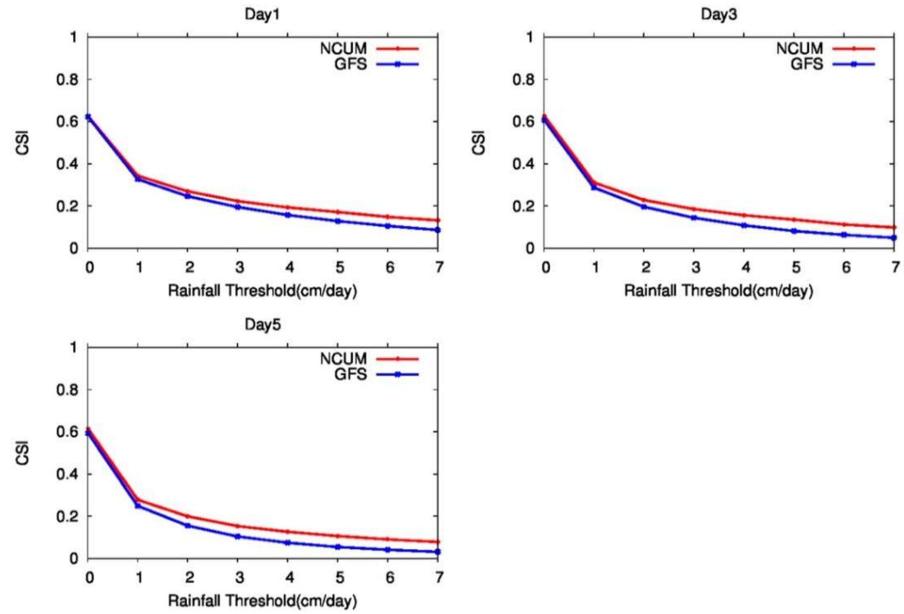

Figure 11. Critical Success Index (CSI) for forecast rainfall exceeding different threshold during Jun-Sept 2019. Panels (a), (b) and (c) correspond to Day-1, Day-3 and Day-5 forecasts.

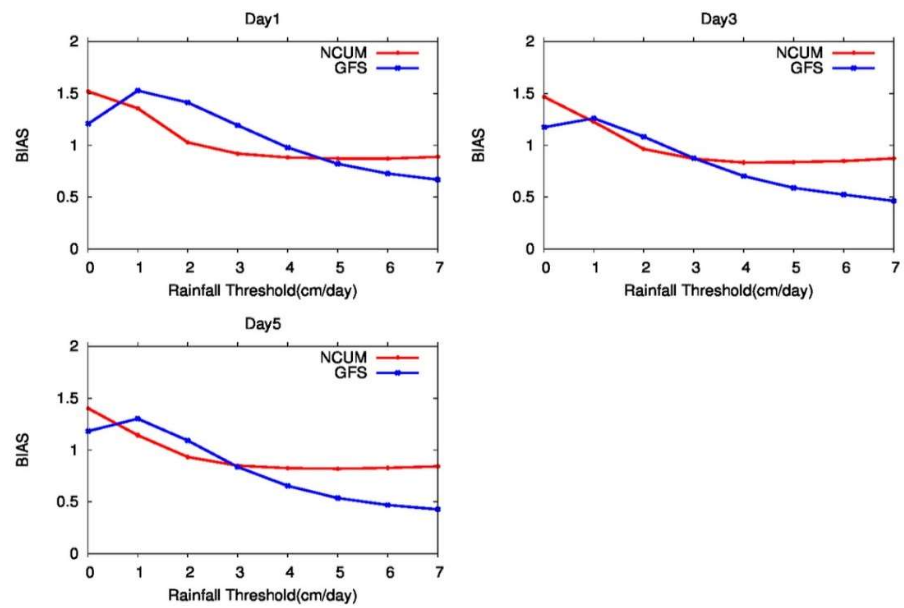

Figure 12. Frequency Bias or Bias Score (BIAS) for forecast rainfall exceeding different threshold during Jun-Sept 2019. Panels (a), (b) and (c) correspond to Day-1, Day-3 and Day-5 forecasts.

3.2 Critical Success Index (CSI) and Frequency Bias (BIAS):

The CSI for different rainfall thresholds is shown in Figure 11. NCUM shows marginally higher CSI than GFS at all lead times and for all rainfall thresholds. BIAS examined for different rainfall thresholds (Figure 12) shows both models overestimate light rains (<1cm/day) and underestimate higher rainfall amounts (>4cm/day). The BIAS score values in GFS forecasts are closer to 1 for most thresholds indicating least frequency bias.

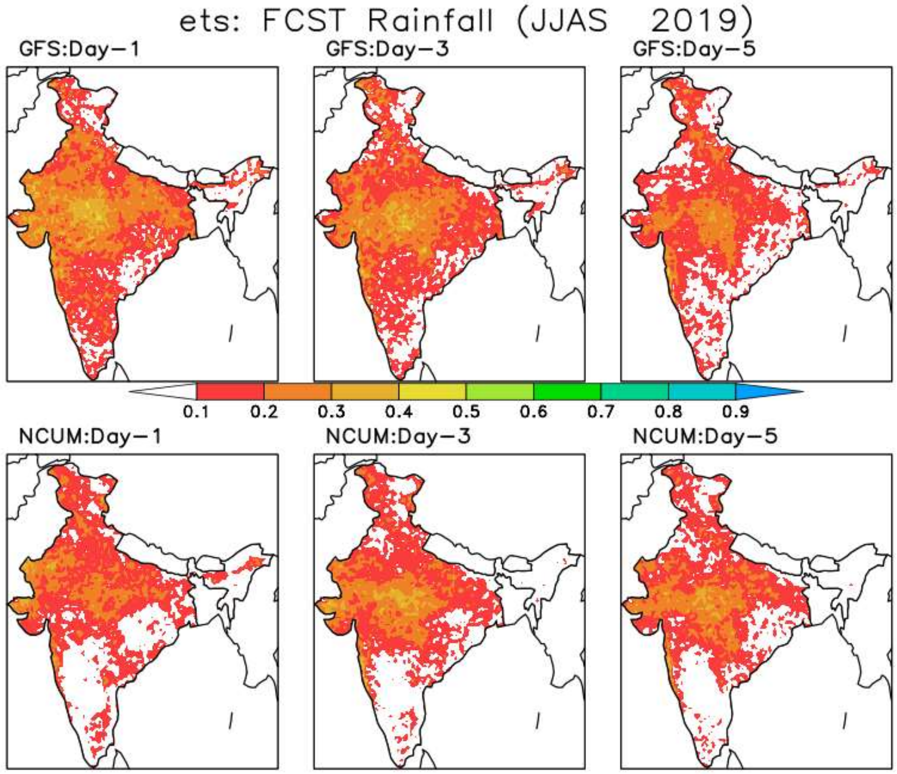

Figure 13. Equitable Threat Score (ETS) for rainfall >=0.1mm/day threshold in the forecast rainfall during Jun-Sept 2019. Panels (a), (b) and (c) correspond to Day-1, Day-3 and Day-5 forecasts based on GFS and panels (d), (e) and (f) correspond to Day-1, Day-3 and Day-5 forecasts of NCUM.

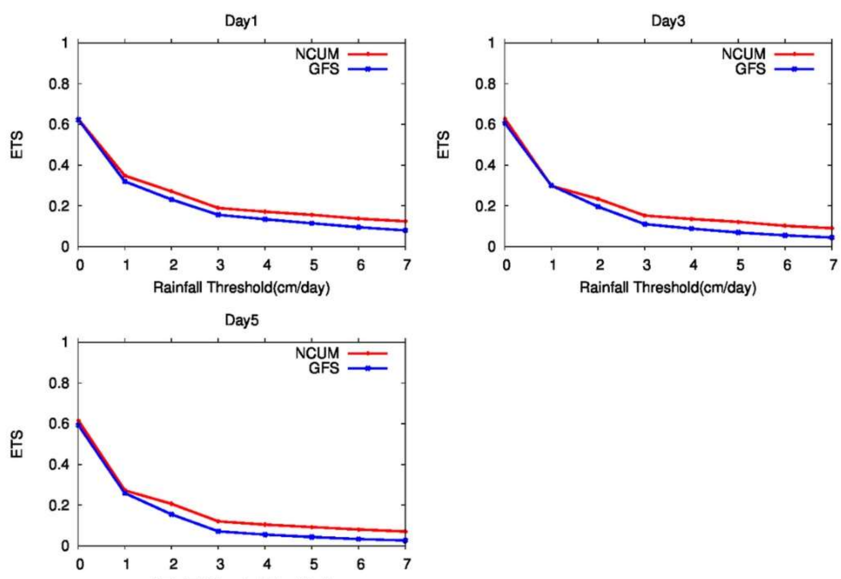

Figure 14. Equitable Threat Score (ETS) for forecast rainfall exceeding different threshold during Jun-Sept 2019. Panels (a), (b) and (c) correspond to Day-1, Day-3 and Day-5 forecasts.

3.3 Equitable Threat Score:

ETS for prediction of a rainy day frequency (>1mm/day) is shown in Figure 13. Both models show very poor skill. High values of ETS (>0.7) are completely missing. Even ETS values exceeding 0.3, which can be considered reasonable, are confined to a small region over NW India. ETS examined for different rainfall thresholds (Figure 14) shows both models have very similar forecast skill at all thresholds. However, NCUM forecast show relatively higher ETS at all thresholds > 1cm/day.

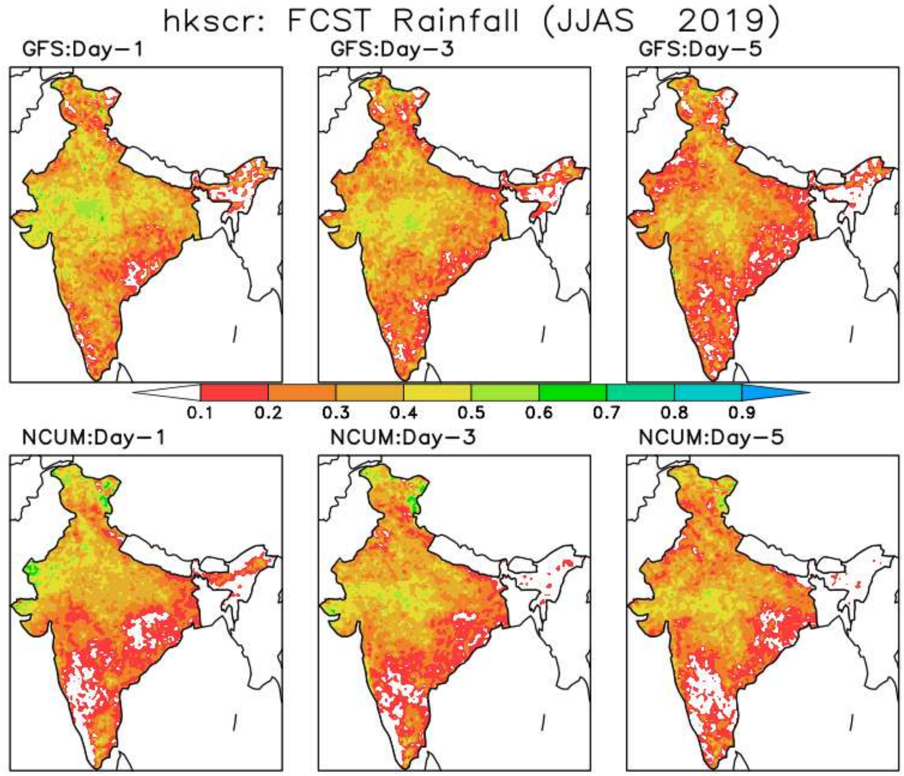

Figure 15. HK Score or Pears Skill Score (PSS) for rainfall >=0.1mm/day threshold in the forecast rainfall during Jun-Sept 2019. Panels (a), (b) and (c) correspond to Day-1, Day-3 and Day-5 forecasts based on GFS and panels (d), (e) and (f) correspond to Day-1, Day-3 and Day-5 forecasts of NCUM.

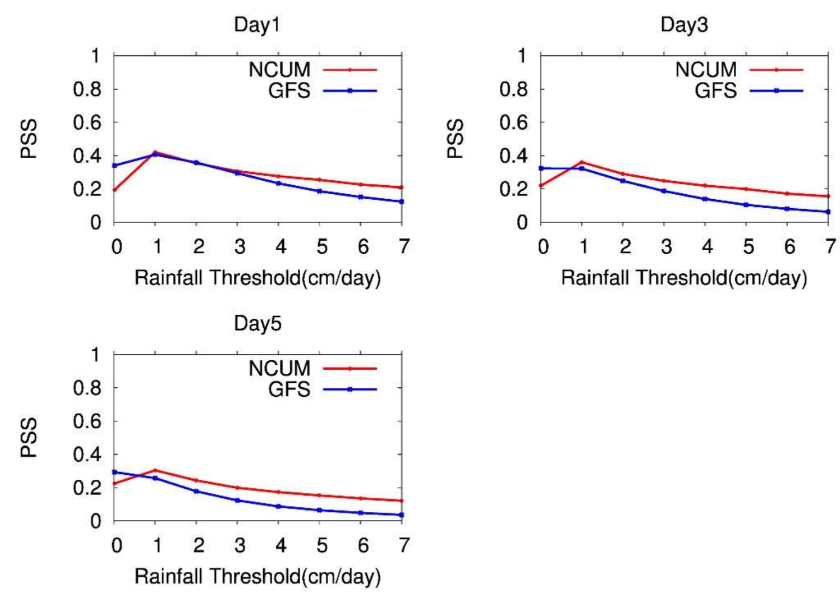

Figure 16. HK Score or Pears Skill Score (PSS) for forecast rainfall exceeding different threshold during Jun-Sept 2019. Panels (a), (b) and (c) correspond to Day-1, Day-3 and Day-5 forecasts.

3.4 Hansenn Kuipper Score:

HK Score is the true skill statistics and is also known as Pears's Skill Score (PSS). PSS for prediction of a rainy day (>1mm/day) is shown in Figure 15. Large parts of western and NW India features higher values (>0.5) suggesting good skill. PSS examined for different rainfall thresholds (Figure 16) shows NCUM consistently has higher skill at all thresholds.

4. Conclusions

(i) Some of the salient conclusions drawn on the basis of verification of rainfall forecasts obtained from the GFS and NCUM are:

- Both the deterministic models i.e., GFS and NCUM predict excessive rainfall over the mountains and neighbouring seas areas. The overestimation (10mm) of rainfall by the deterministic models over most parts of India is seen from the Mean Error (ME) plots. The Mean Error is seen to be more than 10 mm.
- Both GFS and NCUM show a higher (by over 20 to 49) number of rainy days (>1mm/day) spread over a large area compared to the observations. For higher thresholds, i.e., moderate rain (>15.6mm/day) the both models indicate reasonable agreement with observations. For Heavy Rain (>65.5 mm/day) NCUM indicate comparable frequency over west coast while GFS indicates underestimation.
- In forecasts from both the models there are large areas with highest rainfall < 5 mm. NCUM is seen to be relatively dryer than IMD GFS over peninsular parts of India.

(ii) Prediction of active/weak rainfall spells and northward propagation of the rainfall bands is studies using Hovemuller plots of observed and model forecast rainfall averaged over longitudes 70-85°E.

- Both GFS and NCUM have excessive rain compared to the observations. The active rainfall spells and northward propagation of rainfall bands during early and latter part of June, centered on mid-July, centered on mid-August and latter part of September are predicted very well in both GFS and NCUM.
- During June and July both GFS and NCUM successfully predict the extended dry spell seen to the north of 20N. However, the dry spell seen to the south over peninsula (5-15N) is missed out in the forecasts.
- Prolonged dry spell from mid-July to mid-Aug is completely missed in GFS, while Day-3 and Day-5 forecasts of NCUM do a better job in predicting the dry spell. The dry spell extending from 1-15 Sept is predicted by both models.
- The dry spell centered around 1st Aug is predicted relatively better in NCUM Day-3 and Day-5 forecasts. Similarly, the dry spell in the middle part of Sept is impressive in NCUM forecasts. In

GFS forecasts, the dry spells are not distinctly dry. The rainfall spells seem continuous without distinct gaps as in observations. Around 10-15°N, it is as though raining all the time in GFS.

(iii) Verification of rainfall forecasts is carried out using continuous as well as categorical verification scores. Continuous verification scores of suggest that:

- Both GFS and NCUM show widespread errors (>3mm/day) over Indo-Gangetic Plain and Eastern India. In NCUM the ME values are much higher (>10mm/day) over Indo-Gangetic plains and NE India. Similarly in the IMD GFS forecasts also have high ME values (10mm/day) over eastern India.
- The RMSE >15mm is evident over the wet regions like the west coast, eastern Indian and NE India. The dry regions of eastern peninsula and NW India have low RMSE. The RMSE is found to increase from Day-1 to Day-5 in both models.
- Both the models show high values of CC over central and western India. Both the deterministic forecasts (NCUM and GFS) show die-off (decay in CC) from Day-1 to Day-5. Particularly GFS forecasts show faster reduction in CC.

From categorical verification scores it is seen that:

- **POD and FAR:** NCUM shows a higher POD for the case of rain/no rain. For the other thresholds the POD values are higher in NCUM compared to GFS. Both NCUM and GFS show relatively high FAR over the dry regions of peninsula and NW India. On the other hand, NCUM shows lower FAR at all the thresholds as compared to IMD GFS.
- **CSI & BIAS**: Both NCUM and GFS show values of CSI with marginal difference at all thresholds. However, NCUM and GFS show wet bias (overestimation) for lower thresholds (<2cm/day) and dry bias (underestimation) for higher thresholds (>2cm/day). Except at lower thresholds, BIAS in NCUM forecast is closer to 1 relatively better performance of NCUM.
- **ETS:** Both models show very poor skill in terms of ETS. High values of ETS (>0.7) are completely missing. Even ETS values exceeding 0.3, which can be considered reasonable, are confined to a small region over NW India. NCUM Day-5 forecast has higher ETS than for GFS. ETS examined for different rainfall thresholds shows that both models have very similar forecast skill.
- **PSS:** GFS Day-1 forecast shows a higher PSS than NCUM for the rain/no rain case. PSS in NCUM Day-5 forecasts are higher than in GFS. NCUM exhibits a higher PSS for rainfall exceeding all the other thresholds.

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