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Verification of heavy rainfall in NWP models : A case study

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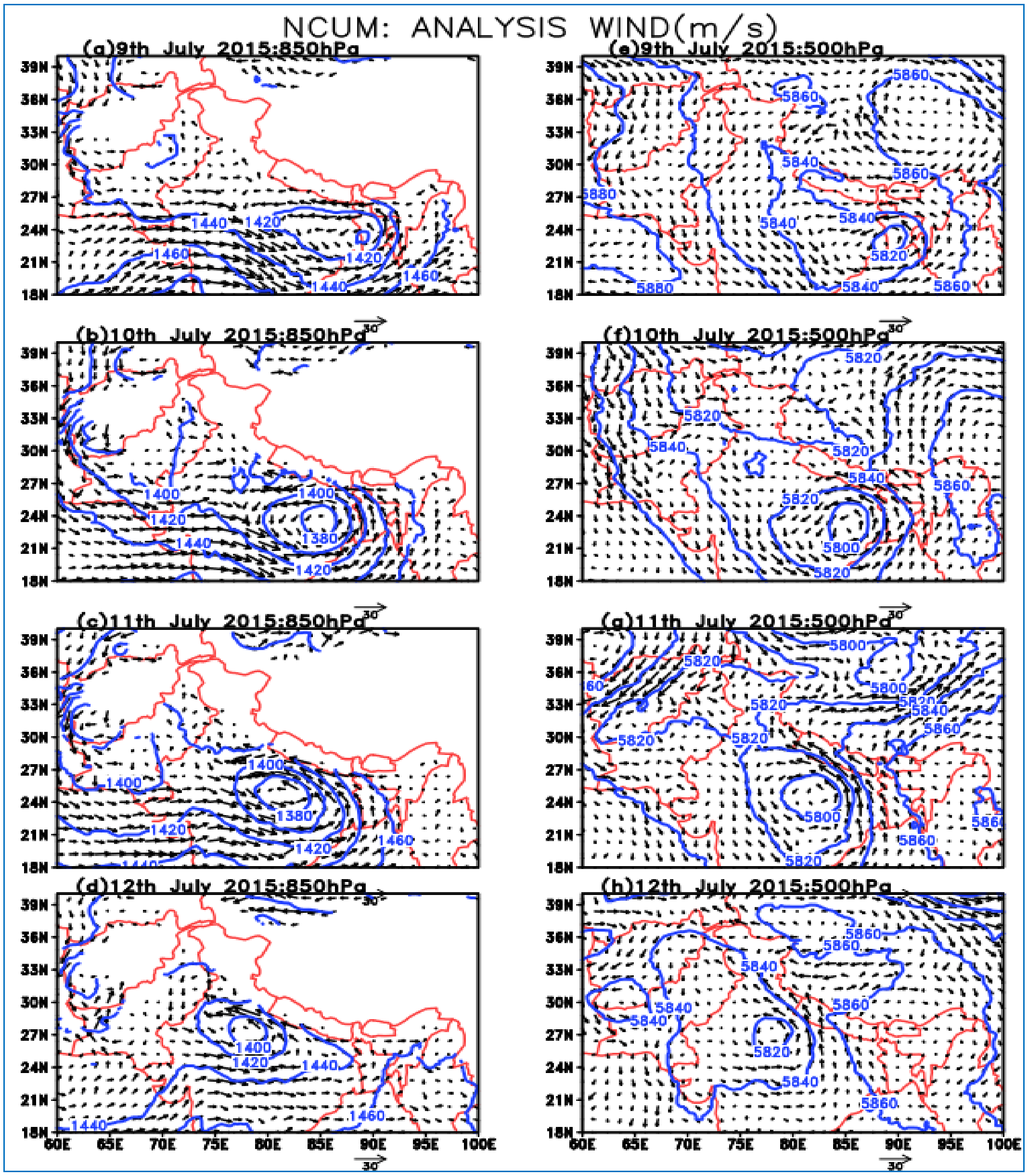
सार - भारी वर्षा की घटनाओं का पूर्वानुमान करना अत्यधिक उन्नत नवीनतम उच्च विभेदन वाले NWP मॉडल सिस्टम के लिए अभी भी चुनौती है। कम दाब प्रणाली के मार्ग और गति से होने वाली काफी स्थानिक त्रुटियों से पूर्वानुमानित वर्षा का सटीक पूर्वानुमान करने में ये मॉडल प्राय: असफल होते है। मॉडल भौतिकी और गतिक समाकृति में परिवर्तनों और सुधारों के प्रभाव का मॉनीटरन करने के लिए वर्षा के स्थान और उसकी मात्रा के पूर्वानुमान में त्रुटियों की मात्रा बढ़ने के बारे में जानना पूर्वानुमानकर्ताओं (पूर्वानुमान का चयन और व्याख्या करना) और मॉडलरों के लिए आवश्यक है। इस शोध पत्र में बंगाल की खाड़ी (BOB) में निम्न दाब प्रणाली से जुड़ी भारी वर्षा के समय वर्षा के पूर्वानुमान में त्रुटियों के परिमाण के लक्षण बताए गए हैं और खुलासा किया गया है। इस जाँच का यह विश्लेषण जून से सितंबर (JJAS) 2015 में हुई भारी वर्षा की तीन घटनाओं के आधार पर किया गया। इन भारी वर्षा वाली घटनाओं का पूर्वानुमान करने के लिए NCMRWF की भूमंडलीय पूर्वानुमान प्रणाली (NGFS), NCMRWF का एकीकृत मॉडल (NCUM) और आस्ट्रेलियाई समुदाय जलवायु और पृथ्वी प्रणाली सिमुलेटर- भूमंडलीय (ACCESS-G) इन तीन निर्धारित मॉडलों के निष्पादन का विश्लेषण किया गया। वर्षा की इन तीन घटनाओं के लिए मॉडलों के सापेक्षिक निष्पादन जानने के लिए चरम वर्षा के सत्यापन पर विशेष बल देते हुए RMSE, ETS, POD और HK स्कोर जैसे मानक सत्यापन मीट्रिक्स के अलावा इस शोध पत्र में EDS (एक्सट्रीम डिवेंडेंसी स्कोर) EDI (एक्ट्रीम डिवेंडेंस इंडैक्स) और सिमीट्रिक EDI जैसे स्कोरों के नए समूह का भी प्रयों किया गया है। इन परिणामों से यह पता चलता है कि वर्षा के पूर्वानुमान में विशेष कर भारत में उच्च लीडटाइम पर NCUM और ACESS-G में एक समान मॉडलिंग फ्रेंमवर्क NGFS से अधिक अच्छा कार्य कर रहा है। NCUM पूर्वानुमान में सापेक्षिक संशोधित कौशल से (*i*) संशोधित विभेदन (~ 17 कि. मी.) और (*ii*) NCUM END गेम डायनमिक प्राप्त किए जा सकते है।

ABSTRACT. Forecasting of heavy rainfall events is still a challenge even for the most advanced state-of-art high resolution NWP modelling systems. Very often the models fail to accurately predict the track and movement of the low pressure systems leading to large spatial errors in the predicted rain. Quantification of errors in forecast rainfall location and amounts is important for forecasters (to choose a forecast and interpret) and modelers for monitoring the impact of changes and improvements in model physics and dynamics configurations. This study aims to quantify and summarize errors in rainfall forecast for heavy rains associated with a Bay of Bengal (BOB) low pressure systems. The verification analysis is based on three heavy rain events during June to September (JJAS) 2015. The performance of the three deterministic models, NCMRWF's Global Forecast Systems (NGFS), NCMRWF's Unified Model (NCUM) and Australian Community Climate and Earth-System Simulator – Global (ACCESS-G) in predicting these heavy rainfall events has been analysed. In addition to standard verification metrics like RMSE, ETS, POD and HK Score, this paper also uses new family of scores like EDS (Extreme Dependency Score), EDI (Extremal Dependence Index) and Symmetric EDI with special emphasis on verification of extreme rainfall to bring out the relative performance of the models for these three rainfall events. The results indicate that Unified modeling framework in NCUM and ACCESS-G by and large performs better than NGFS in rainfall forecasts over India specially at higher lead times. Relatively improved skill in NCUM forecasts can be attributed to (*i*) improved resolution (~17 km) and (*ii*) END Game dynamics of NCUM.

Key words – NCUM, NGFS, ACCESS-G, EDI, EDS and Symmetric EDI.

1. Introduction

Rainfall during the monsoon season is characterized by active and weak spells associated with the movement of monsoon trough and intra-seasonal oscillations (Rajeevan *et al.*, 2010). While the Bay of Bengal low pressure systems also contribute significantly to the seasonal rainfall, they often lead to incessant rainfall



Figs. 1(a-h). (a-d) 850 hPa and (e-h) 500 hPa wind analysis from NCUM valid on 9, 10, 11 and 12 July, 2015

episodes and flooding over parts of eastern and central India (Krishnamurthy and Ajaymohan, 2010; Mooley and Shukla, 1987; Krishnamurti *et al*., 1975; Sikka, 1977, 2006). In the recent years state-of-art NWP models are operationally used to forecast the rainfall over different spatial and temporal scales. With the use of high resolution models and advanced data assimilation methods, NWP models have demonstrated continued improvement in the forecast skill and accuracy (Bougeault, 2003; Mass *et al*., 2002; Klingaman and Woolnough, 2013, 2014; Bush *et al*., 2015). High resolution models often successfully predict the heavy and very heavy rainfall amounts typically associated with the lows and depressions. However, there are still challenges for the NWP for accurate prediction of location, timing and duration of heavy rainfall spells associated with these lows and depressions. Very often the models fail to accurately predict the track and movement of the low pressure systems leading to large spatial errors in the predicted rain. Quantification of the errors in forecast rainfall is important for operational forecasters (to choose a forecast and interpret) and modelers (for monitoring the impact of changes and improvements in model physics and dynamics configurations). This study aims to quantify and summarize errors for recent case of the depression that formed as low pressure over Head Bay of Bengal.

TABLE 1

Brief description of the three models used in the study

Model Features	NGFS	NCUM (UM8.5)	ACCESS-G (UM7.5)
Horizontal Resolution	Spectral truncation of 574 waves in the zonal direction (T574) with a Gaussian grid of 1760 × 880 points (~22 km resolution near equator)	N768 (~17 km at mid-latitude) with a EW-NS grid of 1536 × 1152 points	N 320 (~40km at mid-latitude) with a EW-NS grid of 640 × 481 points
Vertical levels	64 hybrid sigma-pressure levels. The hybrid coordinate system is terrain following in the lower levels and transforming to pure pressure levels in the upper levels.	70 vertical levels (height-based and terrain-following near the bottom boundary)	70 vertical levels (height-based and terrain-following near the bottom boundary)
Model Time step	2 Minutes	7.5 Minutes	12 Minutes
Data Assimilation	3D-Variational Grid point Statistical Interpolation–GSI (Wu *et al*., 2002)	4D-Variational Data Assimilation System (Rawlins et al., 2007)	4D-Variational Data Assimilation System (Rawlins *et al*., 2007)
Forecast Lead Time	10 Days	10 days	10 Days
Dynamics	Spectral, Hybrid sigma-p, reduced Gaussian grids	ENDGame (Even newer dynamics for general atmospheric modeling of the environment)	Non-hydrostatic dynamics with deep atmosphere. Height vertical coordinates with levels transitioning from terrain following to height.
Time Integration	Leapfrog/Semi-implicit	Semi-implicit integration with 3D semi-Lagrangian advection	Semi-implicit integration with 3D semi-Lagrangian advection
Convection	New Massflux scheme for shallow convection and SAS for deep convection	Massflux with CAPE closure (Jayakumar *et al*., 2015)	Modified form of mass flux scheme based on Gregory and Rowntree (1990) with modified CAPE closure to enhance model stability

In India, National Centre for Medium Range Weather Forecasting (NCMRWF) provides real-time weather predictions based on two deterministic NWP models: NCMRWF's Global Forecast System [NGFS] and NCMRWF Unified Model (NCUM). Additionally the global model forecasts obtained from the Australian Community Climate Earth System Simulator (ACCESS-G) are also investigated. The study compiles the verification and statistics of NCUM, NGFS and ACCESS-G modelsalong the track of the monsoon depression which originated over Bay of Bengal and move north-westward giving wide spread rainfall over Gangetic West Bengal, Bihar, Jharkhand, Madhya Pradesh, Uttar Pradesh, Delhi, Haryana and Punjab during 11th and 12th July 2015. Additionally, two more cases are also investigated to assess the consistency of results. The verification categorical scores like ETS, POD etc. followed by a new set of scores (EDS, EDI and SEDI) for extreme rainfall even tare also presented.

The paper is organized into five sections. The first section besides providing introduction also summarizes the synoptic situation (Section 1.1) of the weather system that was observed during 11th and 12th July. Section 2 is devoted to describing the observed and model forecast data used in this study. A brief discussion on verification methodology is presented in section 3. The results are discussed in detail based on synoptic and categorical verification in Section 4. Conclusions are summarized in Section 5.

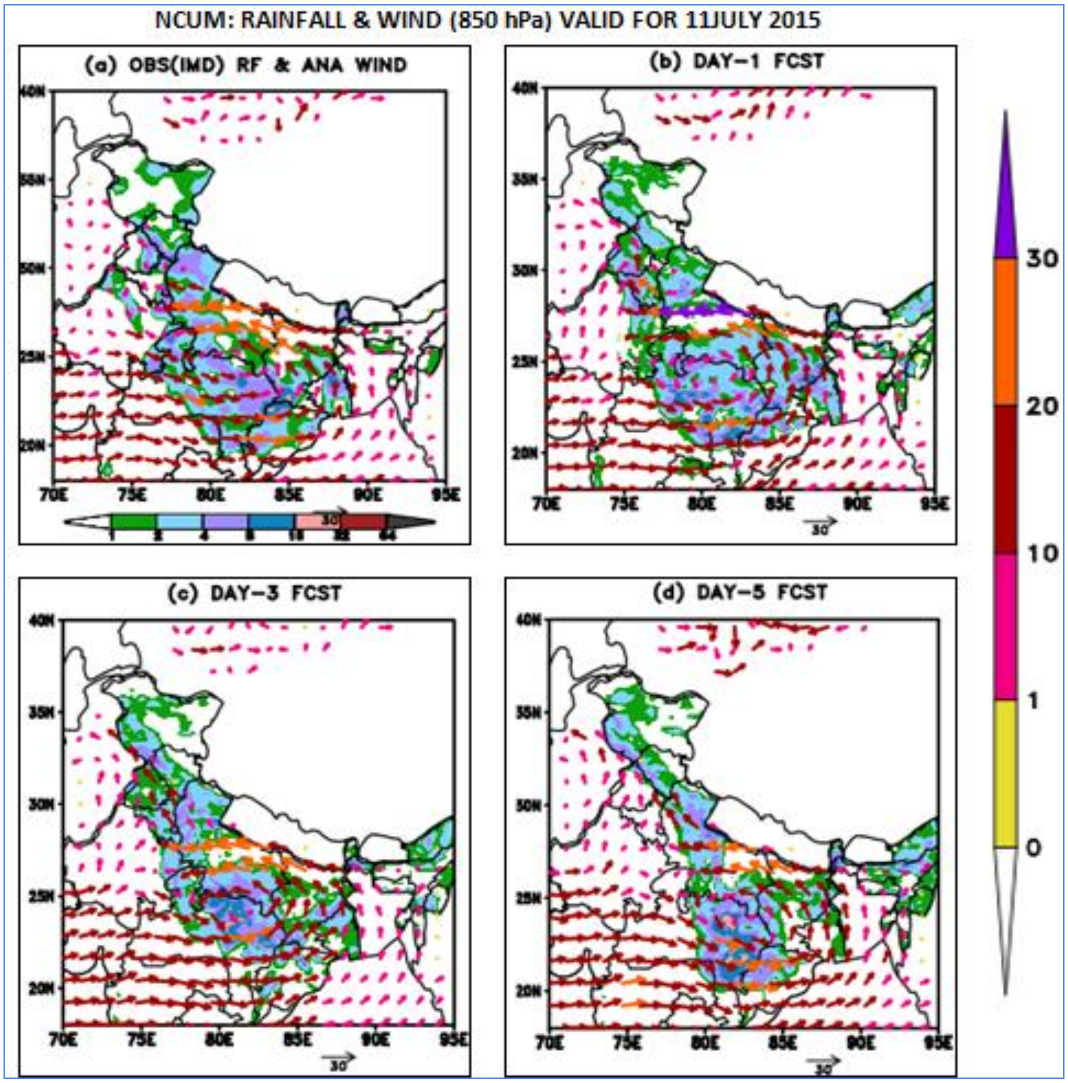
TABLE 2

Contingency table representing the frequencies of forecast observation pairs for which the event and non-event were forecasted and observed

		Observed		Total
		Yes	No	
Forecast	Yes	Hits	False alarms	Forecast yes
	No	missed	Correct negatives	Forecast no
	Total	Observed yes	Observed no	total

1.1. *Synoptic features as observed during 11-12 July, 2015*

Some of the major synoptic features observed on 11th and 12th of July 2015 were taken from the All India



Figs. 2(a-d). Observed and NCUM model predicted wind (m/s) rainfall (cm/day) over 70-95° E, 18-40° N valid for 0300 UTC 11th July, 2015

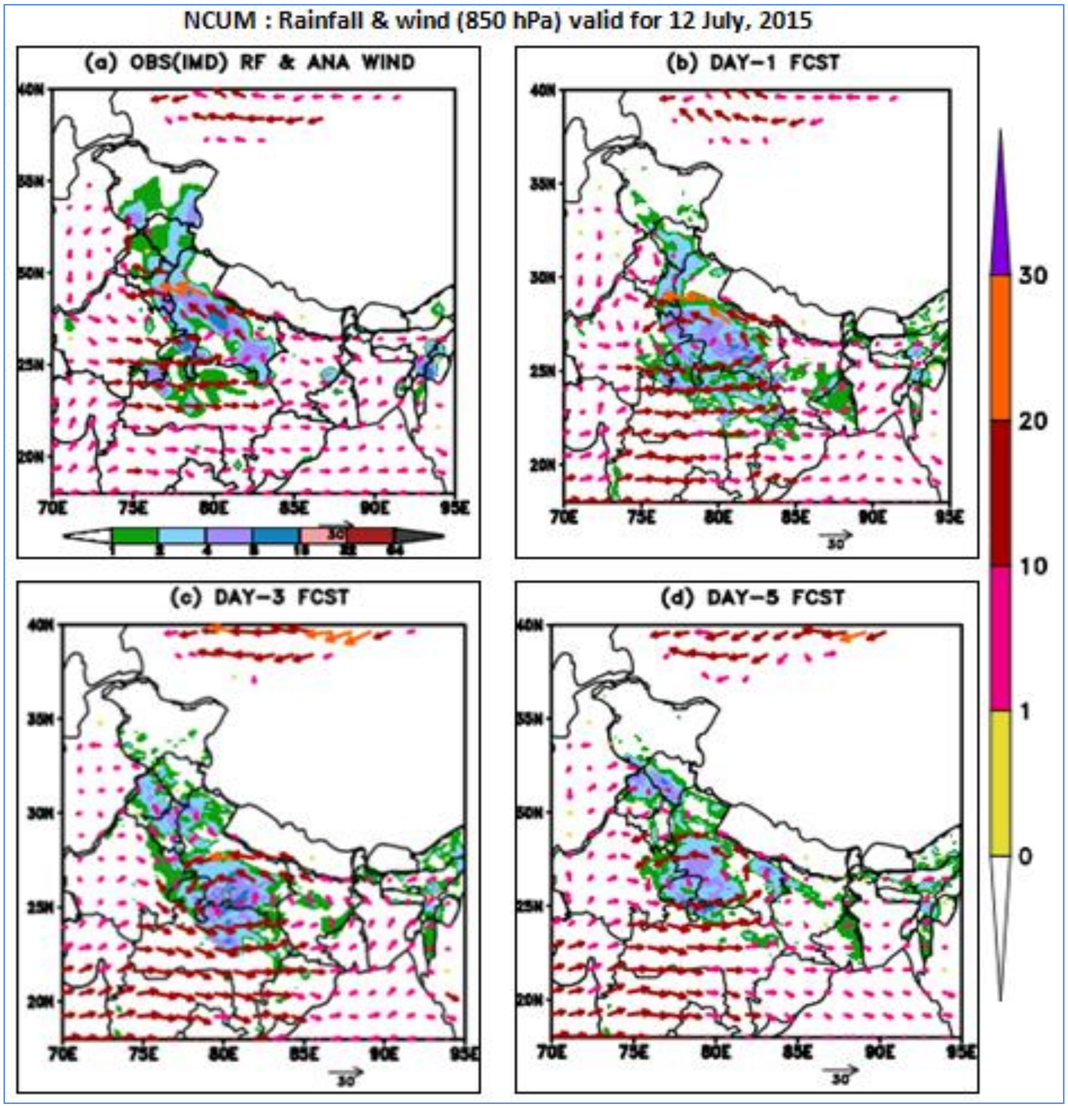
Weather Summary released by India Meteorological Department and are listed below:

(*i*) The monsoon trough was seen extending from the Bay of Bengal up to Punjab through the low pressure area over Uttar Pradesh and adjoining Madhya Pradesh region.

(*ii*) A low pressure system which was formed over Head Bay of Bengal on 8th July, 2015 which moved north-west ward direction. It further intensified and became a well-marked low on 9th July. The rainfall system sustained its north-westward movement till 12th July and dissipated afterwards.

(*iii*) A western disturbance in the form of trough in the middle tropospheric levels was observed over North Pakistan and adjoining areas on 9th July which moved further eastward and it was observed near northern regions of India (Punjab, Haryana, Uttarakhand and adjoining areas) on 11th July, 2015.

Figs. 1(a-h) depicts the 850 and 500 hPa NCUM's analysed winds from 9th to 12th of July 2015. The analysis of NGFS and ACCESS-G (Fig. not shown) are almost similar. The 850 hPa analysed winds [Figs. 1(a-d)] shows low pressure system which was observed on 9th July near Gangetic West Bengal and Bihar moving north-westwards from 9th to 12th of July. On 12th July, this system is located near western region of Uttar Pradesh and eastern parts of Haryana.



Figs. 3(a-d). Observed and NCUM model predicted wind (m/s) rainfall (cm/day) over 70-95° E, 18-40° N valid for 0300 UTC 12th July, 2015

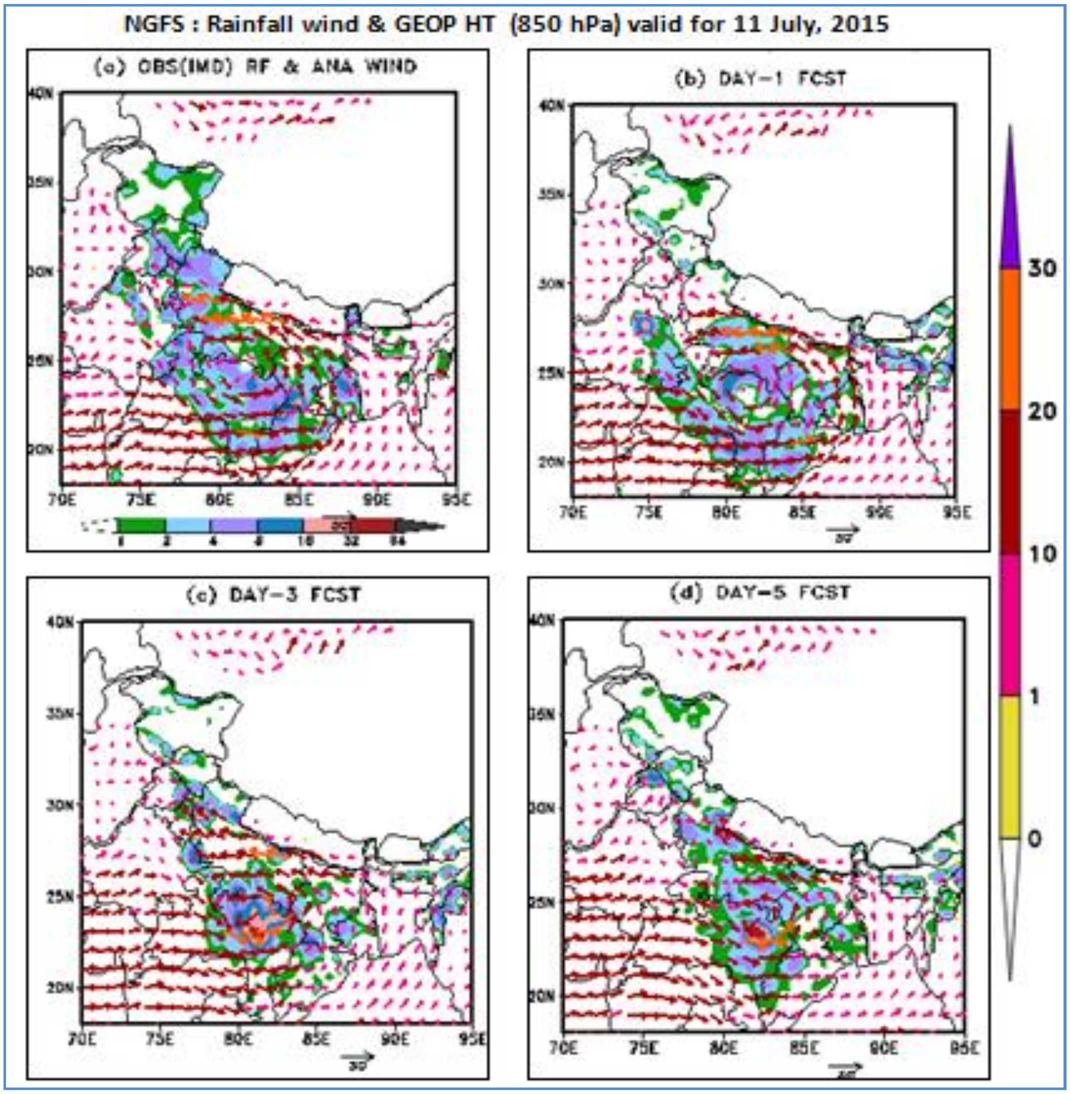
2. Data used in this study

2.1. *Observed rainfall data*

The rainfall data used for verification of the model forecasts is the IMD and NCMRWF merged satellite gauge (NMSG) data (Mitra *et al*., 2009; Mitra *et al*., 2013). This rainfall data is a merged product of satellite estimates of Tropical Rainfall Measuring Mission (TRMM) 3B42 (V7) and rain gauge observations (IMD) at 0.5° horizontal resolution, accumulated for 24 hours daily at 0300 UTC. The forecast rainfall from NGFS, NCUM and ACCESS-G are 24-hour accumulations valid at 0300 UTC to match with the observations. The merging of the IMD gauge data into TRMM 3B42 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).

2.2. *Model forecast rainfall data*

The real-time forecasts from NCMRWF are based on the two high resolution models NGFS and NCUM which have resolution of T574L64 (~22 km in tropics) and N768L70 (~17 km in Mid-latitudes) respectively. The ACCESS-G (~40 km in Mid-latitudes) model forecasts are available at a relatively coarser resolution. Additional details about the deterministic models NGFS and NCUM operational at NCMRWF can be found at Prasad *et al*. (2011) and Rajagopal *et al*. (2012) respectively. More details about ACCESS-G are



Figs. 4(a-d). Observed and NGFS model predicted wind (m/s) rainfall (cm/day) over 70-95° E, 18-40° N valid for 0300 UTC 11th July, 2015

given in http://www.bom.gov.au/australia/charts/bulletins/apob93.pdf.The forecast rainfall data from the three models has been re-gridded on to a common grid spacing of 0.5 × 0.5 degree to match with the observations using bilinear interpolation. Table 1 gives a brief description about the three models used in the study.

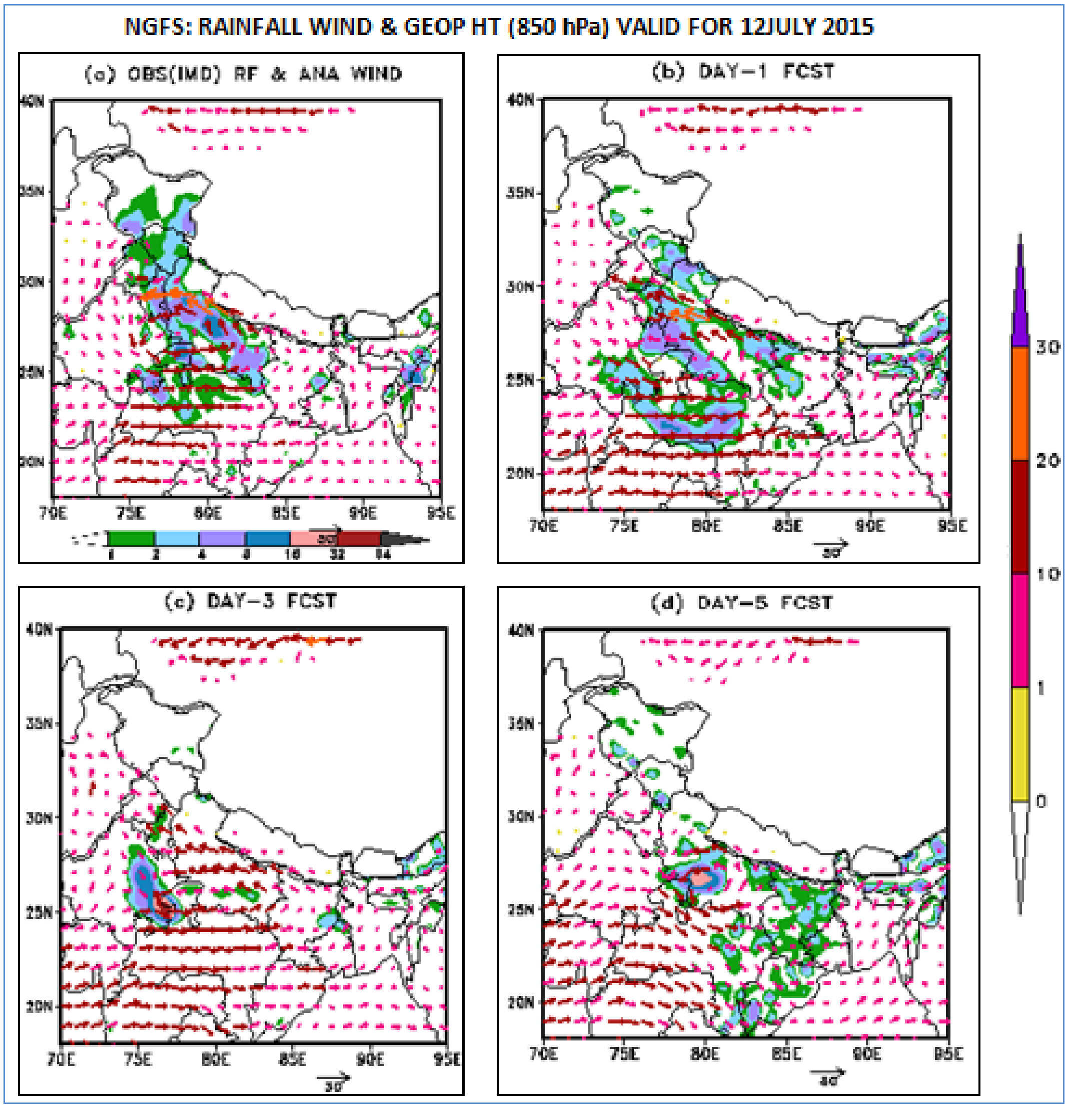
3. Verification methodology

In this study, the categorical verification is used based on the components of contingency table (Table 2) analysis. This approach is applied for rainfall forecast along the track of the depression, *i.e*., East M. P., Chhattisgarh, Bihar, Jharkhand and Gangetic West Bengal on 11th July and West U. P, North M. P., Haryana and Delhi and adjoining areas on 12th July, 2015. All grids over the neighbouring seas and over Himalayas above 4000 m were masked out to focus on the heavy rainfall over the land regions unaffected by the orography. Categorical statistics based on the components of contingency table (Table 2) to describe the particular aspects of forecast performance. Jolliffe and Stephenson (2011) and Wilks (2011) provide detailed descriptions of these scores. Table 3 provides the list of some of the scores used in the study.

4. Results and discussion

4.1. *Synoptic features and rainfall*

A qualitative summary of verification and intercomparison is presented first mainly involving the



Figs. 5(a-d). Observed and NGFS model predicted wind (m/s) and rainfall (cm/day) over 70-95° E, 18-40° N valid for 0300 UTC 12th July, 2015

synoptic features of the rainfall system. Figs. 2(a-d) and 3(a-d) show the observed and predicted rainfall along with circulation at 850 hPa for NCUM valid for 11 and 12 July, 2015 respectively. The rainfall is valid at 0300 UTC accumulated in last 24 hours while the winds at 850 hPa are valid at 0000 UTC. Figs. 2(a-d) depict the Day 1, Day 3 and Day 5 forecasts valid on 11th July, 2015. Day-1 to Day-5 forecast shows good skill over Gangetic West Bengal, Bihar, Jharkhand, Chhattisgarh, Central and East Madhya Pradesh, Uttar Pradesh and West Himachal Pradesh.Wind circulation over Bihar, East U.P., North and east M. P. is also well captured from Day-1 to Day-5 forecast. Day-1 to Day-5 forecast valid for 12th July, 2015 [(Figs. 3(a-d)] again shows reasonable agreement of observed and forecast rainfallover Uttar Pradesh, North Madhya Pradesh, Delhi and Haryana. In the analysis, easterlies are seen over west U. P. These easterlies are fairly well captured till Day-3 forecast while in Day-5, these are slightly overestimated.

Figs. 4(a-d) and 5(a-d) show the observed and predicted rainfall along with circulation at 850 hPa for NGFS valid for 11 and 12 July, 2015 respectively. The rainfall again is valid at 0300 UTC accumulated in last 24 hours while the winds at 850 hPa are valid at 0000 UTC. Day-1 forecast predicted by NGFS on 11th July [Figs. 4(a-d)] shows good skill over East and Central Parts of MP and UP while model shows poor skill over west UP, Himachal Pradesh, Delhi and Haryana. Day-3 and Day-5 forecast shows overestimation of rainfall over East

M. P. and Chhattisgarh. The 850 hPa cyclonic circulation seen in the analysis over Gangetic West Bengal, Bihar, North and East M. P. is well captured in Day-1 and Day-3 forecast while in Day-5 forecast; weak easterlies can be seen rather than a circulation. Day-1 forecast valid for 12th July, 2015 [Figs. 5(a-d)] depicts good skill over North and West UP, Delhi, Haryana and some parts of North M. P. Rainfall in Day-3 forecast over U. P., Punjab and Himachal Pradesh is completely missed out while spurious rainfall over East Rajasthan has been predicted by NGFS.

Figs. 6(a-d) and 7 (a-d) shows the observed and predicted rainfall for ACCESS-G valid for 11 and 12 July, 2015 respectively. Day-1 and Day-3 forecast valid for 11th July [Fig. 6(a-d)] shows very good skill over Gangetic West Bengal, Bihar, Jharkhand, East and Central Parts of M. P., East and West U. P. while rainfall over M. P. is completely missing in Day-5 forecast. Day-1 to Day-5 forecast valid for 12th July [Fig. 7(a-d)] depicts very good skill over East and Central Uttar Pradesh.

4.2. *Verification for Rainfall on 11th and 12th July, 2015*

Verification statistics are computed for area bounded by the domain 20-25° N, 78-87° E. Fig. 8 shows RootMean Square Error (RMSE) verification for Day-1 to Day-5 forecasts valid on 11th and 12th July respectively. The comparison of RMSE among NCUM, NGFSand ACCESS-G reflect that NGFS has larger error than NCUM and ACCESS-G which implies the performance of NCUM and ACCES-G are better than NGFS valid for 11 and 12th July. However, NCUM and ACCESS-G are comparable to each other in all the days forecast with ACCESS-G slightly better till Day-4 while NCUM performs better in Day-5 forecast for both days.

4.3. *Event verification of QPF statistics*

Quantitative verification of the heavy rainfall associated to the depression using standard verification methods has been done.The rainfall forecast has been categorized as "hits","misses" depending upon whether the position and intensity were well predicted for two rainfall ranges occurred between 10-20 mm/day and 20-40 mm/day. Based on the components of contingency table, various statistical score like Equitable Threat Score (ETS), Probability of Detection (POD) Hansen and Kuiper Score (HK-score) are also computed.

ETS measures the fraction of events that are correctly predicted accounting for hits by random chance. High ETS would imply that there is a large number of correctly predicted forecast entities near to the location of

TABLE 3

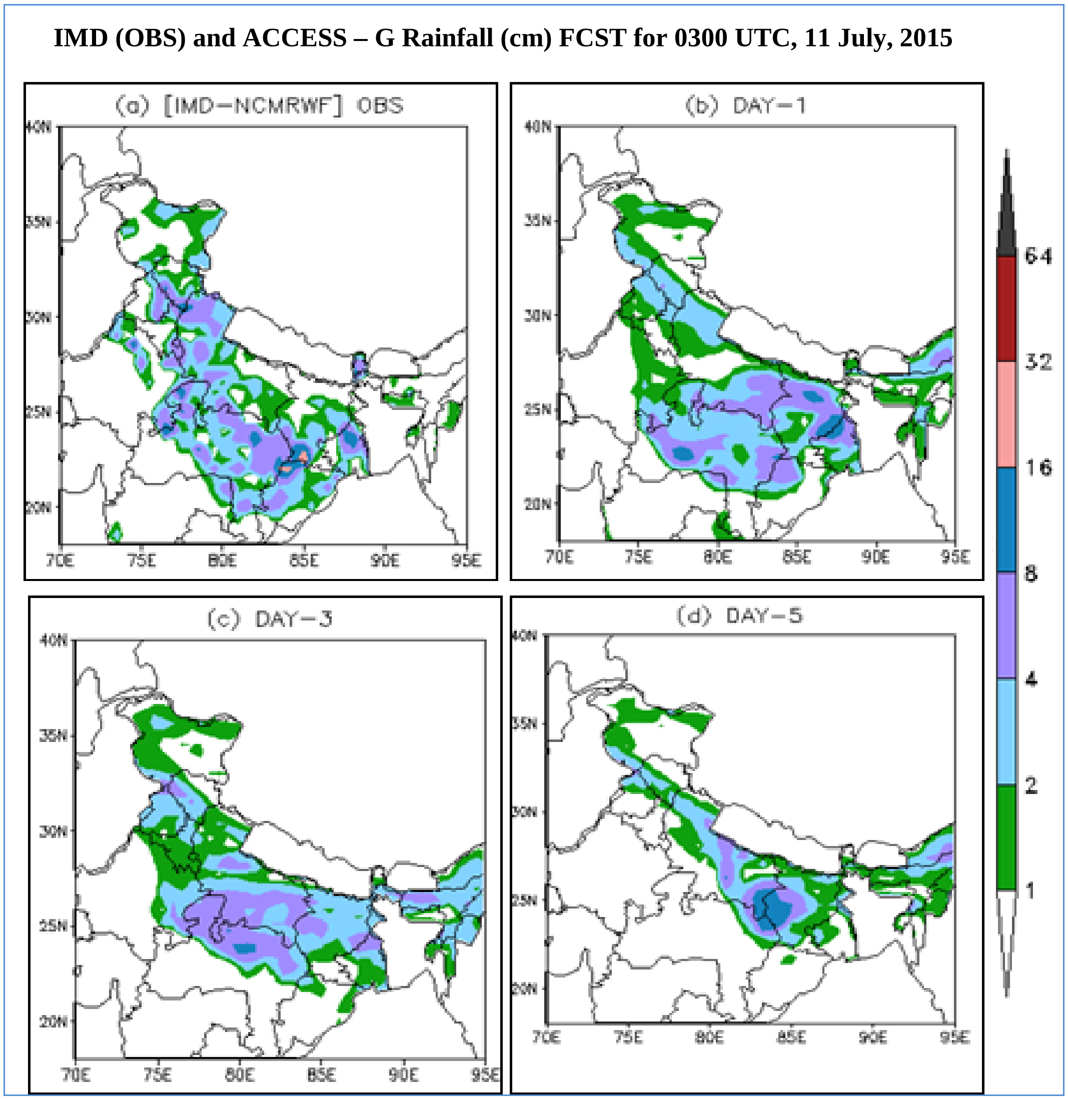
List of scores used for evaluation of categorical rainfall forecasts

$POD = \frac{hits}{hits + missess}$
$ETS = \frac{hits - hits_{random}}{hits + misses + false\ alarms - hits_{random}}$ $hits_{random} = \frac{(hits + misses)(hits + false\ alarms)}{total}$
$Accuracy = \frac{hits + correct\ negatives}{total}$ (also called proporation correct PC)
$EDS = \frac{2\log\left(\frac{hits + Misses}{total}\right)}{\log\left(\frac{hits}{total}\right)} - 1 = \frac{\ln p - \ln H}{\ln p + \ln H}$ H - hitrate
$EDI = \frac{\ln F - \ln H}{\ln F + \ln H}$ H - Hitrate, F - False alarms rate
$SEDI = \frac{\ln F - \ln H + \ln(1-H) - \ln(1-F)}{\ln F + \ln H + \ln(1-H) + \ln(1-F)}$
where, p = (hits + misses)/total is the base rate (climatology), q = (hits + false alarms)/total, is the frequency with which the event is forecast, H is the hit rate, also known as the probability of detection and F is the false alarm rate, also known as the probability of false detection

the matching observed entities (hits) and lesser number of forecast entities far away from the observations (misses and false alarms). The top panel of Figs. 9 and 10 show ETS from Day-1 to Day-5 forecast for two rainfall thresholds (10-20 mm/day: left panel and 20-40 mm/day: right panel) valid for 11 and 12 July respectively. NCUM and ACCESS-G shows higher ETS than NGFS from Day-1 to Day-5 for both the rainfall threshold (10-20 mm/day and 20-40 mm/day).

POD is defined as the fraction of observed events that were correctly predicted therefore a high POD indicates good forecast skill of a model. In the current case a high POD would imply that many forecast entities with intensities approximately matching the observations were lying close enough to the observed entities. From the middle panels of Figs. 9 and 10, it is seen that POD is consistently higher for ACCESS-G and NCUM (Day 1 to Day 5) as compared to NGFS for the forecast valid for 11th and 12th July. NCUM and ACCESS-G again shows good skill for all lead times from Day-1 to Day-5.

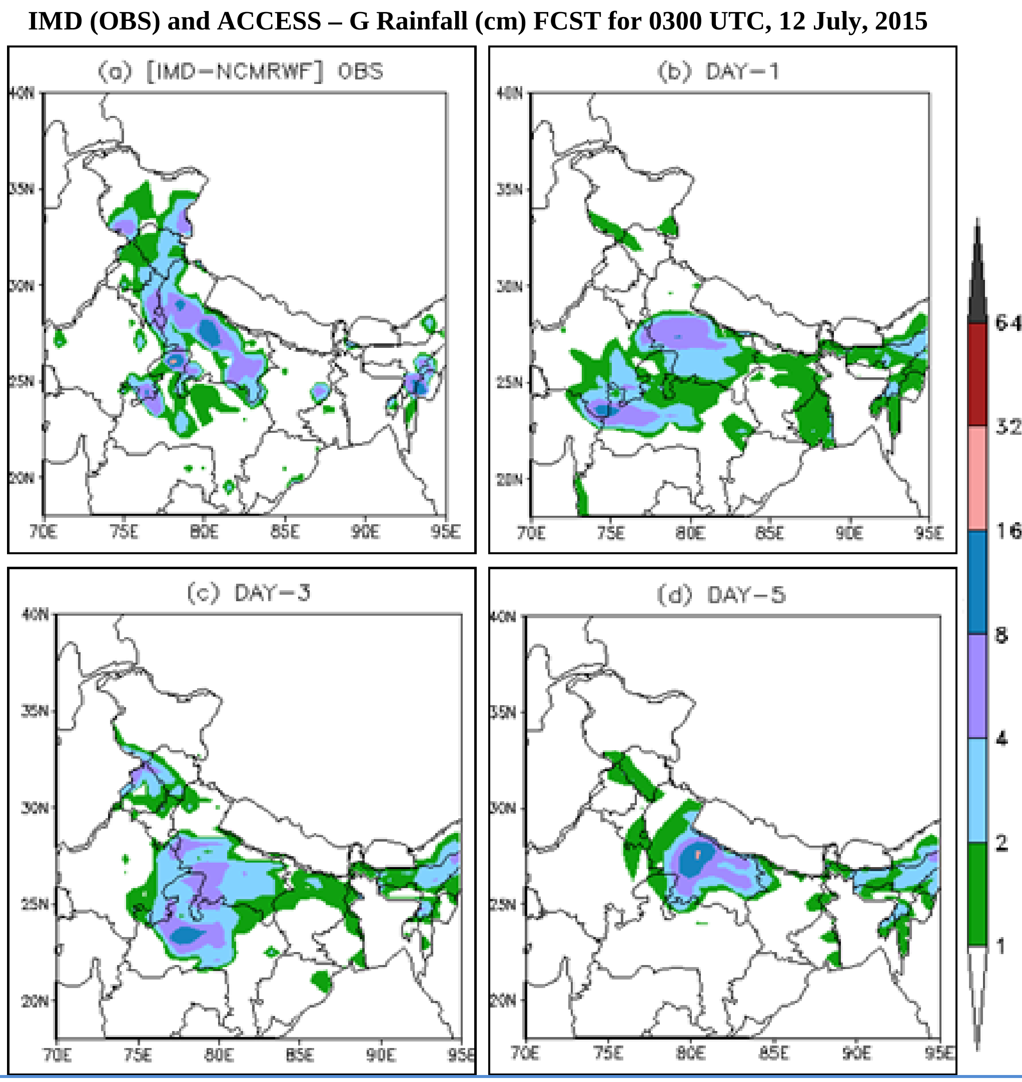
HK score, also known as the True Skill Score (TSS), is defined as the difference between the hit rate and the



Figs. 6(a-d). Observed and ACCESS-G model predicted rainfall (cm/day) over 70-95° E, 18-40° N valid for 0300 UTC 11th July, 2015

false alarm rate (Hanssen and Kuipers, 1965). A high HK score indicates more hits relative to false alarms. The bottom panel of Figs. 9 and 10 show HK score from Day-1 to Day-5 forecast for two rainfall thresholds (10-20 mm/day: left panel and 20-40 mm/day: right panel) valid for 11 and 12 July respectively. Here in the present case, for 11 and 12 July, ACCESS-G and NCUM shows higher HK score than NGFS till Day-5 for both the rainfall thresholds. However ACCESS-G performs slightly better than NCUM till Day-4 while NCUM has an edge in Day-5 forecast for both the days.

Categorical scores (like, ETS, POD etc) are less skilfulfor higher thresholds (Ashrit *et al*., 2015). These scores could be used to monitor the forecast performance and model improvements. It can be seen in Figs. 9 and 10 (Right panels), for the rainfall range of 20-40 mm/day, the categorical scores decreases especially in higher lead times. Figs. 11 and 12 show Extreme Dependency Score (EDS), Extremal Dependence Index (EDI) and Symmetric EDI (SEDI) which can be collectively called as EDS family of scores. These scores measure the association between the observed and forecast rare events. These scores range from -1 to 1 with 0 meaning no skill and 1 indicating perfect score. Though EDS does not approach 0, it has several undesirable properties like it base rate dependant sensitive to hedging, varies from -1 to 1 etc. EDI and SEDI overcome most of the drawbacks since they have non-degenerate limit and are base-rate independent, insensitive to hedging etc. (Ferro and



Figs. 7(a-d). Observed and ACCESS-G model predicted rainfall (cm/day) over 70-95° E, 18-40° N valid for 0300 UTC 12th July, 2015

Stephenson, 2011). As can be seen in Figs. 11 and 12 (right panels), for rainfall range 20-40, these scores do not converge to trivial values even at higher lead times. Further, these scores allow one to examine the relative difference in the model to modelskill. Thus EDI and SEDI make very useful candidates for forecast model intercomparison for extreme rainfall forecasts.

4.4. *Verification of QPF statistics for two more heavy rainfall events*

In the above sections, we have evaluated the skill of the three models in predicting the heavy rainfall over Delhi and its neighboring region during 11-12 July, 2015. However, Evaluation of the model's skill using a single case study in quantitative precipitation forecast (QPF) is inadequate for a conclusive assessment of the relative performance of NWP modeling systems. In order to address this issue, two more cases of heavy rainfall events out of 8 cases (heavy rainfall associated to 6 depressions and 2 cyclonic storms) during the monsoon season of 2015 have been included to evaluate skill of NCUM,NGFS and ACCESS-G. The synoptic descriptions of these cases are as follows:

(*i*) A Deep Depression (27-30 July, 2015) formed over land near Rajasthan and neighborhood. It earlier concentratedinto a depression over the Southwest Rajasthan near on 27th July and intensified into a deep depression. Itlay over southwest Rajasthan and adjoining Gujarat near on 28th July. Moving north-northeastwards, it weakened into a depression over west Rajasthan near

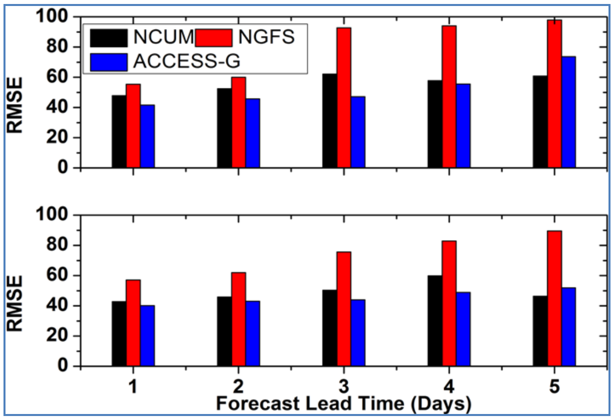


Fig. 8. Bar Graph showing RMSE for NCUM, NGFS and ACCESS-G for Day1 to Day-5 forecasts valid for 11th July, 2015 (Top panel) and for 12th July, 2015 (bottom Panel) for rainfall threshold 40 mm/day

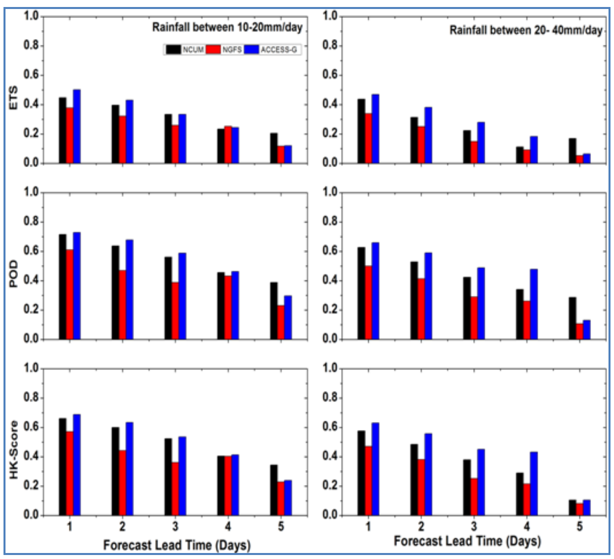


Fig. 9. Bar Graph showing various statistics for NCUM, NGFS and ACCESS-G for Day1 to Day-5 forecasts valid for 11th July, 2015 based on 10-20 mm/day (Left panel) and 20-40 mm/day (Right Panel)

Lat. 27.2° N / Long. 73.0° E, at 0300 UTC on 29th Thislow-pressure system caused persistent heavy rains over Gujarat and Rajasthan on 28 and 29 July, 2015.

(*ii*) A depression (4-5 August) from the remnants of Tropical Storm "KOMEN" formed over East MadhyaPradesh and adjoining Chhattisgarh at 0300 UTC on 4th August and moved westwards over central partsof Madhya Pradesh near close to Hoshangabad on evening of 4th August. It weakened into a well-markedlow pressure area and lay over southwest Madhya Pradesh and neighborhood on 5th August. This depression also caused a very heavy rainfall on 4th August, 2015 over M. P. region.

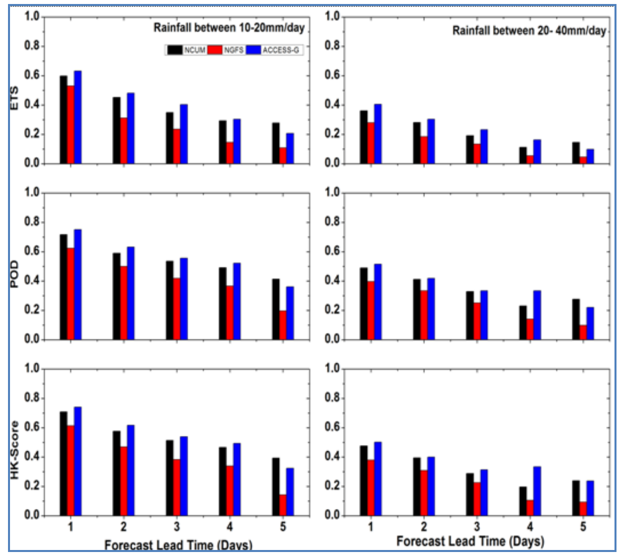


Fig. 10. Bar Graph showing various statistics for NCUM, NGFS and ACCESS-G for Day1 to Day-5 forecasts valid for 12th July, 2015 based on 10-20 mm/day (Left panel) and 20-40 mm/day (Right Panel)

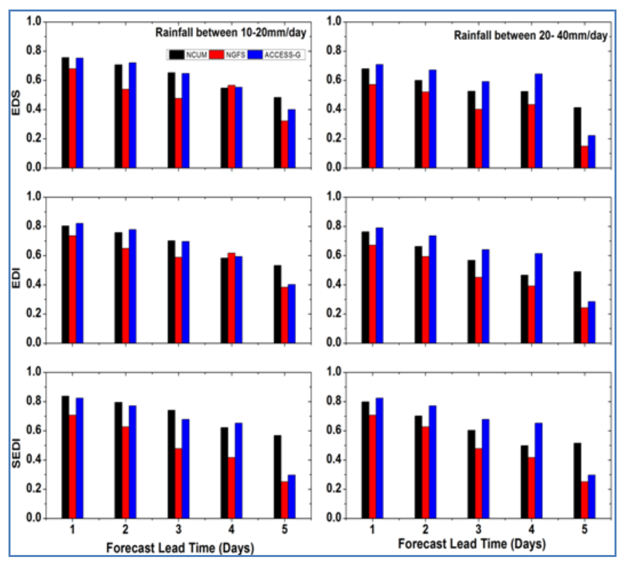


Fig. 11. Bar Graph showing various statistics for NCUM, NGFS and ACCESS-G for Day1 to Day-5 forecasts valid for 11th July, 2015 based on 10-20 mm/day (Left panel) and 20-40 mm/day (Right Panel)

Quantitative verification of the heavy rainfall episodes associated to the deep depression (28-29 July, 2015) and depression (4th August, 2015) has also been carried out based on the components of the contingency table. The domain of interest chosen for the verification is 18-27° N, 68-75° E over Gujarat and 19.5-25° N, 76.5-84.5° E over M. P. The verification is carried out like before for both the thresholds, however for brevity the results are presented here for 20-40 mm/day rainfall range alone. The top panel of Fig. 13 shows ETS from Day-1 to

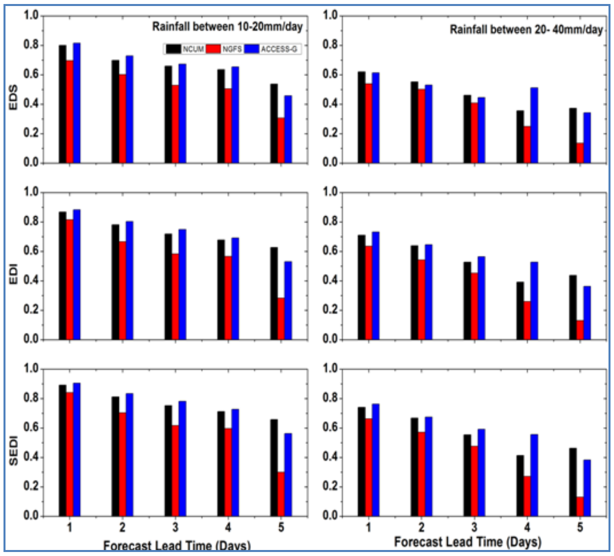


Fig. 12. Bar Graph showing various statistics for NCUM, NGFS and ACCESS-G for Day1 to Day-5 forecasts valid for 12th July, 2015 based on 10-20 mm/day (Left panel) and 20-40 mm/day (Right Panel)

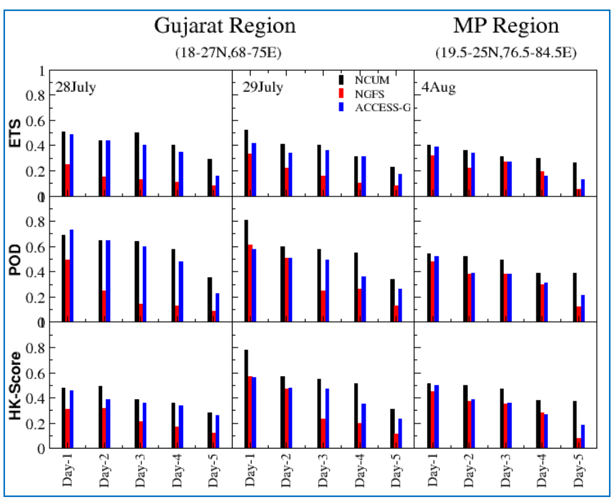


Fig. 13. Bar Graph showing various statistics for NCUM, NGFS and ACCESS-G for Day1 to Day-5 forecasts valid for 28th July, 2015 (left column), 29 July (Middle Column) and 4 August (Right Panel) based on 20-40 mm/day over different regions

Day-5 forecast for rainfall range of 20-40 mm/day valid for 28-29 July and 4th August, 2015 respectively. NCUM and ACCESS-G shows higher ETS than NGFS from Day-1 to Day-5. The middle panel of Fig. 13 displays POD computed from the contingency table valid for 28-29 July and 4th August, 2015. NCUM shows higher POD in both cases of 28-29 July and 4th August in all lead times. However, for 29 July, NGFS and ACCESS-G shows almost similar POD till Day-2 forecast while ACCESS-G takes an edge beyond Day-3 forecast. NGFS and ACCESS-G show comparable POD till Day-4 forecast for 4th August. HK-score verification score for both the heavy

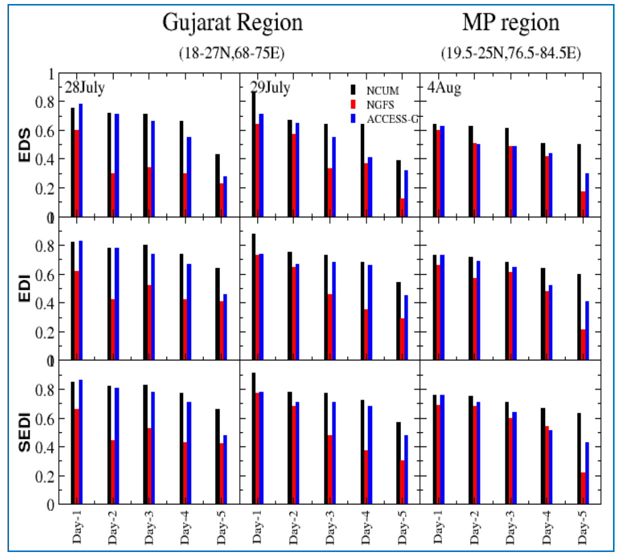


Fig. 14. Bar Graph showing various statistics for NCUM, NGFS and ACCESS-G for Day1 to Day-5 forecasts valid for 28th July, 2015 (left column), 29 July (Middle Column) and 4 August (Right Panel) based on 20-40 mm/day over different regions

rainfall events is shown in the bottom panel of the Fig. 13. NCUM again shows the higher HK-score as compared to ACCESS-G and NGFS for both cases. ACCESS-G and NGFS shows similar skill in terms of HK-score for 29th July upto Day-2 while ACCESS-G performs better than NGFS beyond Day-2 forecast.

Extreme Dependency Score (EDS), Extremal Dependence Index (EDI) and Symmetric EDI (SEDI) are also computed for these two heavy rainfall episodes of 28-29 July as well as 4th August, 2015 for the same rainfall range of 20-40 mm/day and are displayed in the Fig. 14. EDS family of scores also shows that NCUM performs better than NGFS at all lead time from Day-1 to Day-5.

5. Summary

In this paper, a comparison of the relative skills of NCUM, NGFS and ACCESS-G in predicting the heavy rainfall associated with a depression over East M. P., Chhattisgarh, Bihar, Jharkhand and Gangetic West Bengal on 11th July and West U. P., North M. P., Haryana and Delhi and adjoining areas on 12th July, 2015.

(*i*) This rainfall occurred due to an interaction of westerly trough (observed from 9-12 July) with a low pressure system which originated in Head Bay of Bengal on 9th July.

(*ii*) Synoptic situation and predicted by NCUM and ACCESS-G is better than the NGFS resulting in improved prediction of location and amount of rainfall seen in affected area. The location of Western Disturbance is fairly captured by NCUM and NGFS. However, the direction of movement of the low pressure was better captured by NCUM and ACCESS-G in comparison of NGFS. This skill of NCUM and ACCESS-G in predicting the low pressure system and its north westerly movements resulted in a better estimation of the resulted rainfall as compared to NGFS in the analysis area.

(*iii*) The spatial verification of this heavy rainfall event shows that average rain rate and rain volume are largely underestimated by NGFS as compared to NCUM and ACCESS-G. Also RMSE confirms the better prediction of the event by NCUM and ACCESS-G compared to NGFS.

(*iv*) Verification of this rainfall event based on the categorical skill scores like ETS, POD and HK-Scores (using the components of contingency table) also confirm that NCUM and ACCESS-G better predicted the phenomenon than NGFS.

(*v*) Verification using the EDS family of the scores reaffirms that NCUM and ACCESS-G performs better than NGFS even at higher thresholds (20-40 mm/day) and higher lead times (even at Day-4 and Day-5).

All the verification metrics indicate that Unified modeling framework in NCUM and ACCESS-G by and large performs better than NGFS in rainfall forecasts over India. This is particularly evident at higher lead times. Relatively improved skill in NCUM forecasts can be attributed to (*i*) improved resolution (~17 km) and (*ii*) END Game dynamics of NCUM. It is important to note that the large samples of data will yield conclusive results. However, for heavy rainfall events and extreme cases, the sample size will always be low. Though this study is based on few cases of just one monsoon season, this method is instructive and results are useful for further work.

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