MAUSAM, **70**, 2 (April 2019), 215-232

551.577 : 556 (540)

On the reliability of medium-range probabilistic rainfall predictions over river basins in India

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सार – जल मौसम विज्ञान अनुप्रयोगों में, विशेष रूप से जलाशय प्रबंधन और बाढ़ पूर्वानुमान के लिए यह आवश्यक है कि मध्यम अवधि के मौसम पूर्वानुमानों के कौशल का मूल्यांकन और प्रलेखन किया जाए। इस शोध पत्र में जुलाई एवं अगस्त 2018 में 7 दिनों तक के वर्षा पूर्वानुमानों की नदी-बेसिन पैमाने पर जाँच की गई है। बेसिन पैमाने पर पूर्वानुमानों की विश्वसनीयता की जाँच हल्के और सामान्य श्रेणी की वर्षा की विश्वसनीयता आरेख का उपयोग करके की गई है। यह देखा गया है कि इस मॉडल में भारतीय क्षेत्रों में 7 दिनों पहले तक के वर्षा का पूर्वानुमान (एनसेम्बल औसत) देने का उचित कौशल है। यह मॉडल वर्षा की कई घटनाओं से श्रेणीबद्ध वर्षा (हिट्स) का पूर्वानुमान कर सकता है हालांकि झूठे अलार्म की संख्या वास्तविक वर्षा (हिट्स) की संख्या से अधिक है। इस मॉडल ने विभिन्न श्रेणियों की कुछ परिघटनाओं को भी छोड़ा है। कई अवसरों पर समुदाय कोई भी एनसेम्बल सदस्य वर्षा की अधिक मात्रा का पूर्वानुमान नहीं कर सका जिसे वास्तव में प्रेक्षित किया गया था। आर एम एस ई और एनसेम्बल विस्तार लगभग सभी नदी बेसिनों के लिए दिए गए पूर्वानुमान की लंबाई बढ़ने पर भी समान रहता है। इसलिए पूर्वानुमान की लंबाई बढ़ने से पूर्वानुमान की गुणवत्ता कम नहीं होती है। एनसेम्बल विस्तार काफी कम है और यह प्रत्येक नदी बेसिन के लिए आर एम एस ई के मान का आधा है। संभावित पूर्वानुमान किसी भी श्रेणी के लिए विश्वसनीय नहीं रहा है। यह मॉडल पूर्वानुमान सभी नदी बेसिनों में प्रेक्षित आवृत्ति को अत्यधिक बतलाता है। 70 प्रतिशत से अधिक के संभाव्यता मूल्यों के आधार पर दिए गए पूर्वानुमानों में कोई कौशल नहीं दिखता है।

ABSTRACT. For hydrological applications especially for reservoir management and flood forecasting, it is required that the skill of the medium-range weather forecasts is evaluated and documented. In this study, rainfall forecasts up to 7 days for July and August 2018 have been examined at river basin scales. Reliability of the forecasts at basin scale was examined using reliability diagram for light and moderate rainfall categories. It is found that the model has reasonable skill in forecasting rainfall (ensemble mean) over the Indian regions up to 7 days in advance. The model could predict categorical rainfall (hits) for several rainfall events, however, the number of false alarms are larger than number of hits. The model also missed quite a few events in various categories. On many occasions, none of the ensemble members could forecast high amount of rainfall that was observed. The RMSE and ensemble spread remains almost the same as the forecast length increases over all the river basins considered. Therefore, forecast quality does not deteriorate as the forecast length increases. The ensemble spread is quite less and almost half the RMSE values for each of the river basin. The probabilistic forecasts are not reliable for any of the categories. The model forecasts overestimate the observed frequency over all the river basins. Forecasts with probability values of more than 70% do not have any skill.

Key words – Rainfall predictions, River basins, Reliability, Probability, RMSE.

1. Introduction

Advances in Numerical Weather Prediction (NWP) in terms of higher accuracy, higher model resolution and longer lead time in the last decades have encouraged the user community for wider range of applications of the NWP products. One of the most important utilization of NWP products is its application to hydrology (such as reservoir management, flood forecasting etc.). However, it is a challenge to integrate precipitation forecasts into hydrological forecasting systems as the skill of precipitation forecasts deteriorate quite fast. Several studies have documented the skill of deterministic medium-range rainfall forecasts from global models (Bhardwaj *et al.*, 2007; Durai and Bhowmik, 2014; Kar and Tiwari, 2016; Kar *et al*., 2018). Satyanarayana and Kar (2016) had found that rainfall in extreme event categories over India during monsoon season could be forecasted with reasonable skill up to three days in advance. It is believed that ensemble prediction systems exhibit greater forecast skill than any single NWP model (Leutbecher and Palmer, 2008). Ensembles increase forecast accuracy and allow for skillful predictions at longer lead times. However, the ensemble members must represent the probability distribution of the state of atmosphere. In an ensemble forecasting system, the initial states and model physics are perturbed to explore the currently understood range of uncertainty in the observations and the model so that t hey provide a range of possible future weather states (Buizza *et al*., 2008).

Hamil *et al*. (2012) examined various products from TIGGE and found that the probabilistic forecasts are better from the ECMWF model. Jie *et al*. (2015) had used a time-lagged ensemble system with ensemble members separated sequentially at 6 hour intervals lagging the last three days and found improved 6-15 day summer precipitation prediction in China. Durai *et al*. (2015) have used forecasts from four operational ensemble prediction system of TIGGE and found that ensemble mean rainfall forecasts from the ECMWF generally had the highest skill. Zhou *et al*. (2017) have described the breeding-based scheme with ensemble transformation and rescaling (ETR) and the ensemble Kalman filter (EnKF)used in the ensemble prediction system of the to generate initial ensemble perturbations. They found that system with EnKF has better reliability in the short-range probability forecasts of precipitation during warm seasons. Sharpe *et al*. (2018) examined the probabilistic predictions from UK Met Office (UKMO) and found that on the majority of occasions, relative-extreme events are predicted with low probabilities and this characteristic of rainfall forecasts is more pronounced as the forecast range increases. Shrivastava *et al.* (2018) have used the probabilistic forecasts from the Indian Institute of Tropical Meteorology (IITM), Pune to identify occurrences of droughts up to 20-days in advance and found that forecasts of low rainfall amounts are reliable. Following the developments in probabilistic weather forecasting, flood forecasting also need to shift from a deterministic approach towards a probabilistic approach based on ensemble techniques. While this probabilistic approach is now more or less common practice and well established in the meteorological community, water resource management agencies have to be communicated such probabilistic weather forecasts and guide them on the ways to interpret and combine these products with rainfall-runoff models. Gouweleeuw *et al*. (2005) had proposed a possible methodology to combine the ECMWF probabilistic forecasts with the large-scale hydrological model LISFLOOD.

A probabilistic forecast is reliable if the observed frequency of the event for a given forecast probability is equal to the forecast probability. Moreover, for a probabilistic system to be reliable, forecasts from ensemble members should be statistically identical to the observations. Therefore, it should be possible to draw the observation as well as an ensemble member from the same underlying distributions. These conditions imply that the observation should lie in between ensemble spread of an ensemble system and the observation should behave like an ensemble member of the model (Doblas-Reyes *et al*., 2005; Weigel *et al*., 2008). In order that the ensemble spread is representative of the uncertainty in the ensemble mean, the root mean square error (RMSE) of ensemble mean should be same as the averaged ensemble spread (weigel, 2008). Further the relation of ensemble mean with observation should be similar to the relation between any member and ensemble mean. (Johnson and Bowler, 2009).

In India, the Central Water Commission (CWC) is responsible for flood forecasting and warning (level forecasting and inflow forecasting. The India Meteorological Department (IMD) provides the hydro-meteorological inputs. The National Centre for Medium Range Weather Forecasting (NCMRWF) and India Meteorological Department (IMD) have implemented two very robust global weather prediction systems for medium-range forecasting. Therefore, opportunities exist for developing and demonstrating application of these forecasts in hydrology. However, the NWP products have to be carefully interpreted and used in various hydrologic application models as these forecasts may have large systematic bias. Dube *et al*. (2017) have compared the probabilistic rainfall forecasts obtained from the NCEP-based Global Ensemble Forecast System (GEFS) and the UKMO based Global and Regional Ensemble Prediction System (MOGREPS) for four monsoon seasons. Recently, the NCMRWF has upgraded its ensemble forecasting system to 12 km resolution (Mamgain *et al*., 2018). A detailed examination of the skill of this forecast system has not been carried out at basin-scale. Before the forecasts are provided to reservoir managers and flood forecasting agencies, reliability of the forecasts needs to documented properly. The main objective of the present study is to examine the reliability of the medium-range probabilistic forecasts of rainfall over the river basins in India during monsoon season of 2018. Section 2 of the paper briefly describes the ensemble forecast system and verification methodology applied. The results are presented in Section 3 and the study is concluded in Section 4.

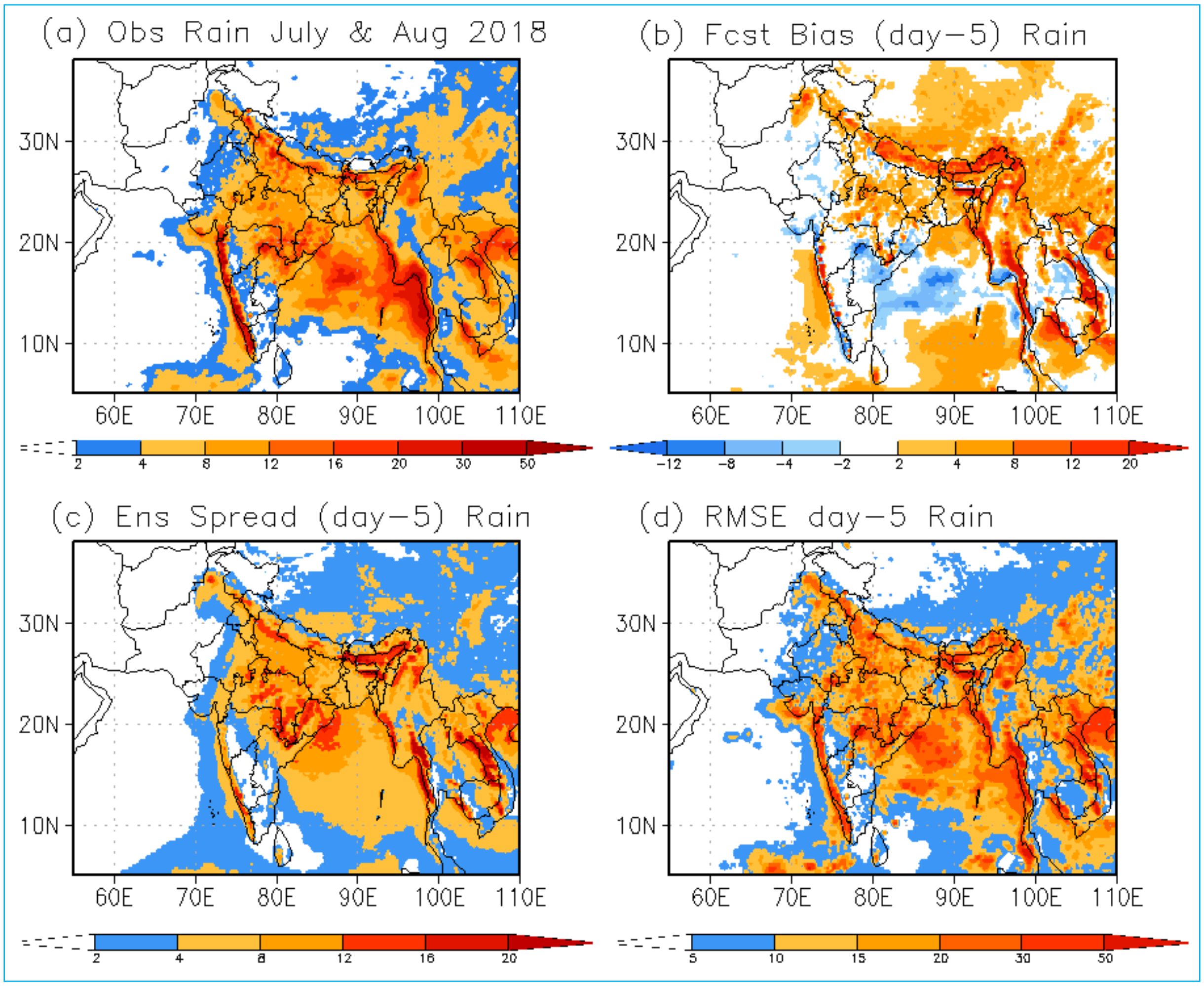
2. Data and methodology

For this study, medium-range forecasts of rainfall (from day 1 to day 7) from the NCMRWF ensemble forecast system have been used. These forecasts are valid for each day of July and August 2018. The forecast system has a total of 23 ensemble members (a control and 22 perturbed forecasts) at ~12 km (N1024L70) resolution. It is based on Unified Model version 10.8 of UKMO. The perturbed initial conditions are generated by Ensemble Transfer Kalman Filter (ETKF) method. The data assimilation system is based on hybrid four-dimensional variational method of Clayton *et al*., 2013). Every day, forecast runs for 10.5 days are made using initial conditions at 0000 UTC and 1200 UTC. Out of 22 ensemble members, forecast runs for 11 members are carried out using perturbed initial conditions of 1200 UTC of previous day and other 11 runs use initial conditions for 0000 UTC of the current day).

Observed rainfall (merged satellite and gauge data) for the Indian region has been taken from www.imdpune.gov.in. This gridded data at 0.25° × 0.25°, prepared jointly by IMD and NCMRWF, has been bi-linearly interpolated to the model grid. Both the observed rain and forecast rain have been put in 7 different categories as per the rainfall magnitude in a day. These categories are (*i*) no rain; (*ii*) very light rain (0.1 to 2.4 mm); (*iii*) light rain (2.5 to 15.5 mm); (*iv*) moderate rain (15.6 to 64.4 mm); (*v*) heavy rain (64.5 to 115.5 mm); (*vi*) very heavy rain (115.6 to 204.4 mm) and (*vii*) extremely heavy rain (>204.5 mm). The probability of rain occurring in a category was computed as the fraction of ensemble member forecasts falling in that category. These probabilistic forecasts are then verified against observations in that category. In addition to standard verification scores such as RMSE bias, hit and false alarm rates; reliability diagrams have been prepared at river basin scale. An attempt is also made to relate the rainfall to water level and amount at various reservoirs. For this purpose, reservoir data for the monsoon period of 2018 from Central Water commission have been used.

The river basins considered in this study are briefly described here. Fig. 4 shows the locations and the basin boundaries. The Ganga River rises in the western Himalayas in Uttarakhand and flows south and east through the Gangetic Plain of North India. The Ganga River has several tributaries originating from the Himalayas or Vindhyas. Anand *et al*. (2018) have examined the water balance and run off trend in the Ganga basin including its tributaries and found a substantial reduction in water resource availability in the basin in recent years. The Chambal River is a tributary of the Yamuna River in central India and thus forms part of the greater Gangetic drainage system. The river flows north-northeast through Madhya Pradesh, Rajasthan forming the boundary between Rajasthan and Madhya Pradesh before turning southeast to join the Yamuna in Uttar Pradesh. Chauhan and Shrivastava (2017) have used Integrated Water Resources Management (IWRM) models to study the water allocation in upper Chambal basin to determine optimum water availability for irrigation purpose. The Satluj River is one of the main tributaries of Indus River in the western Himalayas and has its origin in the Tibetan plateau at an elevation of about 4572 m. The Spiti River watershed experiences extensive snowfall in the winters and substantially contributes to the Satluj River in the form of snowmelt runoff in the spring and summer months. Tiwari *et al*. (2016a&b) have examined inter-annual variability of snowfall and snow melt in the Satluj basin using observed in situ and remote sensing data. Tiwari *et al.* (2017) have carried out stream flow modeling for the Satluj model and found that stream flow simulation in the Satluj River critically depends on the precipitation and temperature data used to force the runoff models. The Brahmaputra River flows through China, India and Bangladesh. Its basin is extensive over Assam and affects the hydrology over the north-east India. Palash and Jiang (2018) have examined the issue of water level and stream flow forecasting in the Ganga, Brahmaputra and Meghna basins and found that the forecasting skill of weather models to capture large-scale rainfall patterns are useful in a data-driven model to obtain skillful flood forecasts up to 10 days in advance.

Narmada River is the largest west flowing in the Indian Peninsula. It originates at Amarkantak in Madhya Pradesh and flows westwards over a length of 1,312 km before draining through the gulf of Khambhat into the Arabian Sea. Sharma *et al*. (2015) have simulated the stream flow in Narmada River at daily scale using observed rainfall data and obtained reasonable skill at daily scale. The Godavari is India's second longest river after the Ganga. It flows east draining Maharashtra, Telangana, Andhra Pradesh, Chhattisgarh, Madhya Pradesh, Odisha and Karnataka and emptying into Bay of Bengal through its extensive network of tributaries. Reddy and Ganguli (2012) had carried out a flood frequency analysis of upper Godavari basin using copula based approach. Koneti *et al*. (2018) examined the impact of land use land cover changes on the hydrology and stream flow in the Godavari River Basin using the Hydrologic Engineering Centre-Hydrologic Modeling System (HEC-HMS) model and found that deforestation leads to decreases in the overall evapotranspiration and infiltration with an increase in runoff. The Mahanadi is one of the major east flowing rivers of India. The Mahanadi basin extends mostly over states of Chhattisgarh and Odisha. The Krishna River originates in the Western Ghats near Mahabaleshwar in Maharashtra. The Krishna River is the fourth-biggest river in terms of water inflows and river basin area in India, after the Ganga, Godavari and Brahmaputra. Nandi and Reddy (2017) have used the Variable Infiltration Capacity (VIC) model to simulate the



Figs. 1.(a-d). (a) Observed rainfall (mm/d) over the Indian regionduring July and August 2018; (b) Day-5 bias (mm/d) in ensemble mean rainfall forecasts; (c) ensemble spread in day-5 forecasts of rainfall and (d) root mean square error (RMSE) of rainfall forecast (mm/d) in day-5

hydrological variables over Krishna River Basin and found the model to over-estimate the stream flow downstream. The Cauvery River has its origin in the foothills of Western Ghats in Karnataka and it flows through the states of Karnataka and Tamil Nadu emptying into the Bay of Bengal.

3. Results and discussion

Observed rainfall (mm/day) over India and its neighborhood during July and August 2018 is shown in Fig. 1(a). The eastern and central region as well as the Gangetic plains of north India received about 8 to 12 mm/day rainfall while the Western Ghats region received rainfall >30mm/day. Some parts of foot hills of Himalayas, southern parts of Odisha and adjoining Telengana and Andhra Pradesh received >12mm/day. Rainfall over the central parts of the Bay of Bengal and Arakkan coast was >20mm/day. The model has a systematic bias to simulate more rain (>4mm/day) over the foothills of Himalayas including Nepal, Sikkim and parts of north-east India in its day-5 forecast as seen in Fig. 1(b). The model simulates about 2-4 mm/day more rainfall over the Gangetic plains and west coast of India. The model simulates less than observed rainfall (by about 2-4 mm/day) over east coast of Odisha and adjoining Andhra Pradesh as well as Kerala. Average ensemble spread for July and August 2018 in day-5 forecasts is shown in Fig. 1(c). The spread is maximum in the east and central parts as well as north-eastern part of India which is >16mm/day. The spread is not large over the Western Ghat region as well large parts of the peninsular India. The RMSE in day-5 forecasts shown in Fig. 1(d) indicates that the zones of maximum RMSE are the same as the zones of maximum rainfall. Over most parts of India, RMSE amount is about 10-20 mm/day with some parts of

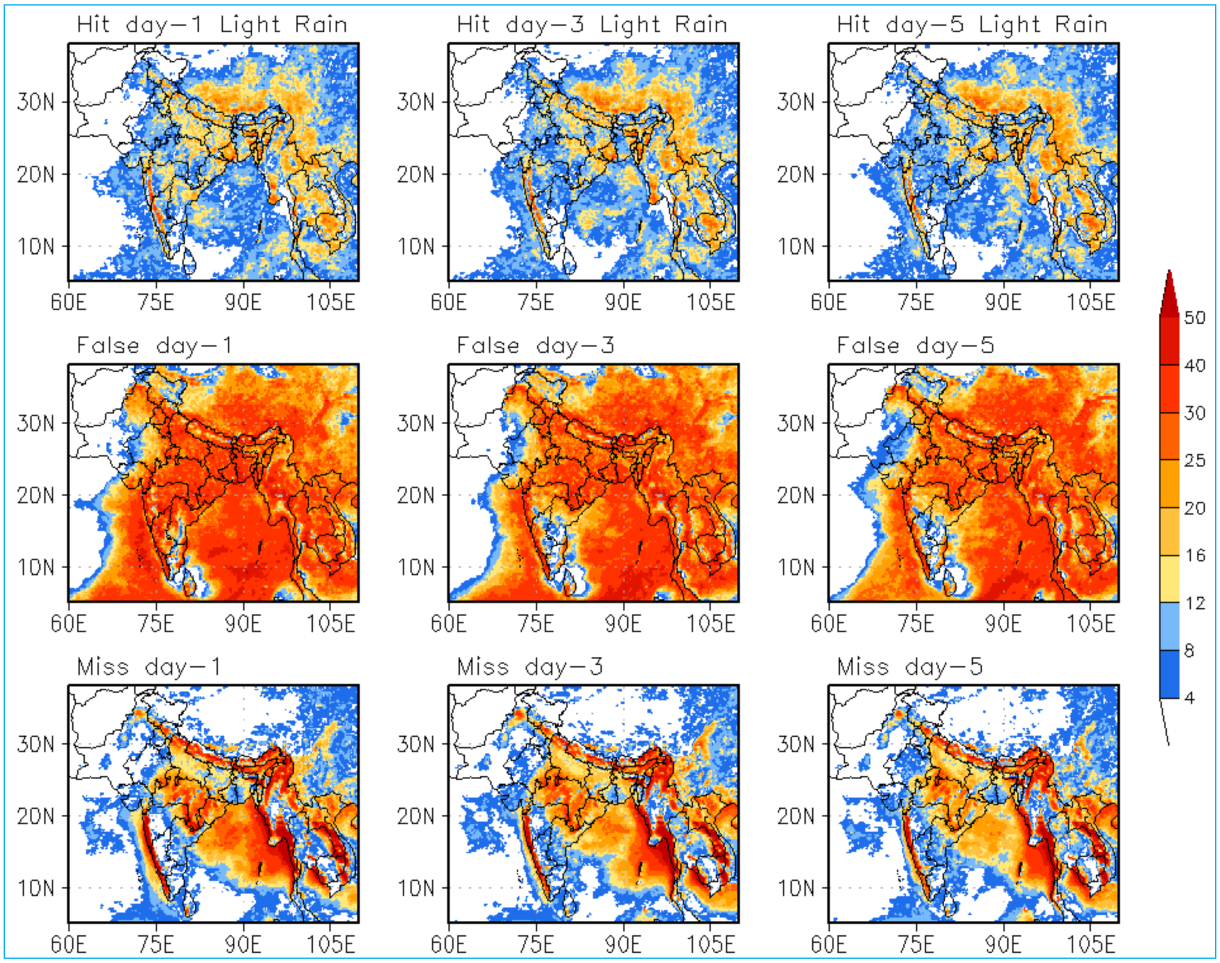


Fig. 2. Number of events that were hit or false alarm or missed in the forecasts in light rainfall category during July-August 2018 in day-1, day-3 and day-5 forecasts

central India, Odisha and Western Ghat region having RMSE>15mm/day. Error of more than 20 mm/day is experienced over central Bay of Bengal and Arakkan coast. The model forecasted rainfall in day-5 is poorly correlated (not shown in figure) with the observed rainfall with correlation coefficient of 0.1 to 0.2 over most parts of India. Negative correlation is seen over the Arabian Sea along the coast of India, Bihar, West Bengal regions.

Fig. 2 has the number of light rain events that were correctly forecasted by the ensemble mean forecast (hits) in day-1, day-3 and day-5 respectively during July-August 2018. The model also wrongly forecasted light rain events (false alarms) or the model missed the events. These are also shown in Fig. 2. It is seen that the number of hits over the Gangetic plain is about 12 to 16 in this rainfall category in all the forecasts. About 16 to 20 events over the Western Ghats and some part of Gangetic West Bengal were correctly forecasted. The number hits in central peninsular region reduced from 16 in day-1 forecasts to less than 12 in day-5 forecasts. The model is able to forecast large number of light rain events over the Himalayas. The number of false alarms forecasted by the model for this rain category is always more than the hits. More than 30 events were wrongly forecasted over most parts of India as well as the Bay of Bengal. Large errors are seen over the eastern parts of India and Western Ghats in day-1 forecast. By day-5, number of false alarms over the Western Ghats is reduced. From the figure, it is also seen that a large number of light rain events could not be forecasted especially over the central and eastern parts of India. Over north-eastern parts of India as well as foothills of Himalayas also, the model missed several light rainfall events. Similar analysis has been carried out for the rainfall forecasts in moderate rain category as shown in Fig. 3. Over the central and eastern parts of India, 8 to 12 events were predicted in correct category in the forecasts in all the ranges. Over Western Ghats, more than 12 events and over the Arakkan coast more than 16 events were correctly forecasted. The number of hits reduced as

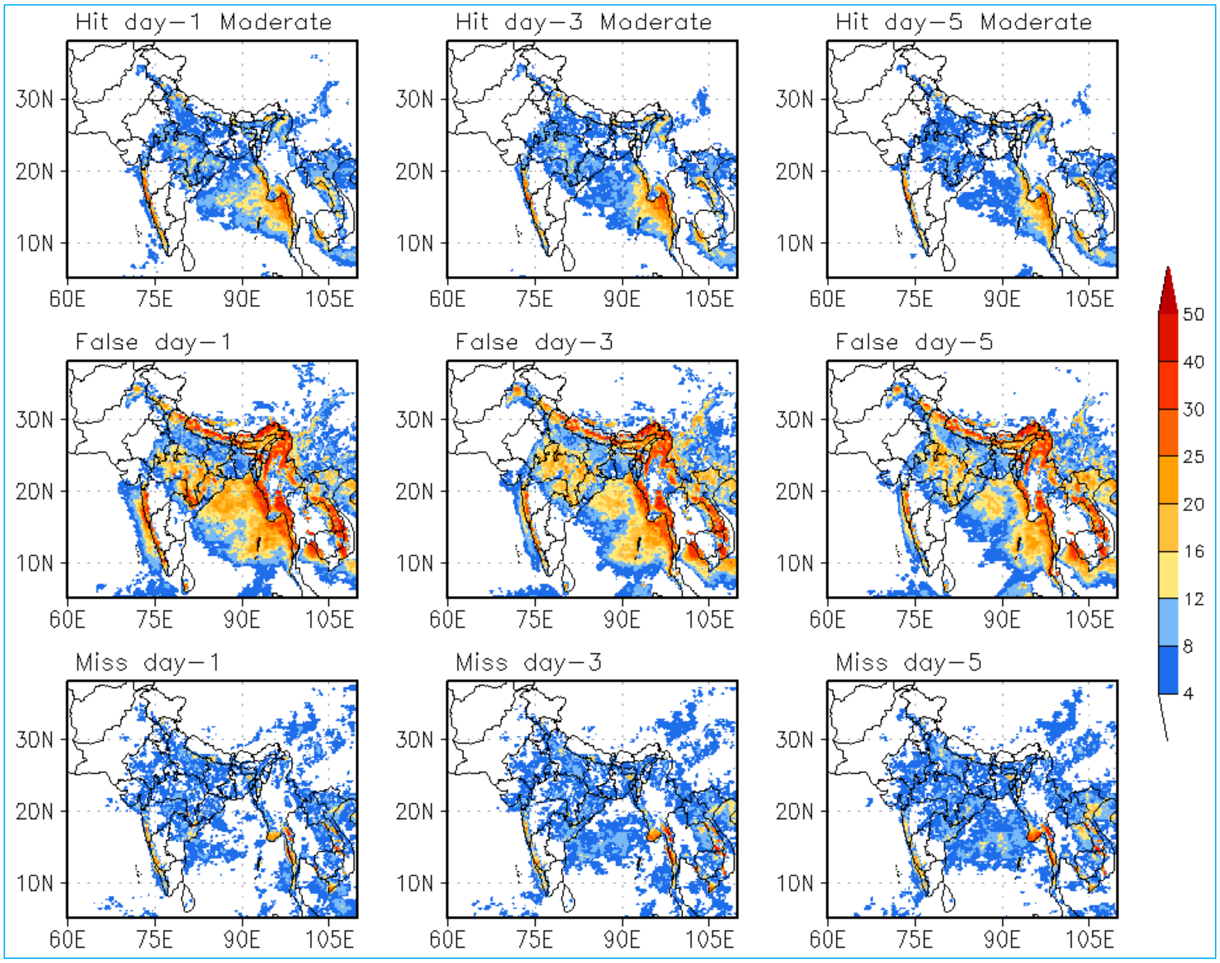
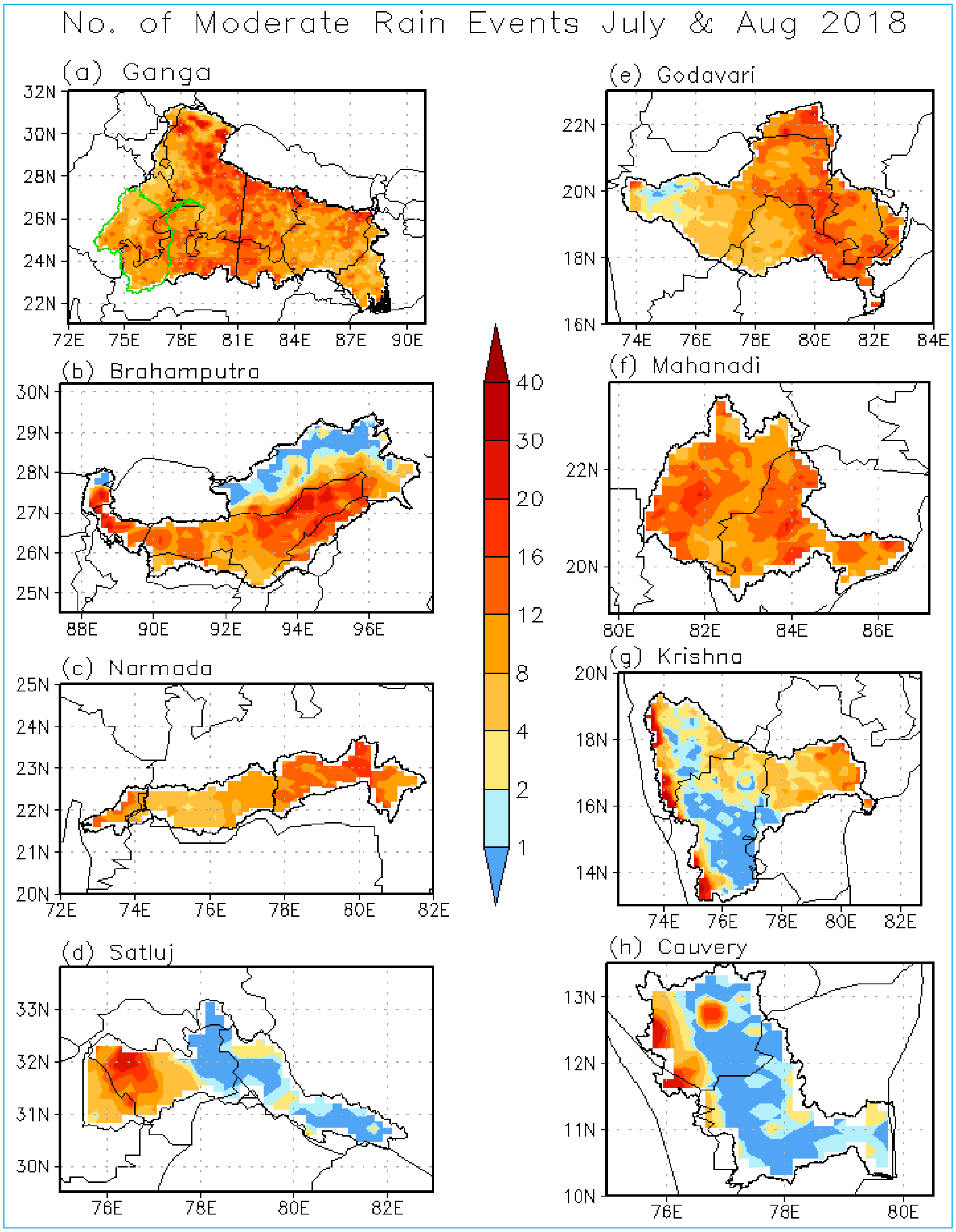


Fig. 3. Number of events that were hit or false alarm or missed in the forecasts in moderate rainfall category during July-August 2018 in day-1, day-3 and day-5 forecasts

the forecast length increased from day-1 to day-5 over the central parts of India. In this rainfall category also, the false alarms are more than the hits. More than 20 events were wrongly predicted as moderate rain over eastern India, Western Ghats and foothills of Himalayas. Similar to the case of light rain category, the model also could not forecast several moderate rain events (about 4-8 events) over various parts of India as seen in the figure. Therefore, it is seen that the number of hits is always less than the number of false alarms in the model forecasts making these forecasts unusable by the user community.

3.1. *Basins and reservoirs*

The outline of the Ganga basin along with number of moderate rain events observed during July and August 2018 is shown in Fig. 4(a). The outline of Chambal basin is shown in green color in the same plot. It is seen that more than 16 moderate rain events over the western parts of the basin along the foot hills of Himalayas. Other regions especially the eastern parts had less than 8 to 12 events with some points experiencing about 16 events in the central parts of the basin. In order to have a detailed examination of the model forecasts, this basin is further sub-divided in to two as Ganga (w) and Ganga (e) in the analysis of results. Number of moderate rain events observed during July and August 2018 over the Indian part of Brahmaputra basin is shown in Fig. 4(b). Over the northern parts of the basin bordering the international boundary, only 1-2 such events were observed while more than 8 events were observed in the eastern parts of the basin with some points experiencing about 16 events. In Fig. 4(c), it is seen that about 8-12 events of moderate rainfall occurred during the study period in the eastern parts of the Narmada basin whereas about 4 events occurred in the western parts. Therefore, the basin is divided in to Narmada (w) and Narmada (e) in this study. In Fig. 4(d), it is seen that on the eastern part of the Satluj River basin, only 2 to 4 moderate rain events occurred while in the eastern parts 12-16 events were observed.



Figs. 4(a-h). Number of moderate rainfall events observed during July and August 2018 over the river basins (a) Ganga; (b) Brahmaputra; (c) Narmada; (d) Satluj; (e) Goadavari; (f) Mahanadi; (g) Krishna and (h) Cauvery

Very few moderate rain events were observed in the western parts of the Godavari basin (about 4), while eastern part experienced 12 to 16 events [Fig. 4(e)]. The basin is further divided in to Godavari (w) & Godavari (e) in this study. The Mahanadi basin [Fig. 4(f)] experienced about 16-20 events during the study period. From Fig. 4(g), it can be seen that over the Western Ghats, about 12-16 number of moderate rain events occurred in the Krishna basin. While in the middle part of the basin, only a few events occurred, about 8 events occurred in the eastern parts of the basin. During July-August 2018, more than 8 number moderate rain events occurred over the Western Ghats region of the Cauvery River basin, while only a few events over rest of the basin as shown in Fig. 4(h).

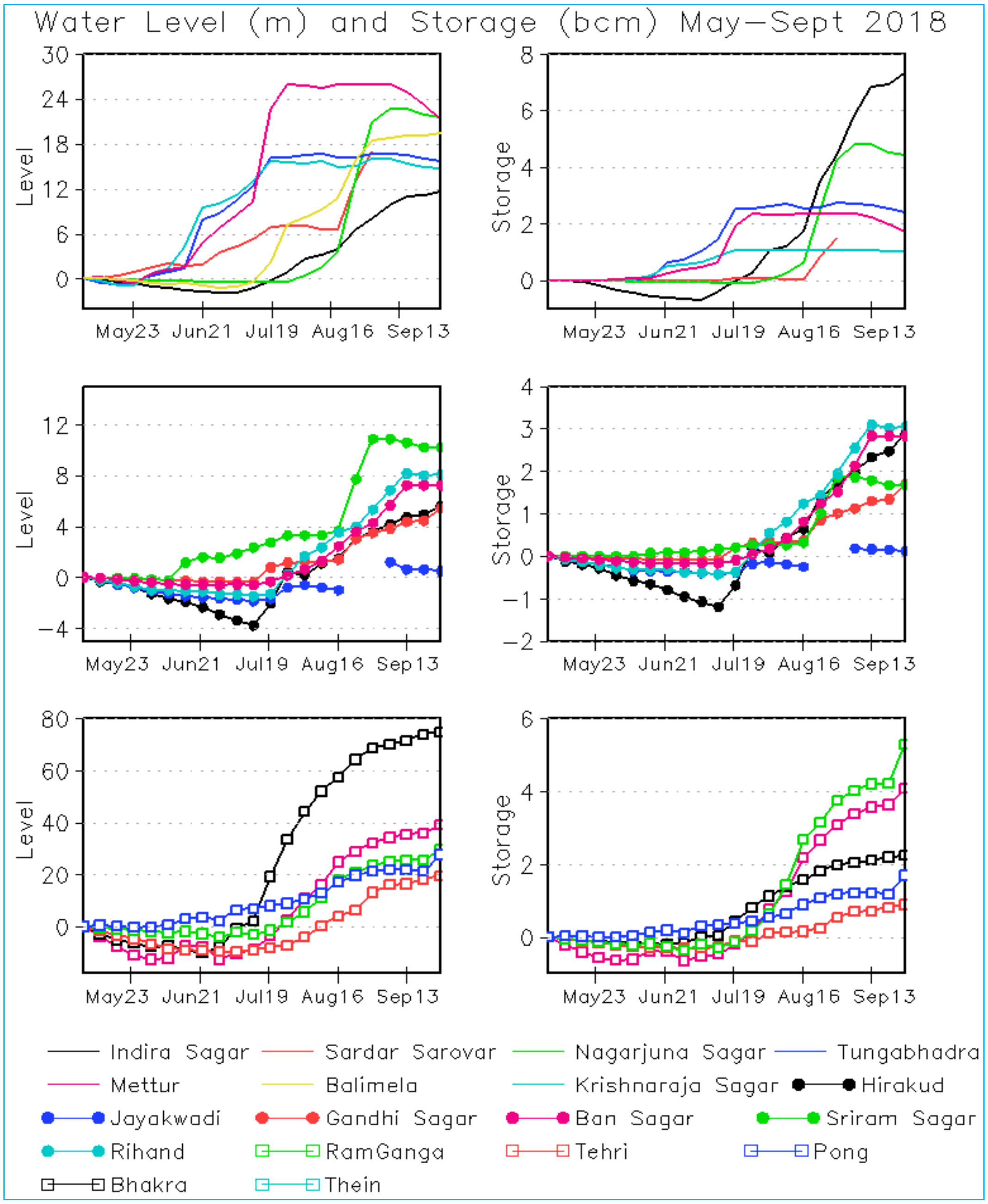
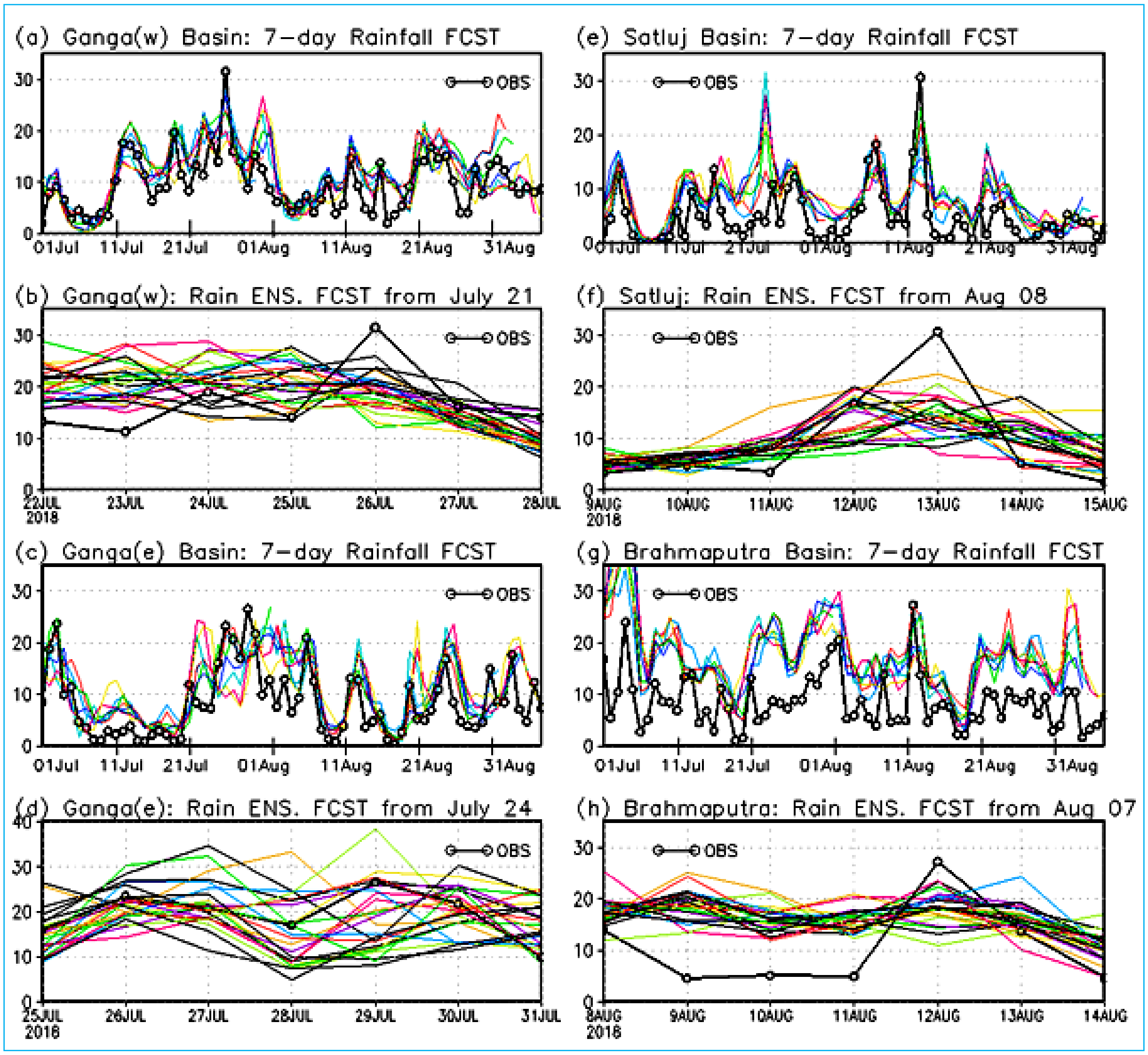


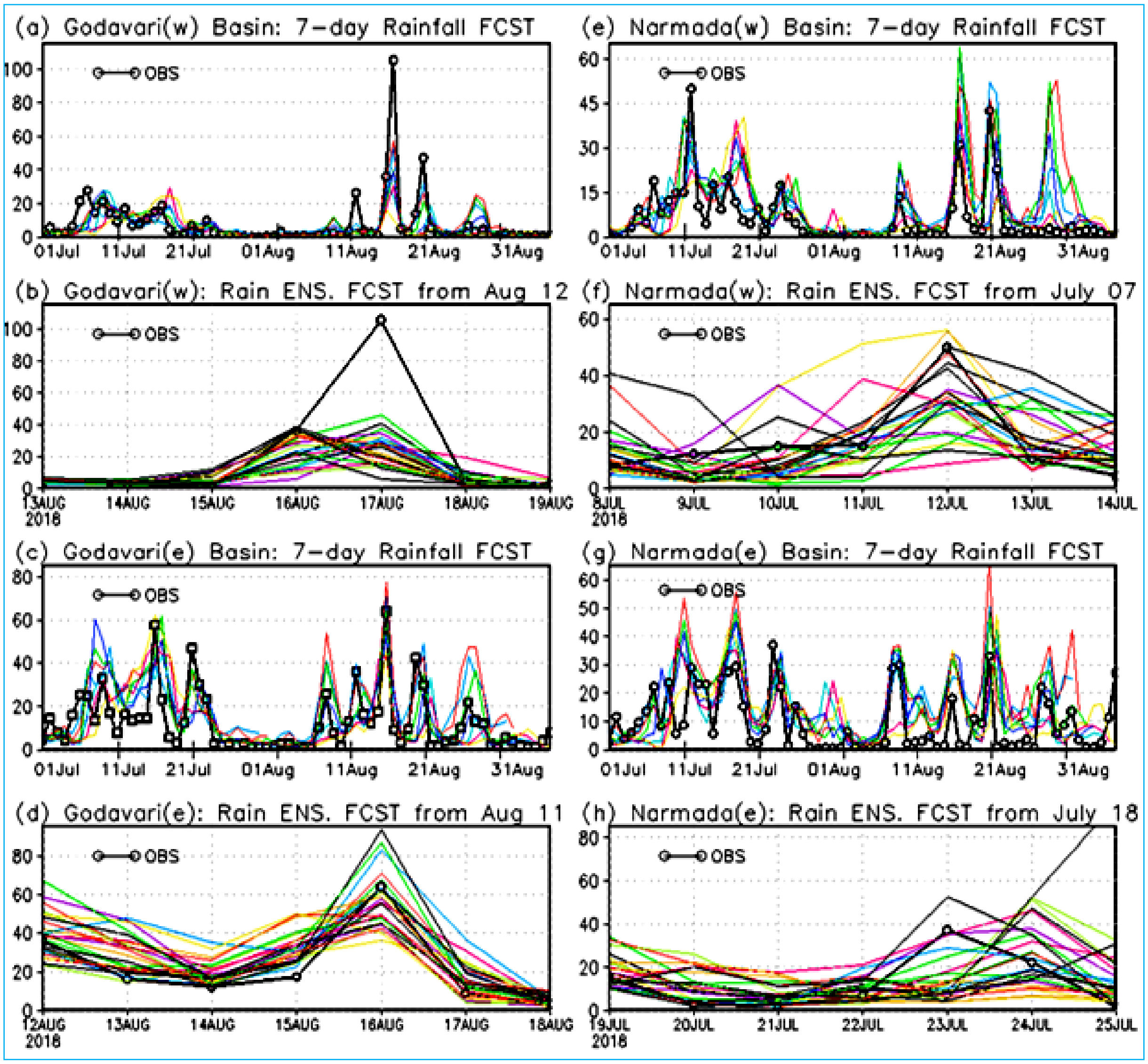
Fig. 5. Changes of water level (m) and storage (bcm) in the reservoirs from first week of May 2018

The forecasts of water level of reservoirs help the user agencies to decide mitigating measures such as shifting people and property to safer locations. The dam authorities use the inflow forecasting for optimum operation of reservoirs for safe passage of flood downstream. This also helps them to ensure adequate storage in the reservoirs for meeting demand during non-monsoon period. In this study, water level and water storage of several reservoirs and dams have been examined for the monsoon season of 2018. An attempt shall be made to examine the change in these quantities based on observed rainfall and forecasted rainfall in the river basins where these reservoirs are located. Fig. 5 shows the reservoir level and storage from the first week of May to end of September, 2018. As actual height and storage capacities of these reservoirs are different, these data have been scaled so that the water level and storage amount are zero on 1st May, 2018. These data are shown in Fig. 5.



Figs. 6(a-h). Observed and ensemble mean forecasts (day-1 to day-7) rainfall and 7day forecasts by each ensemble member averaged over river basins (a&b) Ganga(w) basin ; (c&d) Ganga(e) basin; (e&f) Satluj basin; (g&h) Brahmaputra basin

The Tehri Dam on the Bhagirathi River near Tehri in Uttarakhand is the highest dam in India. On July 10, 2018, the water level in Tehri dam was 753.15 m and storage amount was 0.251 bcm. On July 19, it rose to 770.1 m and 0.636 bcm; on July 26, it became 784.35 m and 1.013 bcm; on August 2nd it became 795.05 m and 1.331 bcm; on August 9th it again rose to 802.95 m and 1.587 bcm, on August 16, it became 808.5 m and 1.776 bcm. By 23 August, the water level rose to 815.1m and 2.016 bcm. Therefore, this water level and storage rose during July and August due to several rain events that occurred on the catchment areas of Bhagirathi River in Ganga basin. The water level of Ramganga dam on the Ramganga River in Uttarakhand on May 30, 2018, was 326.99 m and storage was 0.251 bcm. However, these reduced to 323.99 m and 0.167 bcm by July 4, 2018. After a few rainfall events in the catchment areas the water level and storage rose to 329.5 m 0.583 bcm by August 2nd, 2018. Several moderate and heavy rainfall events increased the water level 346.76 m and 1.012 bcm by August 30th, 2018. The catchment area of Rihand dam on the Rihand River extends over Uttar Pradesh, Madhya Pradesh & Chhattisgarh. In the beginning of the season, the water level was 255.3 m and 0.643 bcm which reduced to 254.81 m and 0.503 bcm on 12th July. Due to several rain events in the catchment areas, these increased to 261.61 m and 2.876 bcm by August 30. Bansagar dam is a multipurpose river Valley Project on Sone River situated in the Ganges Basin in Madhya Pradesh. On May 31, water level and storage were 334.03 m and 2.224 bcm



Figs. 7(a-h). Observed and ensemble mean forecasts (day-1 to day-7) rainfall and 7 day forecasts by each ensemble member averaged over river basins (a&b) Godavari (w) basin; (c&d) Godavari (e) basin; (e&f) Narmada (w) basin; (g&h) Narmada (e) basin

which reduced to 333.83 m and 2.165 bcm till July 12, 2018. It then increased to 340.07 m and 4.466 bcm by September 5th. The water level of the Gandhi Sagar dam on Chambal River on May 31 was 387.02 m and storage was 1.154 bcm which reduced to 386.84 m and 1.11 bcm on July 12, 2018. It started to increase after that to reach 390.68 m and 2.207 bcm by the end of August. Bhakra dam on the Sutlej River forms the Gobind Sagar reservoir. On May 31, water level and storage were 454.69 m and 0.359 bcm respectively which increased to 478.3 m and 1.76 bcm on August 2nd and 499.56 m and 4.089 bcm on August 30. The Pong dam is on the Beas River in Himachal Pradesh. On May 31, the water level was 391.99 m and storage was 0.562 bcm which reduced to 390.84 m and 0.457 bcm on 12 July. It increased to 417.53 m and 4.502 bcm on August 28. In the beginning of monsoon season of 2018, the water level and storage of the Ranjit Sagar dam (Thein Dam) on the Ravi River were 499.05 m and 0.583 bcm which increased to 509.9 m and 1.111 bcm on July 31 and 520.51 m and 1.76 bcm on August 30, 2018.

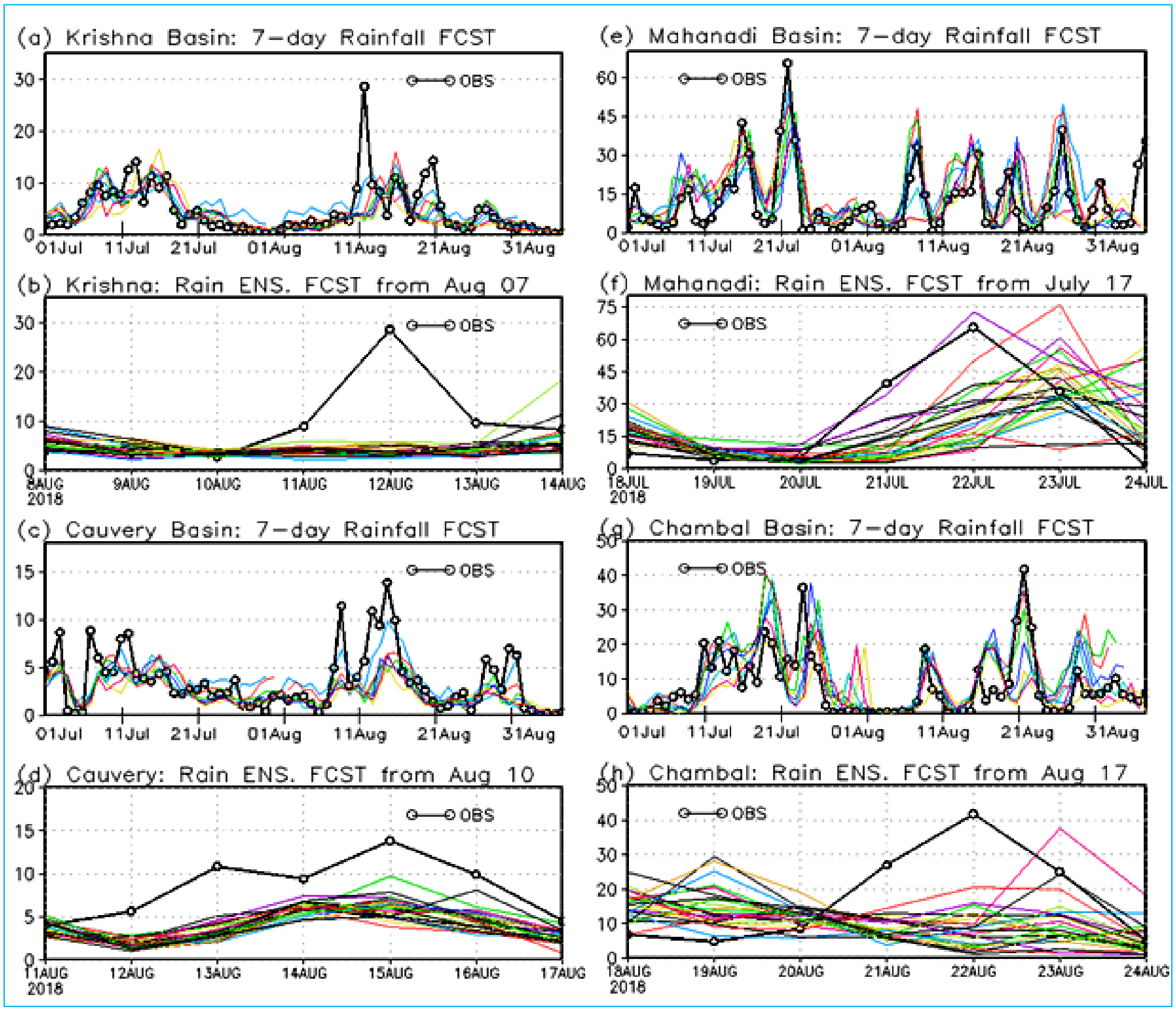
In the beginning of the monsoon season, the water level and storage the Indira Sagar dam on the Narmada River were 249.25 m and 1.88 bcm respectively, which reduced to 249.12 m and 1.828 bcm on July 12th. These increased to 252.95 m and 3.306 bcm on 2nd August and further increased to 258.37 m and 6.661 bcm on August 30.

The Sardar Sarovar dam on the Narmada River had the water level of 105.91 m on May 31 2018, which increased to 107.96 m on June 28 and 111.53 m on July 26. By the end of August, the water level and storage were 121.43 m and 1.477 bcm respectively. Nagarjuna Sagar dam on Krishna River had water level of 156.06 m and storage of 0.097 bcm on May 31. As the rainfall amount was not large during June and July in the catchment areas, the water level and storage reduced to 155.75 m and 0.048 bcm respectively by July 26. Few rain events in the second part of August led to increase in water in the dam to 177.09 m and 4.368 bcm. The Tungabhadra dam is in Karnataka on the Tungabhadra River, a tributary of the Krishna River. On May 30, 2018, the water level and amount were 481.37 m and 0.10947 bcm respectively which increased to 489.57 m and 0.807 bcm on June 28. Rain events in the catchment areas of the river helped the water level and storage to rise in July to 497.39 m and 2.73128 bcm on 1st August. Krishna Raja Sagara in Karnataka is in Cauvery basin. On May 31, the water level was 737.26 m and water amount was 0.121 bcm which rose to 746.51 m and 0.643 bcm on June 27 and 751.92 m and 1.163 bcm on 1st August. By the end of August, these were 752.5 m and 1.163 bcm respectively. The Mettur dam in Tamil Nadu located across the river Cauvery receives inflows from its own catchment area, Kabini and Krishna Raja Sagara dams in Karnataka. On May 31, water level was 215.6 m and total storage was 0.305 bcm. On June 27, these were 221.47 m and 0.629 bcm which rose to 240.53 m and 2.603 bcm due to rain events in the week of July 11 to July 19, 2018.

On May 30, the water level and storage of Hirakud dam on the Mahanadi River in Odisha were 184.88 m and 1.307 bcm respectively. It continued to reduce to 182.38 m and 0.574 bcm till July 12. It increased to 189.79 m and 3.462 bcm by the end of August 2018. Jayakwadi is located on Godavari River in Maharashtra. On May 30, the water level and storage were 458.72 m and 0.581 bcm which reduced to 457.92 m and 0.419 bcm by July 11. It started to increase thereafter to 461 m and 1.029 bcm by September 4. On May 31, water level and storage of Sriramsagar across Godavari River in Telangana were 320.25 m with 0.187 bcm respectively which increased to 323.67 m and 0.447 bcm by July 26 and on August 30, these were 331.23 m and 2.046 bcm. The Balimela Reservoir is located in Odisha on the river Sileru which is a tributary of the Godavari River. On May 30, water level was 441.90 m with storage amount of 0.22 bcm which reduced to 441.29 m and 0.17 bcm by June 27. After this few rain events in the catchment areas increased these to 449.67 m and 0.91 bcm by July 26 and 460.95 m and 2.46 bcm by 29 August.

Fig. 5 indicates that the water level and amount in various reservoirs started to increase by only the middle of July 2018. For some of the reservoirs such as Nagarjuna Sagar and Sriram Sagar, water level increased only in August. Therefore, it will be interesting to see if the observed rainfall and forecast rainfall from ensemble members are able to explain this change in water level and amount in the reservoirs. Observed daily rainfall averaged over the basins in July and August 2018 and day to day-7 forecasts valid for the observation days are shown in Figs. 6-8. Rainfall in moderate category began in the Ganga (w) basin on July 12 and continued more or less consistently till the end of the month with more than 30mm rain occurring on July 26. The rainfall activity picked up again on August 21 as shown in Fig. 6(a). The model forecasts for day-1 to day-7 shown in the figure indicate that some of the events could be forecasted by the ensemble mean reasonably well. However, on August 30 and 31, forecasts in all time ranges were much higher than that was observed. In order to further examine the ensemble members in the day-5 forecast valid for July 26, 5-day forecasts (all ensemble members) are shown in Fig. 6(b) starting with the initial condition of July 21. It is seen that all the ensemble members predict higher amount of rainfall for each day from July 22 up to July 25. On the day of observed highest rainfall, all the ensemble members forecast rain that is less than observed. None of the ensemble member could forecast this highest rainfall event in this basin in 5-day forecast. Rainfall in moderate category began in the Ganga (e) basin [Fig. 6(c)] was observed in the first week of July as well as starting from July 25 to July 30 with more than 20 mm rain occurring on July 29. 7 day forecasts shown in the figure indicate that the model predicted a good rainfall activity around 22 July (>20mm/day) which did not occur. In August, the model always forecasted higher rainfall amount over the basin. 5-day forecasts valid for July 29, (all ensemble members) are shown in Fig. 6(d) starting with the initial condition for July 24. It is seen that most of the ensemble members forecasted less amount of rainfall on the day of observed highest rainfall (July 29), however, few members were able to correctly predict the rainfall category. Most of the members predicted that rainfall activity would enhance on July 30 (day 6 forecast) whereas the activity actually reduced.

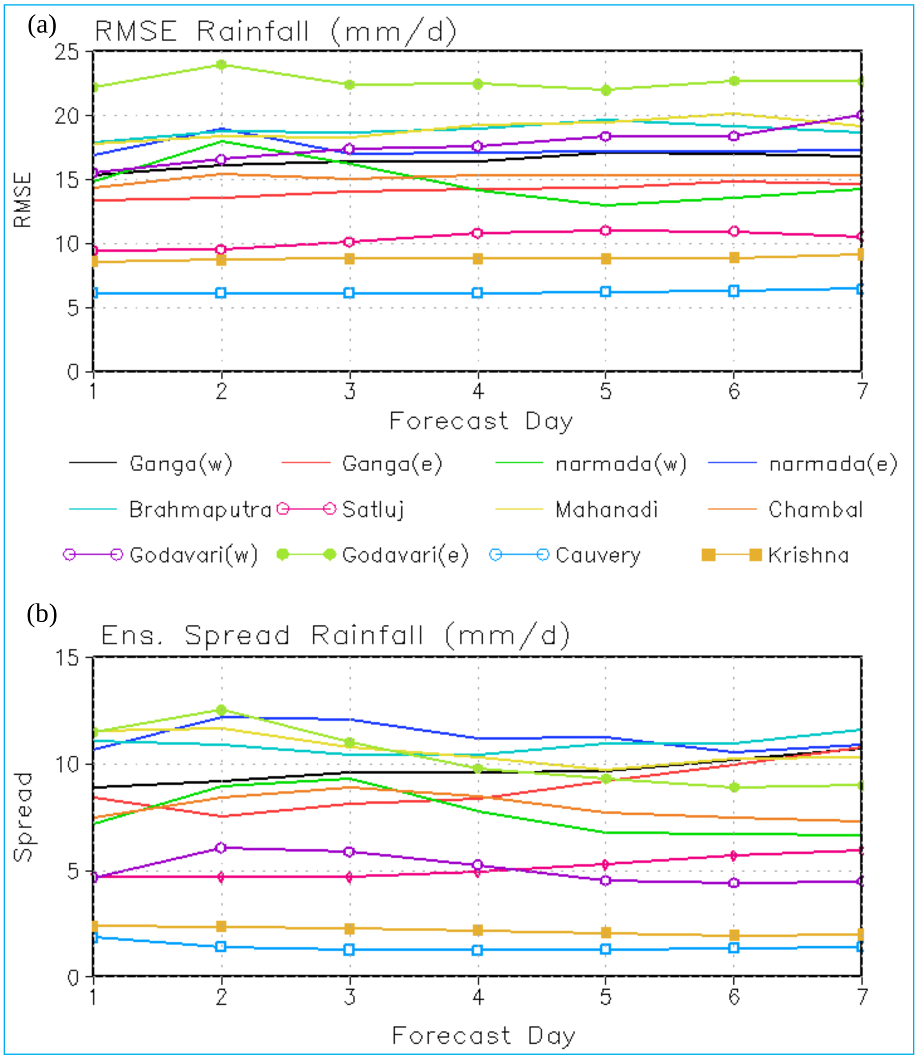
Very few activity of rainfall in moderate category occurred in the Satluj basin during July-August 2018. One of such episode was on August 6 and 7 and the other one was on August 13 as shown in Fig. 6(e). 7day forecasts shown in the figure indicate that the model over-estimated the rainfall amount on almost every occasions. The model has a systematic tendency to predict more rain in its forecasts in all ranges (day-1 to day-7) when the actual rainfall was less. The model wrongly predicted a moderate



Figs. 8(a-h). Observed and ensemble mean forecasts (day-1 to day-7) rainfall and 7day forecasts by each ensemble member averaged over river basins (a&b) Krishna basin; (c&d)Cauvery basin; (e&f) Mahanadi basin; (g&h) Chambal basin

rain activity on July 24 which did not occur. The ensemble members in the day-5 forecast valid for August 13 [Fig. 6(f)] starting with the initial condition of August 8 show that all the ensemble members predicted less rainfall while for all other dates, the forecasted amount is higher than the observed. While most of the ensemble members could forecast the rainfall category 5-days in advance, none could actually capture the peak of the event. Three to four moderate rainfall activities occurred in the Brahmaputra basin during July-August 2018. One of such episode was on August 6 and 7 and the other one was on August 12 as shown in Fig. 6(g). 7 day forecasts shown in the figure indicate that the model over-estimated the rainfall amount on every day with double the observed rainfall amount on many occasions. The model has a systematic tendency to predict more rain in its forecasts in all ranges over the basin when the actual rainfall was less. The day-5 forecasted rainfall from all the ensemble members valid for 12th August [Fig. 6(h)] starting with the initial condition for August 7 indicates that all the ensemble members predict less rainfall for the day while for all other dates, the forecasted amount is higher than the observed. Therefore, the model is not able to distinguish between rainfall categories and it does not capture the peak amount of rainfall as is observed in Brahmaputra basin.

The most dominant rainfall activity in Godavari basin occurred during 16-17 August when more than 100 mm rainfall was observed putting this rainfall amount in heavy rainfall category. In the western parts of the basin *i.e.* Godavari(w), few moderate rainfall activities were also observed [Fig. 7(a)]. While the rainfall peak observed on July 8 was not forecasted in any range, other moderate



Figs. 9(a&b). (a) Root mean square error (RMSE) of ensemble mean rainfall with respect to observed rainfall averaged over the river basins; (b) ensemble spread averaged over July and August 2018 over the river basins

rain events were predicted by the model except for the case of 12 August. More importantly, the weak or no rainfall activity from July 20 to August 10 was predicted by the model correctly in all the time ranges. The model could not forecast the heavy rainfall event which occurred on August 17 in its day-5 forecast [Fig. 7(b)]. Though some of the members had a peak on 17th August, some members forecasted the peak on 16th August. For the all members, maximum peak obtained was only 40 mm whereas more than 100 mm rainfall had occurred. The model skill is better for Godavari (e) basin where all the rainfall activities could be predicted well by the model in 7 day forecasts [Fig. 7(c)]. Though the rainfall amount in the peaks varied (with over-estimation of the peaks), it can be said that the performance of the model was reasonably good. For the case of 16 August, all the members could capture the rainfall event as observed from August 11. In the day-5 forecast for August 16, some of the ensemble members had forecasted about 90 mm rainfall while the observed amount was 60 mm as seen in Fig. 7(d). Several moderate rainfall events were observed in Narmada basin during July and August 2018. The event on July 17 over Narmada (w) basin was not predicted correctly by the model in any of the forecast from day-1 to day-7 as shown in Fig. 7(e). In most of the time ranges, one peak event was forecasted a day later, *i.e.*, on July 18 which did not occur. In this sub-basin, all the forecasts predicted more rain in August especially in the last week of August when the model consistently predicted 30-40 mm rain, the observed amount was about 5 mm or less. Rainfall forecasts from the ensemble members from July 7 was examined [Fig. 7(f)] to see if the model could predict the

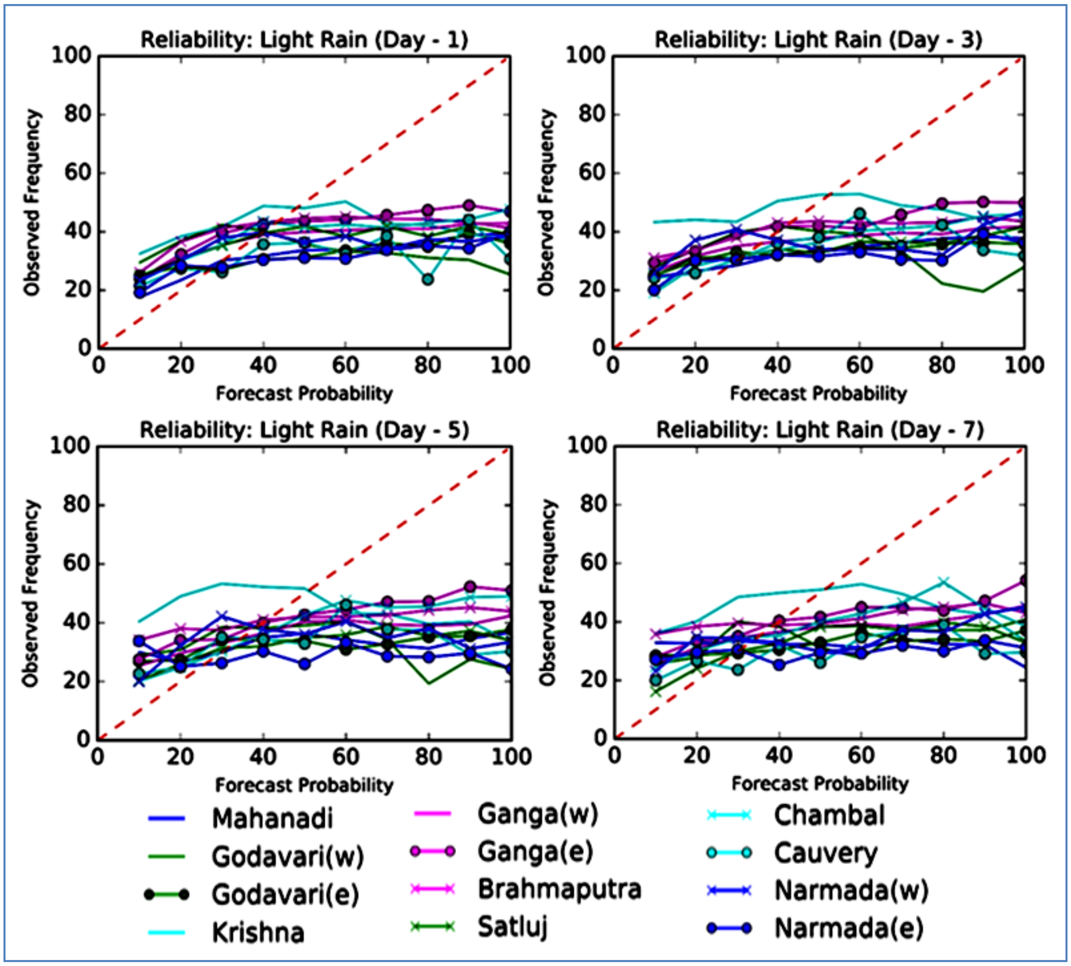


Fig. 10. Reliability diagram of probabilistic forecasts for each river basin in light rainfall category

peak rainfall amount of about 50 mm. It is seen that only a couple of ensemble members could predict that event. Some of the members predicted the event on the next day which was not realized. Similarly for Narmada (e) sub-basin, the model's performance shown in Fig. 7(g) is mixed with several events not getting forecasted in from day-1 to day-7. The peak event on July 23 was also not forecasted correctly as shown in 7 h with many members indicating a peak to occur on July 24 which did not occur. For July 23, many members suggested rainfall amount to be less than 20 mm while the observed amount was about 40 mm.

Most dominant rainfall activity in Krishna basin occurred during August 11 and 22 when moderate rainfall was observed. The model could reasonably well predict the rainfall peak activity in July as shown in Fig. 8(a). The weak or no rainfall activity from July 11 to August 10 was predicted by the model correctly in all the time ranges (from day-1 to day-7 forecasts). The peak rainfall for 12 August was not forecasted at all by the model in any of its forecasts. Moreover, none of the ensemble member had predicted a significant rainfall activity starting from August 7 in the 5 day forecast shown in Fig. 8(b). Only a few moderate rainfall activity was observed in Cauvery basin and the model provided mixed skill. The model generally underestimated the rainfall amount in its day-1 to day-7 forecasts shown in Fig. 8(c). The 5-day forecast from August 10 also shows [Fig. 8(d)] that all the members predicted less amount of rainfall as compared to observed peak on August 15. Several moderate rainfall activities were observed in Mahanadi basin and the model provided reasonable skill in its 7-day forecasts as seen in Fig. 8(e). Most important of the events was on July 22, 2018 when about 70 mm rainfall (heavy rain category) occurred averaged over the entire basin. However, the day-5 forecasts from July 17 could not forecast the event as seen in Fig. 8(f). Most of the ensemble members of the model forecasted an event on the 6th day forecast, *i.e.*, on July 18, which was not observed. Some of the moderate events in the Chambal basin could be forecasted well but with lower or higher intensities in 7-day

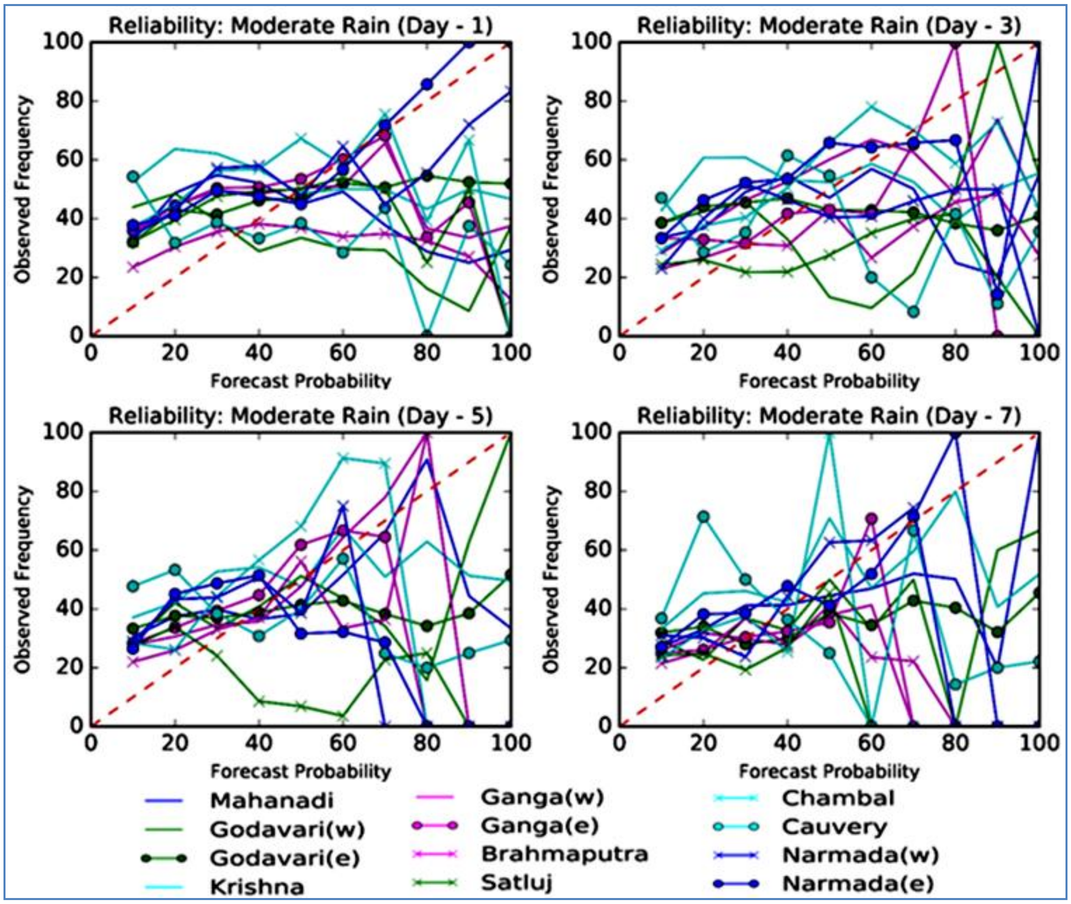


Fig. 11. Reliability diagram of probabilistic forecasts for each river basin in moderate rainfall category

forecasts [Fig. 8(g)]. However, the event on August 22 when the rainfall amount was more than 40 mm was not forecasted by the model in its 5-day forecast starting from August 17. In fact, some of the ensemble members were forecasting a reduction in rainfall amount from the day-4 forecasts to day-5 forecast as seen in Fig. 8(h).

Therefore, it is seen that the model has reasonable skill in predicting basin-averaged rainfall in its forecasts from day-1 to day-7. However, some of the major peaks in rainfall activity could not be forecasted well by the model (ensemble mean or any of the ensemble members). Therefore, these forecasts may not be very useful to predict the rise in water level or water amount (Fig. 5) in the reservoirs with confidence. There is a need to simulate the inflow and water level to these reservoirs using the forecast data in order to get a clearer picture. This will be taken up as a separate study.

3.2. *Ensemble spread, errors and reliability*

For a reliable probabilistic forecast system, RMSE and ensemble spread should be same. Kar *et al*. (2011) have examined the systematic errors and ensemble spread of an ensemble prediction system and had found that both the spread and error increased as the forecast length increased. As the main objective of the present study is to examine the reliability of rainfall forecasts at basin scale, RMSE and ensemble spread have been averaged for each basin as well as averaged over July and August 2018 and shown in Figs. 9(a&b). It is seen that RMSE values for most of the basins remain the same as the forecast length increases from day-1 to day-7 [Fig. 9(a)]. The Cauvery River basin has the least RMSE of rainfall (about 5mm/day) while the Godavari€ basin has the maximum RMSE of about 23 mm/day. For the Narmada (w), it is seen that RMSE value marginally increases from day-1 to day-2 from 15 mm/day to 18mm/day and then reduces to about 13 mm/day. As such, the basin averaged RMSE values of rainfall for all the basins are not large. The ensemble spread is very less for most of the river basins and are within 5 mm/day for Cauvery, Krishna and Satluj basins as seen in Fig. 9(b). Narmada (e) basin experienced maximum spread of about 12 mm/day from day-3 to day-5 forecasts. Over the Godavari basin, the spread reduced from 12 mm in day-2 forecasts to about 8 mm in day-7 forecasts. For the Ganga (e) basin, the spread increased from about 7 mm in day-2 forecast to about 11 mm/day in day-7 forecast. Therefore, it is seen that the spread amount is less as compared to the RMSE for all the river basins. As one of the requirement for reliable probabilistic rainfall predictions is that RMSE and spread for a region should be same, in the present study, it is found that the rainfall spread of ensemble members is less than RMSE values. Moreover, as the spread is too less (between 5 mm to 10 mm) for most of the basins and many of the moderate or heavy rainfall events occurring over the basins were not forecasted by the ensemble members (Figs. 6-8), there is a need of examining reliability of such probabilistic predictions.

For examining the reliability, rainfall forecasted in the categories of light and moderate have been used. In the heavy category, very few events were forecasted or observed during July-August 2018. Therefore, reliability for this event has not been included in this study. Fig. 10 has the reliability diagram for light rain category in day-1, day-3, day-5 and day-7 forecasts for each of the river basin. Similar analysis has been carried out for very light rain category also but not shown in figure. For the forecast to be most reliable, forecast probability should be same as the observed frequency making the reliability line to fall on the best line (diagonal line in the figure connecting lower-left and upper-right corners. From Fig. 10, it is seen that most of the forecasts over all the river basins are not reliable for this category of rain. The reliability pattern mostly does not change from basin to basin as well as it does not change much as the forecast length increases from day-1 to day-7. As the number of events vary from basin to basin, the no-skill line has not been drawn in the figure. However, the forecasts are found to be skillful when the forecast probability is between 10 to 60% though with overestimation after 30% forecast probability. Forecasts over Narmada (e) do not have any skill. Forecasts issued with more than 70% probability are mostly unskillful and are grossly over-estimated. This indicates that when most of the ensemble members have rainfall forecast in the same category (light rain), it is correct only in less than 50% of the cases the observed frequency being less than 40% as seen in the figure.

For Moderate rainfall category, the probabilistic forecasts are more reliable than that in the light rain category for each river basin (Fig. 11). However, all the forecasts above 40% forecast probability over-estimate the observed frequency. Though the no-skill line has not been drawn in the figure (due to difference in number of events in different basins), it is seen that the forecasts have some skill up to about 70% forecast probability. Forecasts over Ganga (e) are skillful in all forecast probabilities and in all forecast ranges. Unlike the other two categories, rainfall in moderate rain category has mixed skill. The skill varies from basin to basin and forecast range. Over the Narmada (e) basin, the day-1 forecasts are reliable in this category of rainfall and reliability reduced in day-3 and day-5 forecasts. Forecasts are more or less reliable up to 60% probability over the Ganga basin. Over all, all the forecasts under-estimate the observed frequency up to 40% forecast probability and over-estimate the observed frequency when forecast probability is more than 40%.

Main purpose of utilizing very high-resolution global model with several ensemble members is that the uncertainties in the initial conditions are represented in the forecasts and the users are able to take a decision for action based on the forecast probabilities. For hydrological operations, even if the forecast is probabilistic, the decision to be taken by the user agencies is essentially deterministic. Therefore, it is important that the rainfall forecasts are skillful and reliable for hydrological applications. As noted by Murphy (1993), the lack of reliability in the forecasts in the present study is a bias in probability. Therefore, in order to obtain improved reliability, several methods for calibration of probabilistic forecasts have been proposed. Such calibration consists of a statistical correction of the forecast probability based on previous verification. In the present study no calibration could be carried out as this is the first season of the present ensemble forecast system.

4. Conclusions

The NCMRWF has recently upgraded its ensemble forecasting system and prepares 23-member ensemble medium-range weather forecasts every day. For hydrological applications of these forecast, it is required that the skill of the model is evaluated and documented. In this study, rainfall forecasts up to 7 days have been examined at river basin scales. The basins considered are Ganga, Brahmaputra, Satluj, Chambal, Godavari, Krishna, Narmada, Mahanadi and Cauvery. The rainfall categories considered are very light, light, moderate, heavy and very heavy. There were only very few heavy or very heavy rainfall events during July and August 2018. Reservoir data from these basins for 2018 were examined to identify when the water level and storage amount increased considerably due to moderate or heavy rainfall events. Reliability of the forecasts at basin scale was examined using reliability diagram for light and moderate rainfall categories. The following are the main findings of the study.

(*i*) The model has reasonable skill in forecasting rainfall (ensemble mean) over the Indian regions up to 7 days in advance.

(*ii*) The model could predict categorical rainfall (hits) for several rainfall events, however, the number of false alarms are larger than number of hits. The model also missed quite a few events in various categories.

(*iii*) The model could predict several rainfall events over the river basins reasonably well. However, on many occasions, none of the ensemble members could forecast high amount of rainfall that was observed.

(*iv*) The RMSE and ensemble spread remain almost the same as the forecast length increases over all the river basins considered. Therefore, forecast quality does not deteriorate as the forecast length increases.

(*v*) The ensemble spread is quite less and almost half the RMSE values for each of the river basin.

(*vi*) The probabilistic forecasts are not reliable for any of the categories. The model forecasts overestimate the observed frequency over all the river basins. Forecasts with probability values of more than 70% do not have any skill.

(*vii*) Statistical bias correction is needed to make the forecast probabilities more reliable and usable.

Acknowledgement

The contents and views expressed in this research paper are the views of the authors and do not necessarily reflect the views of their organizations.

References

Anand, J., Gosain, A. K., Khosa, R. and Srinivasan, R., 2018, "Regional scale hydrologic modeling for prediction of water balance, analysis of trends in streamflow and variations in streamflow: The case study of the Ganga River basin", *Journal of Hydrology: Regional Studies*, **16**, 32-53.

Bhardwaj, R., Kumar, A., Maini, P., Kar, S. C. and Rathore, L. S., 2007, "Bias-free rainfall forecast and temperature trend-based temperature forecast using T-170 model output during the monsoon season", *Meteorological Applications*, **14**, 4, 351-360.

Buizza, R., Leutbecher, M. and Isaksen, L., 2008, "Potential use of an ensemble of analyses in the ECMWF Ensemble Prediction System", *Q. J. R. Meteorol. Soc.*, **134**, 2051-2066.

Chauhan, M. K. and Shrivasava, R. K., 2017, "A critical study of water availability and water use in upper Chambal sub-basin in Madhya Pradesh", *J. Indian Water Resour. Soc.*, **37**, 47-55.

Clayton, A. M., Lorenc, A. C. and Barker, D. M., 2013, "Operational implementation of a hybrid ensemble/4D-Var global data assimilation system at the Met Office", *Q.J.R. Meteorol. Soc.*, **139**, 1445-1461.

Doblas Reyes, F. J, Hagedorn, R. and Palmer, T. N., 2005, "The rationale behind the success of multi-model ensembles in seasonal forecasting-II calibration and combination", *Tellus A.*, **57**, 234-252.

Dube, A., Ashrit, R., Singh, H., Arora, K., Iyengar, G. and Rajagopal, E. N., 2017, "Evaluating the performance of two global ensemble forecasting systems in predicting rainfall over India during the southwest monsoons", *Meteorological Applications*, **24**, 2, 230-238.

Durai, V. R. and Roy Bhowmik, S. K., 2014, "Prediction of Indian summer monsoon in short to medium range time scale with high resolution global forecast system (GFS) T574 and T382", *Clim. Dyn.*, **42**, 1527-1551.

Durai, V. R., Bhardwaj, Rashmi, Roy Bhowmik, S. K. and Rama Rao, Y. V., 2015, "Verification of quantitative precipitation forecasts from operational ensemble prediction systems over India", *MAUSAM*, **66**, 3, 479-496.

Gouweleeuw, B. T., Thielen, J., Franchello, G., De Roo, A. P. J. and Buizza, R., 2005, "Flood forecasting using medium-range probabilistic weather prediction", *Hydrol. Earth Syst. Sci.*, **9**, 365-380.

Hamill, T. M., 2012, "Verification of TIGGE Multimodel and ECMWF Reforecast-Calibrated Probabilistic Precipitation Forecasts over the Contiguous United States", *MWR*, **140**, 2232-2252.

Jie, Weihua, Tongwen Wu, Jun Wang, Weijing Li and Thomas Polivka, 2015, "Using a deterministic time-lagged ensemble forecast with a probabilistic threshold for improving 6-15 day summer precipitation prediction in China", *Atmospheric Research*, **156**, 142-159.

Johnson, C. and Bowler, N., 2009, "On the reliability and calibration of ensemble forecasts", *Mon. Wea. Rev.*, **137**, 1717-1720.

Kar, S. C. and Tiwari, Sarita, 2016, "Model simulations of heavy precipitation in Kashmir, India, in September 2014", *Natural Hazards*, **81**, 1, 167-188.

Kar, S. C., Iyengar, G. R. and Bohra, A. K., 2011, "Ensemble spread and systematic errors in the medium-range predictions during the Indian summer monsoon", *Atmosfera*, **24**, 2, 173-191.

Kar, S. C., Joshi, S., Shrivastava, S. and Tiwari, S., 2018, "Dynamical characteristics of forecast errors in the NCMRWF Unified model (NCUM)", *Clim. Dyn.*, DOI: 10.1007/s00382-018-4428-4.

Koneti, S., Sunkara, S. L. and Roy, P. S., 2018, "Hydrological modeling with respect to impact of land-use and land-cover change on the runoff dynamics in Godavari River basin using the HEC-HMS model", *ISPRS Int. J. Geo-Inf.*, **7**, 6, p206, DOI: 10.3390/ijgi7060206

Leutbecher, M. and Palmer, T. N., 2008, "Ensemble forecasting", *J. Comp. Phys.*, **227**, 3515-3539.

Mamgain, Ashu, Sarkar, A., Dube, A., Arulalan, T., Chakraborty, P., George, J. P. and Rajagopal, E. N., 2018, "Implementation of Very High Resolution (12 km) Global Ensemble Prediction System at NCMRWF and its Initial Validation", *Technical Report*, NMRF/TR/02/2018, National Centre for Medium Range Weather Forecasting, Noida, India

Murphy, A. H., 1993, "What is a good forecast? An essay on the nature of goodness in weather forecasting", *Wea. Forecasting*, **8**, 281-293.

Nandi, S. and Reddy, M. J., 2017, "Distributed rainfall runoff modeling over Krishna river basin", *European Water*, **57**, 71-76.

Palash, Wahid and Jiang, Yudan, 2018, "A Stream flow and Water Level Forecasting Model for the Ganges, Brahmaputra and Meghna Rivers with Requisite Simplicity", *Journal of Hydrometeorology*, **19**, 201-225.

Reddy, M. and Ganguli, Jangaand Poulomi, 2012, "Bivariate flood frequency analysis of upper Godavari River flows using Archimedean copulas", *Water Resour. Manage*., **26**, 3995-4018.

Satyanarayana, G. C. and Kar, S. C., 2016, "Medium-range forecasts of extreme rainfall events during the Indian summer monsoon", *Meteorological Applications*, **23**, 2, 282-293

Sharma, Rajat K., Goswami, S. B., Tiwari, S. and Kar, S. C., 2015, "Evaluation of Daily Rainfall-Runoff Simulations in Narmada River Basin", *Int. J. Earth Sciences and Engineering*, **8**, 3, 1123-1132.

Sharpe, M. A., Bysouth, C. E. and Stretton, R. L., 2018, "How well do Met Office post-processed site-specific probabilistic forecasts predict relative-extreme events?", *Met. Apps*, **25**, 23-32. doi:10.1002/met.1665.

Shrivastava, S., Kar, S. C., Sahai, A. K. and Sharma, A. R., 2018, "Identification of drought occurrences using ensemble predictions up to 20-days in advance", *Water Resource Management*, **32**, 2113-2130.

Tiwari, Sarita, Kar, S. C. and Bhatla, R., 2016a, "Interannual Variability of Snow Water Equivalent (SWE) over Western Himalayas", *Pure and Applied Geophysics*, **173**, 4, 1317-1335, DOI 10.1007/s00024-015-1163-1.

Tiwari, Sarita, Kar, S. C. and Bhatla, R., 2016b, "Examination of snowmelt over Western Himalayas using remote sensing data", *Theoretical and Applied Climatology*, **125**, 227-239, DOI 10.1007/s00704-015-1506-y.

Tiwari, Sarita, Kar, S. C., Bhatla and Bansal, R., 2017, "Temperature index based snowmelt runoff modelling for the Satluj River basin in the western Himalayas", *Meteorological Applications*, 1-12, https://doi.org/10.1002/met.1692.

Weigel, A. P., Baggenstos, D., Liniger, M. A., Vitart, F. and Appenzeller, C., 2008, "Probabilistic verification of monthly temperature forecasts", *Mon. Wea. Rev*., **136**, 5162-5182

Zhou, X., Zhu, Y., Hou, D., Luo, Y., Peng, J. and Wobus, D., 2017, "The NCEP global ensemble forecast system with the EnKF initialization", *Weather and Forecasting*, **32**, 1989-2004.