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Evaluation of operational forecasts from weather research and forecasting model during southwest monsoon 2011 using MET 3.0

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सार – इस शोध पत्र में मौसम केंद्र बंगलुरू में वास्तविक समय में अत्याधुनिक मौसम अनुसंधान एवं पूर्वानुमान (WRF) मॉडल से वर्ष 2011 की मॉनसून ऋतु के दौरान दिए गए वर्षा पुर्वानुमानों के कौशल पर चर्चा की गई है। इस WRF (डब्ल्यू आर एफ) मॉडल को दक्षिणी प्रायद्वीप भारत के 9-22° उ./ 74-87° पूर्व के सीमित क्षेत्र के लिए चलाया गया है। भारत मौसम विज्ञान विभाग के ग्रिडेड तथा स्थान विशेष के वर्षा आँकड़ों का उपयोग करके मॉडल मूल्यांकन टूल्स पैकेज के द्वारा इसका सत्यापन किया गया है। परिणामों से पता चला है कि यह मॉडल पश्चिम तटीय क्षेत्र एवं पूर्वी भारत में अधिकतम वर्षा की और अंतरदेशीय प्रायद्वीपीय भारत में न्यूनतम वर्षा की ऋतुनिष्ठ तस्वीरें तैयार करने में सक्षम है। समय श्रृंखला में क्षेत्र में हुई कुल दैनिक वर्षा का औसत और पूर्वानुमानित वर्षा के औसत से पता चलता है कि अधिकांश दिनों में दिए गए पूर्वानुमान के ट्रेन्ड प्रेक्षित किए गए ट्रेन्ड से मेल खाते हैं। हालांकि मात्रात्मक पूर्वानुमान की मात्रा प्रेक्षित मात्रा से कम है। 24 और 48 घंटों के वर्षा पूर्वानुमान में औसत त्रुटि, औसत निरपेक्ष त्रुटि तथा वर्गमूल औसत त्रुटि क्रमशः 3.1 एवं 1.4, 11.6 एवं 10.9, 26.8 एवं 24.9 मि.मी. प्रतिदिन पाई गई है। सुनिश्चित स्कोर्स जैसे:- प्रोबेब्लिटी ऑफ डिटेक्शन, फाल्स अलार्म रेशियो, फ्रिक्वेन्सी बाइअस, क्रिटीकल सक्सेस इंडेक्स तथा हाइडके स्किल स्कोर्स की गणना विभिन्न अवसीमाओं के लिए की गई है। इसमें हाइडके स्किल स्कोर्स को सकारात्मक देखा गया है और यह निचली अवसीमाओं में 24 एवं 48 घंटों के पूर्वानुमान के लिए 0.38 एवं 0.37 से 10 मि.मी. तक पाया गया है। इन स्कोर्स से पता चलता है कि कम वर्षा अवसीमा के लिए मॉडल का कार्य निष्पादन अच्छा है परन्तु उच्चतर वर्षा अवसीमा के लिए यह क्रमशः खराब होता जाता है। अतः प्रचालनात्मक पूर्वानुमानकर्त्ता इस मॉडल पूर्वानुमान को हल्के वर्षा वाले दिनों में विश्वासपूर्वक अपना सकते हैं परन्तु तीव्र वर्षा वाले दिनों में नहीं।

ABSTRACT. This study discusses the skill of rainfall forecasts during monsoon 2011 from the state-of-art Weather Research and Forecasting (WRF) model run real-time at the Meteorological Centre Bangalore. The WRF is run for the limited domain of 9-22° N / 74-87° E covering the southern peninsular India. Rainfall verification is performed using continuous and categorical approaches. It's verified using India Meteorological Department's gridded and point rainfall by Model Evaluation Tools package. The results show that model is capable of reproducing seasonal picture of rainfall; maxima over west coast and eastern India and minima over inland peninsular India. Time series of area averaged daily accumulated observed and forecasted rainfall shows that forecast trend matches observed trend on most of the days. However, quantitative forecast amount is less than the observed. The mean error, mean absolute error and root mean square error of rainfall are found to be 3.1 & 1.4, 11.6 & 10.9 and 26.8 and 24.9 mm/day for 24 and 48 hours forecasts. The categorical scores like probability of detection, false alarm ratio, frequency bias, critical success index and Heidke skill scores are calculated for various thresholds. The Heidke skill score is found to be positive and is 0.38 and 0.37 in the lower thresholds up to 10 mm for 24 and 48 hour forecasts. These scores indicate that model's performance is good for lower rainfall threshold but degrades considerably for higher rainfall thresholds. Hence, an operational forecaster can accept model forecast of a rainy day with confidence but not the intensity.

Key words – Model, Forecast verification, Model evaluation tools, WRF.

1. Introduction

This is the age of super-computers and sophisticated numerical models are being run at almost every weather forecasting centre. Numerous advantages like the capability to assimilate conventional and unconventional data, number of physics and numeric options to choose from have made them a flexible tool for research and operational forecasts. Hence, under the modernisation project of the India Meteorological Department (IMD), High Performance Computing systems (HPC's) were installed at New Delhi and at a total of six Regional and Meteorological Centres (MC). These cities were chosen as they represent different topographical features and are under different weather regimes. The idea was to run the latest state of art numerical model for each regional domain in order to augment the forecasts issued by each of the RMC and MC's. The Weather Research and

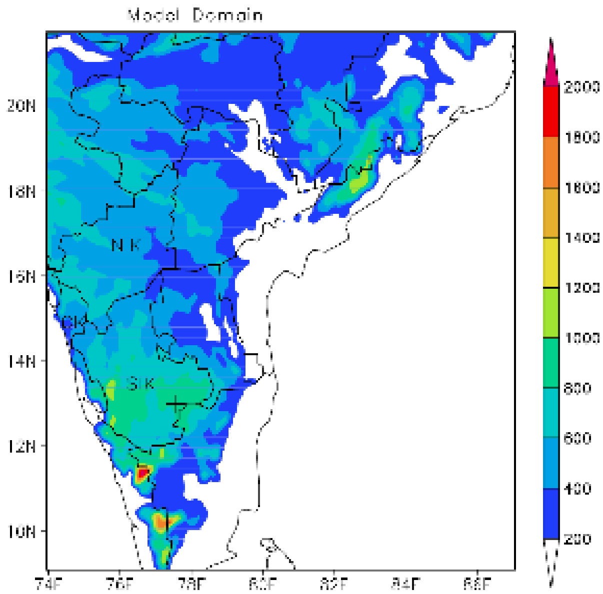


Fig. 1. Model domain and the height (metres); '+' is location of Meteorological Centre Bangalore, CK, NIK and SIK are 3 meteorological sub divisions namely coastal, south interior and north interior Karnataka

Forecasting model (WRF) is being run based on the initial conditions of 0000 UTC every day at MC Bangalore, State capital of Karnataka, is shown by '+' sign in Fig. 1. This State has three meteorological sub-divisions namely, coastal (CK), north interior and south interior Karnataka (NIK, SIK) (Fig. 1). The southwest monsoon season (SWM) is the primary rainy season in India. The CK met-subdivision lies on the windward side of Western Ghats and receives heavy orographic rainfall amounting to 300 - 350 cm during this season (Rao, 1976). The daily station rainfall over CK can range from 10-20 cm/day during this season. There is a steep gradient in rainfall from CK to NIK and SIK. The coefficient of variation of annual rainfall is 15% over CK and between 20-30% over NIK and SIK (Climate of Karnataka, 1984).

Forecast verification is an indispensible part of any forecasting system. It is important that we verify the forecasts because of large expenditure incurred in setting up this kind of infrastructure at regional centres. It will give an insight into the strengths and weaknesses of the model and most importantly, will help to answer the question 'is the model forecast good and reliable?' Rainfall is particularly of great interest as it has direct impact in agriculture, defence and air quality. It is an input for hydrological models for flood forecasting and has greatest socio-economic impact. This parameter was chosen as the verifying parameter as it is discontinuous in space and time and is the most difficult parameter to forecast from a model. Rainfall is usually verified by interpolating model data to point location (Ebert *et al.*, 2003) or by converting point data into gridded data (McBride and Ebert, 2000). Gomez *et al.* (2014) have used point data of 18 stations to verify air temperature, relative humidity, wind speed and direction of the model output. They have verified the rainfall forecasts using yes/no table and scatter plots. Their results show that rainfall is in general over-predicted with marked differences between different seasons. The verification of Indian summer monsoon precipitation was carried out by measure-oriented and distribution-oriented methods over the three diverse regions of India by Mandal *et al.* (2007). They have concluded that the performance of the model is reasonably good for day-1 forecasts and the weekly rainfall forecast is quite good for all forecast lead times. The other studies over Indian region (Das *et al.*, 2008; Durai *et al.*, 2010) have also used gridded rainfall data and concluded that global and mesoscale models are capable of reproducing seasonal picture very well but suffer from errors on day to day basis. This study was also taken up keeping same goal in mind, i.e. assessing the performance of short range deterministic forecast from WRF run operationally at MC Bangalore. The focus is on the performance of the model over Karnataka State during monsoon 2011. Section 2 gives the model details and the data used for verification. Section 3 is about Results and Discussions and finally Conclusions and scope for future work are summarised in Section 4.

TABLE 1

Details of the WRF model configuration at M. C., Bangalore

Parameter	Details
Horizontal Resolution	9 km
Vertical Levels	38
Dynamical Core	ARW
Cumulus parameterization	Grell and Devenyi, 2002
Micro Physics	WSM3 (Hong *et al*., 2004)
Short Wave Radiation	Dudhia Scheme (Dudhia, 1989)
Long Wave Radiation	RRTM (Mlawer *et al*., 1997)
Surface Layer	Monin and Obukhov, 1954
Land Surface Process	Unified Noah land surface model (Chen and Dudhia, 2001)
Boundary layer	YSU scheme (Hong *et al*., 2006)
Time step for integration	45 sec

2. Model details and methodology

The real-time weather forecasts at the MC Bangalore were generated using the advanced WRF 3.0 model. The model domain, height (in metres) and location of MC

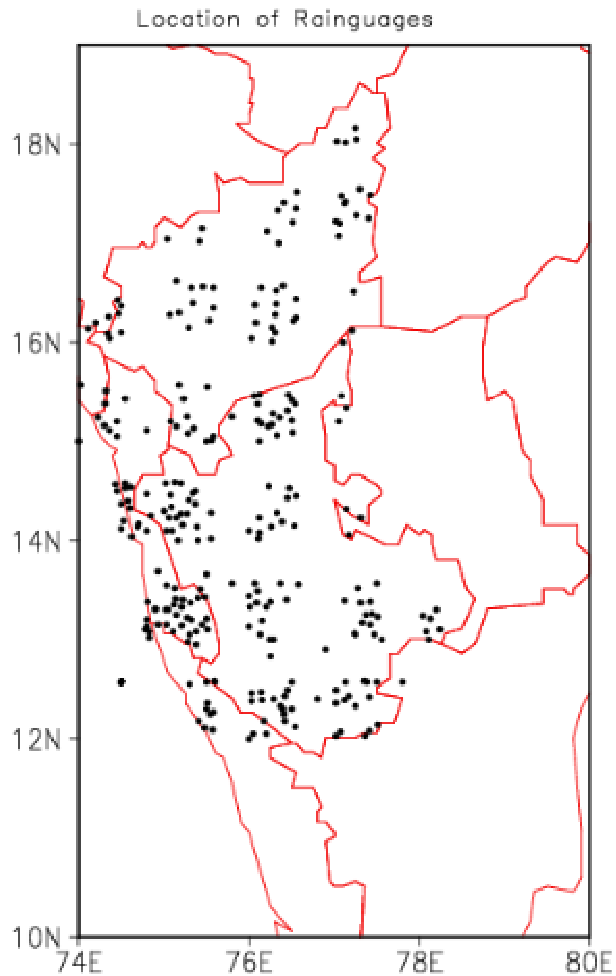


Fig. 2. Location of the raingauges

Bangalore (marked by '+') are shown in the Fig. 1. WRF is run for nested domains of 9 and 3 km horizontal resolution for region within 74-87° E / 9-22° N. The initial and boundary conditions for 0000 UTC runs are taken from National Centers for Environment Prediction (NCEP) (ftp://ftpprd.ncep.noaa.gov/pub/data/nccf/com/gfs/prod/). The model was run from 1 June to 30 September, 2011 for 24 and 48 hour forecasts. Details of the model configuration used are given in Table 1. Rainfall forecast at 9 km resolution is verified as this domain covers the entire State and its validation is done using two products of IMD; merged rainfall at 0.5° × 0.5° and 24 hour accumulated rainfall received from a dense network of raingauges under various rainfall monitoring schemes. The purpose of using merged product was to see if the spatial pattern of rainfall is represented well by the model. In order to quantify the forecast metrics using standard scores, point rainfall data was used. There are a total of 340 rainfall stations in the Karnataka state and out of these 80% of stations report the data in real time everyday at 0300 UTC to MC. These stations are located at the taluk and sub-taluk level of the state representing a dense network of rain gauges over the state (Fig. 2).

TABLE 2

2 × 2 Contingency Table

	Observed	
Forecast	F_yO_y (a) (Hits)	F_yO_n (b) (Miss)
	F_nO_y (c) (False alarm)	F_nO_n (d) (Correct non-events)

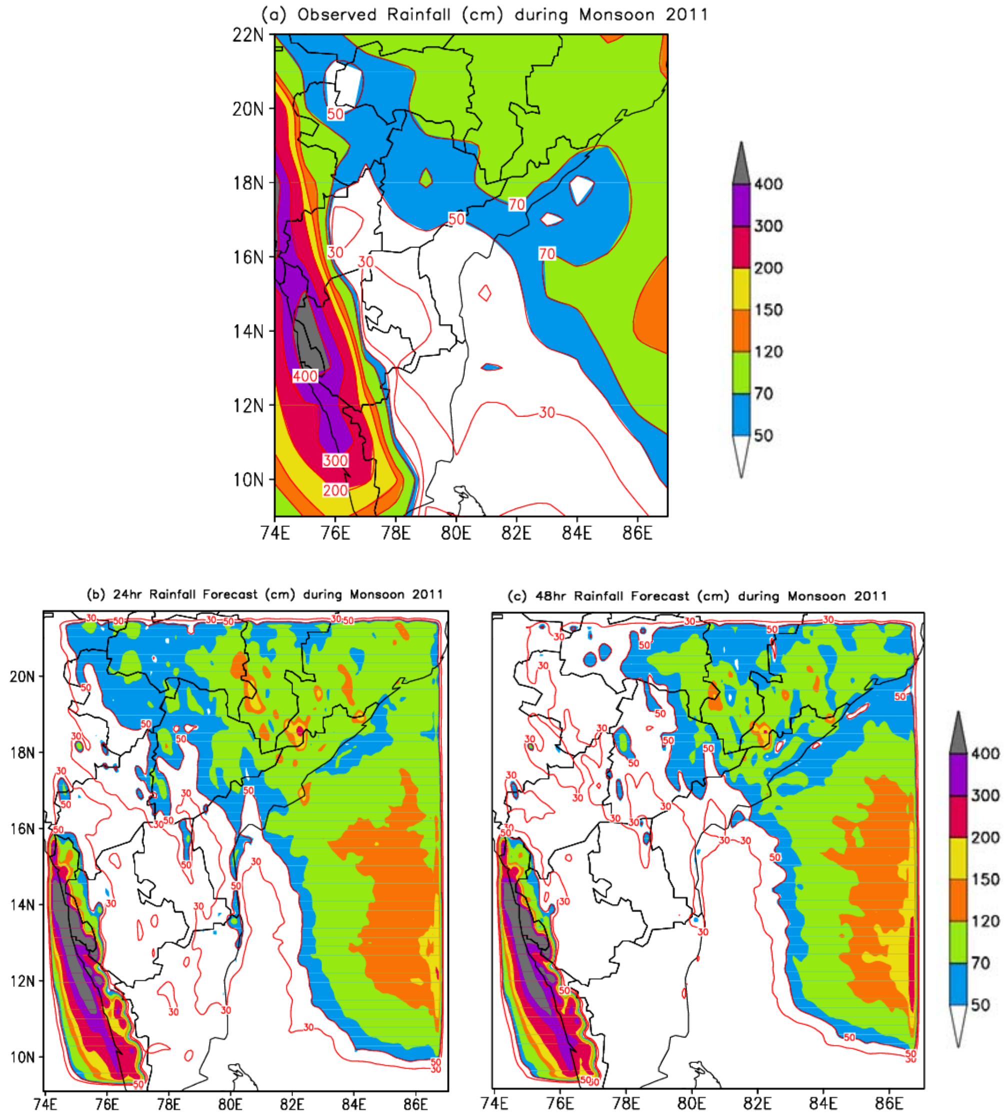
Model Evaluation Tools (MET 3.0) (http://www.dtcenter.org/met/users/index.php) is a verification package developed by WRF Developmental Testbed Center (DTC) and National Center for Atmospheric Research (NCAR), USA. This is free software provided to the user community and has various tools for verification. The point stat tool in this package interpolates the gridded forecast from model to a station location. In this study, the nearest neighbour method was employed for interpolating the model forecast to station location. This procedure created a set of matched pairs (MPR) consisting of forecasts and observations. Out of total of 122 days of monsoon season, the forecast of 110 days was available and a total of 33269 and 33291 numbers of MPR's for 24 and 48 hours forecast were generated. MPR approach suffers from the problem of double-penalty (Rossa *et al*., 2008). Another issue is the error in representing the observed data, whether point or gridded, at a scale other than its own (Tustison *et al*., 2001). In spite of these issues, it was felt the verification by using point and gridded data will be helpful in assessing the performance of the model to some extent.

Rainfall verification is performed using both continuous and categorical approaches. Some traditional verification scores like Mean Error (ME), Mean Absolute Error (MAE) and Root Mean Square Error (RMSE) were calculated treating it as a continuous variable. The categorical scores (yes/no forecasts) like Probability of Detection (POD), False Alarm Ratio (FAR), Frequency Bias (FB), Critical Success Index (CSI) and Heidke Skill Score (HSS) were calculated by taking various thresholds of 0.1, 2.5, 5, 7.6, 10, 20, 30, 35.5, 40, 50, 60, 64.4, 70, 80, 100, 120 mmday^{-1}. The contingency table used is shown in Table 2 (Wilks 1995).

3. Results and discussions

3.1. *Broad features of monsoon 2011*

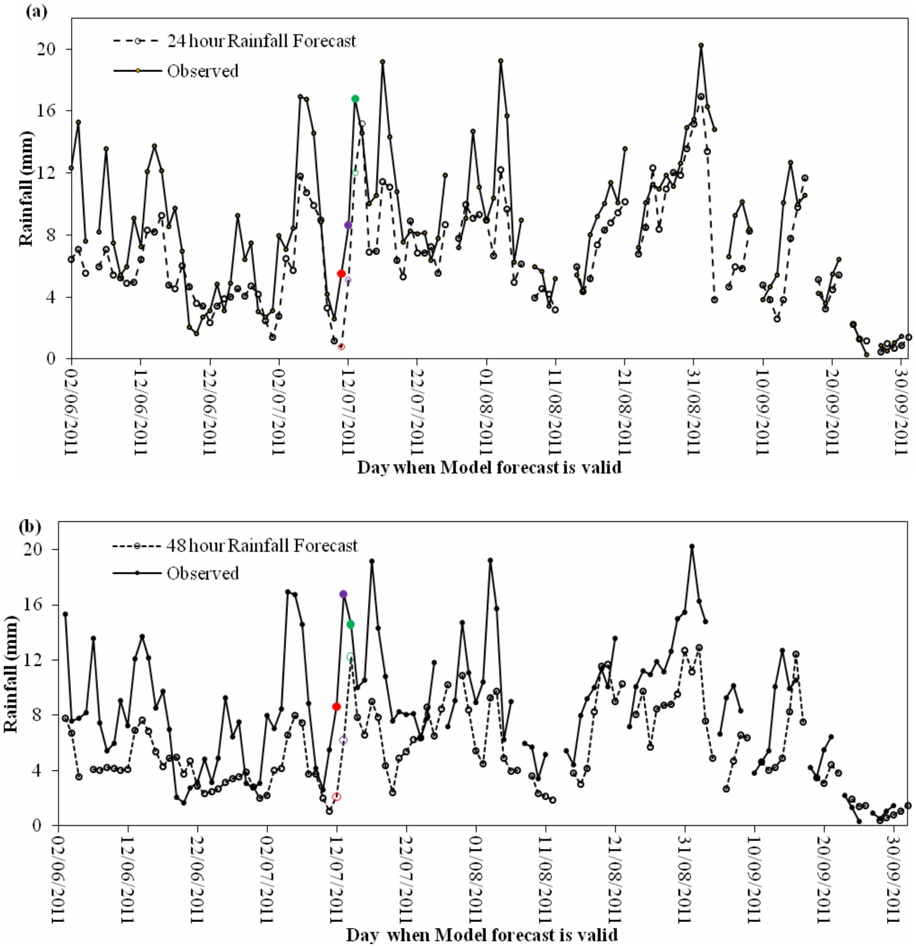
The observed rainfall used in this study is a merged product from the Tropical Rainfall Measuring Mission



Figs. 3(a-c). Cumulative rainfall (cm) (a) Observed (b) 24 hour forecast (c) 48 hour forecasts during Monsoon 2011

(TRMM) Microwave Imager (TMI) and Precipitation Radar (PR) and IMD rain gauge data (Mitra *et al.*, 2009). The need for generating merged rainfall product arose because microwave imager data was available at high spatial resolution over Indian monsoon domain and good quality gauge data over land areas. The inter-comparison of this data with the gridded analysis only over land (Rajeevan *et al.*, 2006) and with Global Precipitation Climatology Project (GPCP) datasets (Mitra *et al.*, 2013) has shown that this data is of good quality and can be used for verification of rainfall forecasts from models. This data has a resolution of 0.5° × 0.5°, covers a large domain (40° N - 40° S / 50 - 120° E) and is available on daily basis. It is used by forecasters for monitoring the advance and withdrawal of the monsoon operationally.

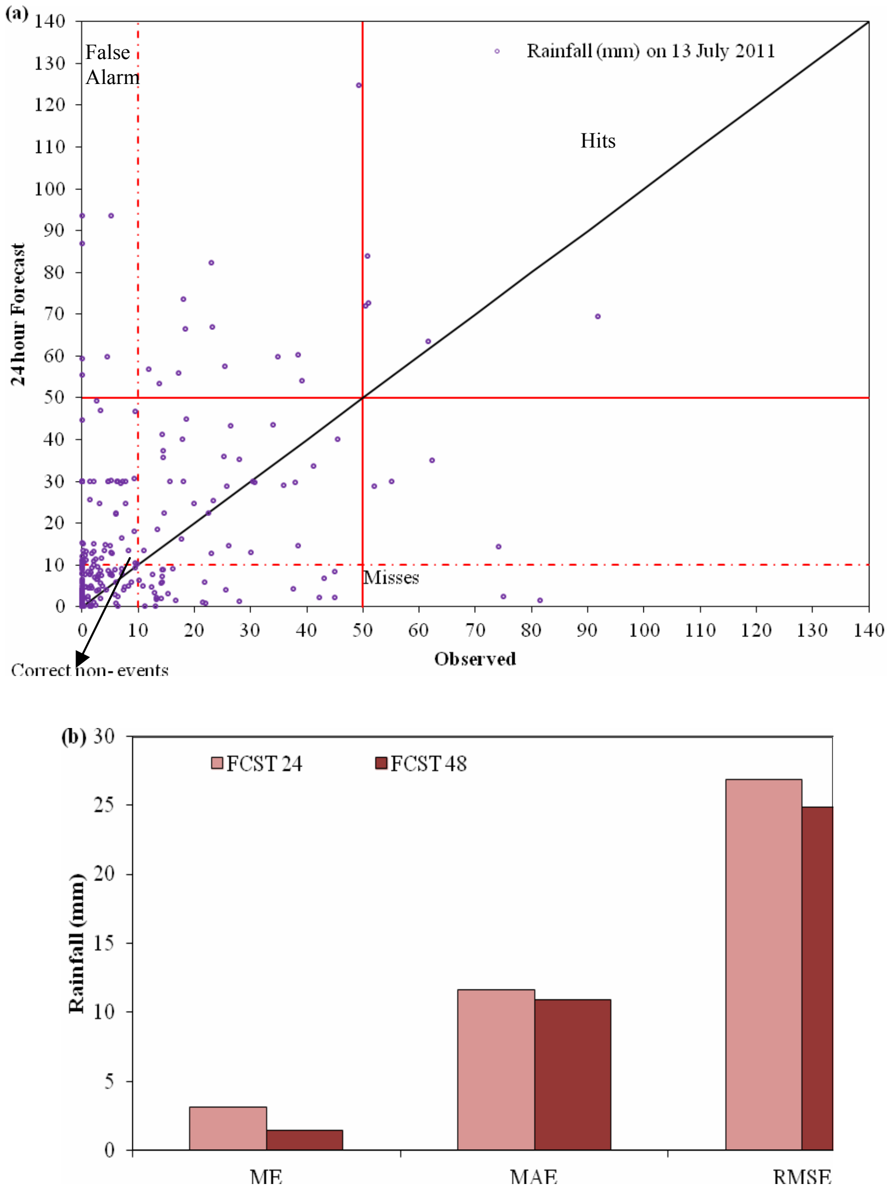
The cumulative observed rainfall during June to September, 2011 is shown in Fig. 3(a). The north-south oriented mountain chains over the western part of the country induce upward vertical velocity enhancing the precipitation at the windward side and suppressing the precipitation at the leeward side (Rao, 1976). This is the region of rainfall maxima and CK subdivision and ghat areas of SIK receive seasonal rainfall of the order of 300-400 cm as shown in the Fig. 3(a). The rain shadow region is spread over a large area of the peninsular India where



Figs. 4(a&b). Time series of (a) 24 hours and (b) 48 hours forecast and observed area average rainfall (mm)

seasonal rainfall is one tenth of CK, of the order of 30-70 cm. This rainfall is primarily due to the local features and due to the passage of synoptic scale systems during monsoon season. The secondary rainfall maxima is over the eastern India (Rao, 1976). This region is dominated by low pressure systems that form due to southward march of monsoon trough into the Bay of Bengal. Movement of these systems in the west-northwest direction contributes significantly to the rainfall over eastern and adjoining central India (Mohapatra, 2007). The Figs. 3(b&c) are the 24 and 48 hour forecast rainfall during monsoon 2011. It is seen from these figures that the model is able to reproduce the seasonal large scale features of rainfall to a very large extent, heavy rainfall over west coast and central India. The region of subdued rainfall over the eastern parts of NIK and SIK and parts of Tamil Nadu is also captured very well. It is also seen from this figure that model rainfall is uneven while the merged product is very smooth. Rainfall has very large spatial and temporal variation and hence it's averaging leads to a very smooth field, different from the original observations. Rainfall maxima can flatten or can increase depending on the neighbouring data.

Time series of area averaged observed and forecast rainfall is shown in the Figs. 4(a&b). The *x*-axis shows the date of forecast validity. The monsoon rainfall varies according to the active and break spells. The active spells are usually associated with the formation of a well organised synoptic scale system over Indian region. The prediction of such active spells is an important component in model verification process. One such event was the formation of a low pressure over the west central and adjoining northwest Bay of Bengal off north Andhra Pradesh-south Orissa coasts during 13-16 July, 2011. The area averaged observed and forecast rainfall during this period is shown in different colours by solid and open circles. The forecast valid for 11, 12 and 13 July, 2011 and observed on the same days is shown by open and closed circles in red, violet and green colour respectively.



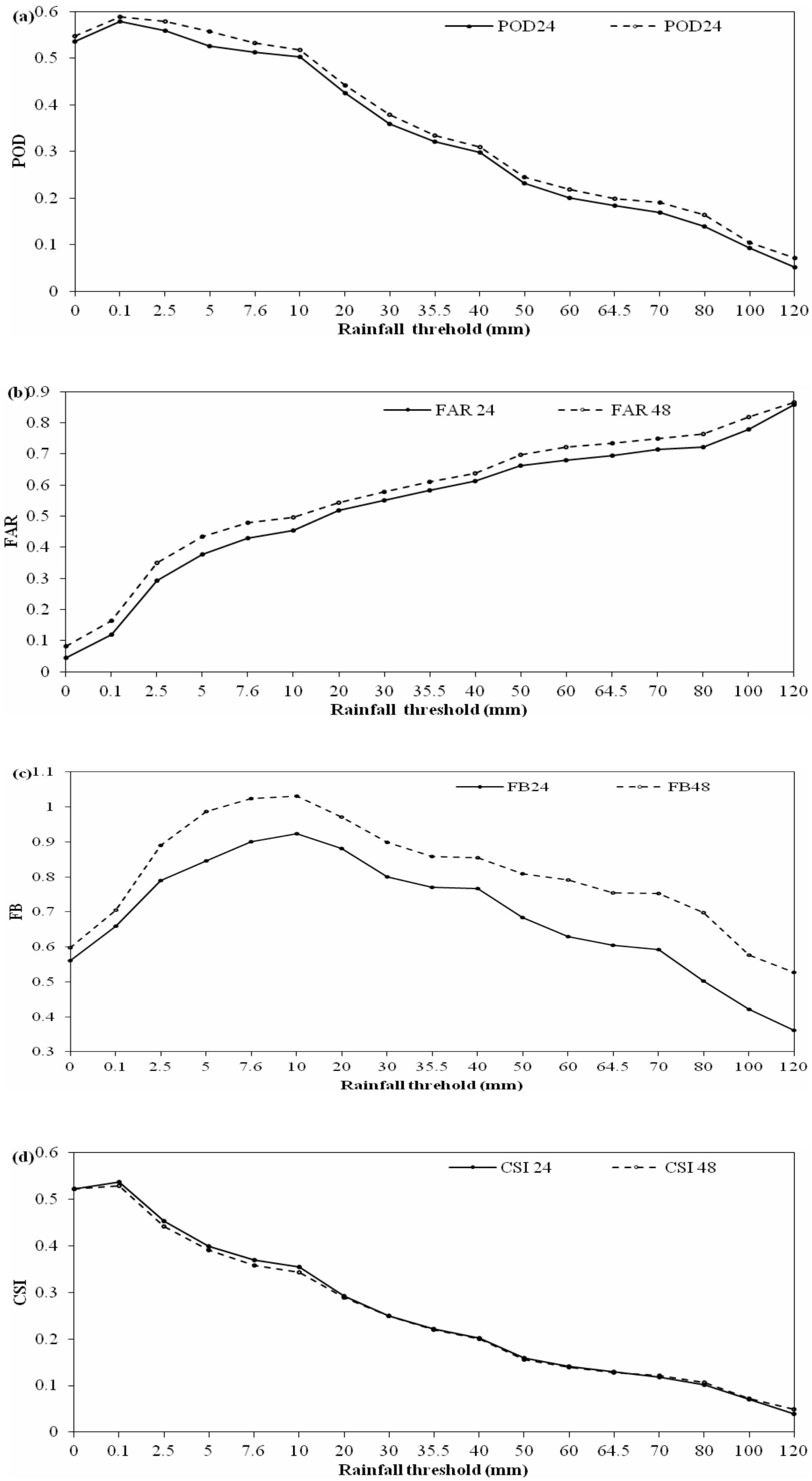
Figs. 5(a&b). (a) Scatter plot of rainfall (mm) on 13 July 2011 (b) ME, MAE and RMSE of rainfall for 24 and 48 hour forecasts

Figs. 4(a&b) show that the forecast trend matches the observed trend very well but quantitative forecast rainfall is always less than the observed. The matching of forecast trend with observed is seen on most of the days.

3.2. *Quality of the forecast*

Stanski *et al*. (1989) have discussed six attributes of a forecast namely accuracy, reliability, skill, resolution, sharpness and uncertainty that make its total quality. Single verification score cannot provide the complete information about the quality of the product. The forecast attributes studied here are the accuracy and skill. The other attributes namely reliability, resolution and sharpness are discussed mostly in terms of probabilistic forecasts. The uncertainty refers to the error in forecast owing to the uncertainty in the observations. This aspect is also not touched upon.

Scatter plot of the MPR's of rainfall on 13 July, 2011 is shown in Fig. 5(a). The observed and forecast data refer to rainfall at point locations. Daily rainfall threshold corresponding to interior Karnataka (NIK & SIK) and CK are taken to be 1 and 5 cm/day and are shown in dotted



Figs. 6(a-d). (a) POD (b) FAR (c) FB (d) CSI for 24 and 48 hour forecasts

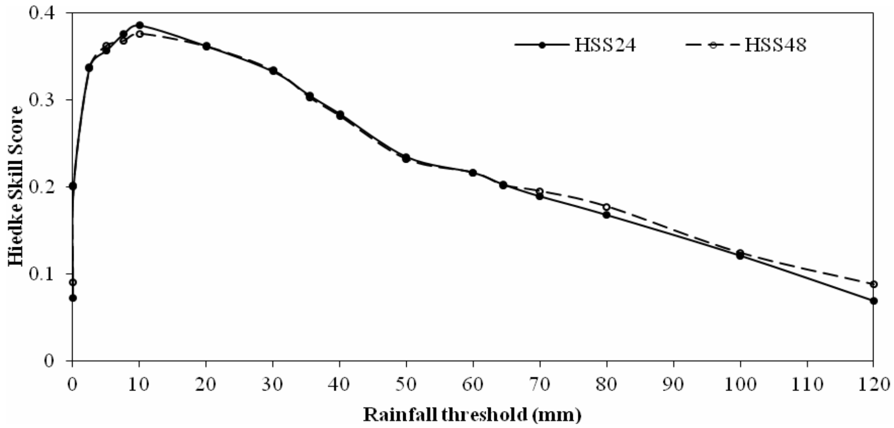


Fig. 7. Heidke skill score for 24 and 48 hour forecasts

and solid red colour in this figure. The points in the north-east, south east, south-west and north-west quadrant of the dotted red (solid red) line represent hits, misses, correct non-events and the false alarms respectively. This figure shows that a large number of points lay off 45° line indicating model's inability to predict rainfall at the point locations. But this is not true for the area averaged seasonal rainfall which is captured well [Figs. 3(a-c)]. The scalar measures of accuracy, MAE and RMSE for 24 and 48 hour forecasts are shown in Fig. 5(b). The ME is found to be positive for both 24 and 48 hour forecasts which implies that the model over forecasts. All the three values are less for 48 hour forecasts as compared to 24 hour forecasts. The ME is found to be 3.1 and 1.4 mm/day while MAE and RMSE are found to be 11.6 and 10.9 mm/day and 26.8 and 24.9 mm/day for these periods.

3.3. *Discussion on categorical scores computed using contingency table*

The contingency table for 24 and 48 hour forecasts is shown in Table 3. POD is the ratio of correct event forecasts to the total number of observations for a category [Fig. 6(a)]. It is sensitive to the hits and misses but is insensitive to the false alarms. FAR is the ratio of false alarms to the total number of event forecasts [Fig. 6(b)]. This score is sensitive to hits and false alarms but insensitive to misses. Both of these scores do not account for correct non-event forecasts. FB is the ratio of frequency of forecasts to frequency of the observations [Fig. 6(c)]. FB > 1 (< 1) implies that the event is forecasted more (less) than the observations. CSI (or Threat score) is important because it incorporates both misses and false alarms [Fig. 6(d)]. Fig. 6(a) shows that the model can detect lower threshold events better than the higher threshold events. The POD is 0.5 till 10 mm threshold after which it decreases to 0.1 at 100 mm/day. The variation of FAR is opposite to that of POD [Fig. 6(b)]. It is less than 0.4 till the rainfall threshold of 10 mm after which it increases. FAR increases with rainfall threshold (greater than 10 mm) indicating degradation in its performance. The FB is slightly less than 1 for both sets of forecasts [Fig. 6(c)]. It is close to 1 in the rainfall range of 7.6 - 20 mm implying that in this range the frequency of forecast events is the same as that of the frequency of observations. This also shows that model under-forecasts both less and high rainfall ranges. The CSI is more than 0.5 till 10 mm threshold after which it decreases [Fig. 6(d)].

3.4. *Skill of the forecast*

Skill scores are designed to evaluate forecasts relative to a standard procedure which can be chance, persistence or climatology. The skill scores used for deterministic forecast are HSS, Gilbert Skill Score (GSS) or Equitable THREAT SCORE (ETS). HSS determines skill of forecast with respect to chance (Stanski *et al.*, 1989). It is defined as

$$\text{Skill} = (\text{score value} - \text{score}_{\text{standard forecast}}) / (\text{perfect score} - \text{score}_{\text{standard forecast}})$$

The perfect score is always 1. HSS in Fig. 7 is found to be positive for both 24 and 48 hour forecasts and implies that model has skill with respect to chance. The maximum HSS is 0.38 and 0.37 in the lower thresholds up to 10 mm for 24 and 48 hour forecasts after which it decreases.

TABLE 3

Contingency Table count for (a) 24 and (b) 48 hour forecasts

	(a) Rainfall threshold				
	A	B	C	D	Total
gt0.0	16401	14236	777	1855	33269
ge0.1	15102	10984	2076	5107	33269
ge2.5	9107	7207	3764	13191	33269
ge5.0	6358	5714	3863	17334	33269
ge7.6	4746	4505	3579	20439	33269
ge10.0	3905	3854	3265	22245	33269
ge20.0	2129	2883	2285	25972	33269
ge30.0	1357	2416	1660	27836	33269
ge35.6	1031	2177	1441	28620	33269
ge40.0	839	1985	1325	29120	33269
ge50.0	500	1662	979	30128	33269
ge60.0	335	1334	714	30886	33269
ge64.5	275	1218	628	31148	33269
ge70.0	216	1063	541	31449	33269
ge80.0	149	920	389	31811	33269
ge100.0	61	594	215	32399	33269
ge120.0	23	425	139	32682	33269
	(b) Rainfall threshold				
	A	B	C	D	Total
gt0.0	15942	13191	1447	2711	33291
ge0.1	14534	10151	2855	5751	33291
ge2.5	8484	6195	4572	14040	33291
ge5.0	5863	4645	4502	18280	33290
ge7.6	4395	3862	4058	20976	33291
ge10.0	3664	3409	3625	22593	33291
ge20.0	2060	2598	2460	26173	33291
ge30.0	1312	2151	1801	28027	33291
ge35.6	998	1987	1564	28742	33291
ge40.0	810	1813	1431	29236	33290
ge50.0	469	1446	1080	30295	33290
ge60.0	304	1083	793	31110	33290
ge64.5	250	1004	695	31342	33291
ge70.0	200	854	594	31643	33291
ge80.0	134	682	435	32040	33291
ge100.0	54	459	242	32536	33291
ge120.0	24	312	153	32802	33291

4. Conclusions

In this study, the performance of real time weather forecasts by WRF 3.0 during monsoon 2011 over the State of Karnataka is carried out using standard scores. The observed data used for this study is the IMD gridded rainfall and point rainfall from a dense network of rain gauges in the State. Following are the findings

(*i*) The model reproduces overall spatial pattern of seasonal rainfall over southern peninsula very well. The regions of maximum (west coast and east coast of India) and minimum rainfall (interior peninsular India) too are reproduced well by the model. But the model is not able to predict daily rainfall at the point locations.

(*ii*) The time series of area averaged observed and forecast rainfall shows that forecast trend matches the observed trend on most of the days. But its quantity is under predicted.

(*iii*) The quality of deterministic forecasts was studied in terms of accuracy and skill of the forecasts. The ME was found to be positive for both 24 and 48 hour forecasts indicating that the model has a tendency to over predict. It is found to be 3.1 and 1.4 mm/day for these periods. The MAE and RMSE are found to be 11.6 and 10.9 mm/day and 26.8 and 24.9 mm/day for 24 and 48 hour forecasts respectively.

(*iv*) POD shows that the model can detect lower threshold events better than the higher threshold events. The maximum values of POD and FAR are found to be 0.6 and 0.4 for rainfall threshold of 10 mm. POD decreases and FAR increases after a threshold of 10 mm indicating model's inability to predict higher rainfall at said locations. Model is more reliable for lower rainfall threshold as compared to higher thresholds. The FB close to 1 only in the range 7.6 - 20 mm. It is less than 1 in both very less and high rainfall ranges. The CSI is found to be 0.5 - 0.1 for rainfall of 10 - 100 mm/day.

(*v*) The HSS is found to be positive and is 0.38 and 0.37 in the lower thresholds up to 10 mm for 24 and 48 hour forecasts.

An operational forecaster can accept the model forecast of a rainy day (rainfall $\geq$ 2.5 mm/day) with confidence but not the intensity. Improvement in the model forecast can be achieved by analysing the region specific and season specific sensitivity studies.

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