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Rainfall forecast skill of Global Forecasting System (GFS) model over India during summer monsoon 2015

Chollangi Sridevi[1], *Kamalesh Kumar Singh*[1], *Pilli Suneetha*[2]
Vairamuthu Reval Durai[1] *and Ashok Kumar*[1]

[1] India Meteorological Department, New Delhi, India

[2] Department of Meteorology and Oceanography, Andhra University, Visakhapatnam, India

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The Indian summer monsoon is one of the most important phenomenon that bring vital rain to India, so the Indian summer monsoon forecast and its verification is always of great interest due to monsoons' importance for India's agriculture. In the present study the categorical (Yes / No) and quantitative verification of rainfall forecast of the Global Forecasting System model running at India Meteorological Department, IMD GFS T574 (25 km resolution) and National Centre for Environmental Prediction, NCEP GFS T1534 is done over Indian domain against 0.25° gridded rainfall observations during summer monsoon season 2015. A detailed verification study for rainfall forecast at 0.25° × 0.25° grid for Indian Window (0 – 40° N and 60 – 100° E) is conducted using two models output; both the / models are indicating that skill of the rainfall forecast is good for all parts of the country except high terrain regions. Regional verification also carried over 5 homogeneous regions of India, *i.e.*, North India, West Coast India, North East India, Central India and Peninsular India using both model outputs. Results show that, in general, both the GFS T1534 and GFS T574 forecasts are skillful to capture climatologically heavy rainfall regions. However, the accuracy in prediction of location and magnitude of rainfall fluctuates considerably. The results documented are expected to be useful to the operational forecasters in day-to-day weather forecasting over Indian monsoon regions.

Keywords: GFS T1534L64, GFS T574L64, NWP, global model, rainfall analysis, Indian summer monsoon, rainfall prediction skill, forecast verification

1. Introduction

The Indian summer monsoon is driven by seasonal variations in land-sea temperature contrast between Asian landmass and adjacent ocean to the south. It lasts from June to September (JJAS) and produce wide spread rainfall over India. Life in India depends mostly on the monsoon rain and it affects India's agriculture. A weak summer monsoon can be accompanied by poor harvests and food shortages and a lack of fresh water among the rural population, a monsoon with higher precipitation than normal, can cause disastrous floods, again leading to a failure of harvest and food shortage. The prediction of the Indian summer monsoon is highly challenging and most important over the Indian subcontinent. So, the verification of an operational NWP model has become equally important for a season like the summer monsoon in India. Forecast verification is the process of determining the quality of a forecast through the assessment of the degree of similarity between that forecast and the observed conditions. The verification process incorporates different methodologies to study the quality of the forecast and may be either categorical or quantitative. There had been great demand from agriculture scientists and farmers for the weather forecast. In this direction, India Meteorological Department (IMD) is giving forecast for ten days.

Historically, a weather forecast in India was mainly issued in qualitative terms with the use of conventional methods assisted by satellite data and synoptic information for the location of interest. These forecasts were subjective and could not be used for risk assessment in quantitative terms. Hence the work was initiated to develop an objective medium range local weather forecasting system in India in 1988 at the National Centre for Medium Range Weather Forecasting (NCMRWF). An R40 general circulation model with a resolution of 2.8° × 1.8° was installed for this purpose in 1989 and a T80 general circulation model with a higher resolution of 1.5° × 1.5° was made operational in 1993. In 2002, a T 170 general circulation model with a still higher resolution 0.7° × 0.7° was made experimentally operational. In 2007, a T254 general circulation model with a much higher resolution 0.5° × 0.5° has been made operational (Bhardwaj et al., 2007). Later on T382 with a higher resolution of 0.35° × 0.35° was implemented and then T574 with a much higher resolution of 0.25° × 0.25° was implemented both at NCMRWF and IMD. At present the Global Forecast System (GFS) at T1534L64 resolution is being used for the operational forecast at IMD. The main purpose of this study is to document the performance skill of the GFS T1534 model run at National Centers for Environmental Prediction (NCEP), against the performance skill of GFS T574 run at IMD, on the basis of daily day-1 to day-5 forecasts generated during summer monsoon 2015 (1st June to 30th September) over India in short to medium range time scale. Model performance is evaluated for day-1 to day-5 forecasts of 24-h accumulated in terms of several accuracy and skill measures.

This paper comprises of five sections. Section 2 gives a brief description of NWP models used in this study. The verification procedures used in this work are described in section 3. Results of verifications are presented in section 4. Rainfall prediction skill and comparison of results are discussed in sub-section 4.1. Verification results of rainfall forecast over homogeneous regions of India are presented in sub-section 4.2. Finally, the summary and concluding remarks are given in section 5.

2. NWP models used in the study

2.1. GFS T574

The GFS T574 run at IMD is a primitive equation spectral global model with state of art dynamics and physics (Kanamitsu, 1989; Kalnay et al., 1990; Kanamitsu et al., 1991; Moorthi et al., 2001; Durai et al., 2010a; Saha et al., 2010). This GFS model is conforming to a dynamical framework known as the Earth System Modeling Framework (ESMF) and its code was restructured to have many options for updated dynamics and physics. Details about the GFS Model are available at http://www.emc.ncep.noaa.gov/GFS/doc.php. The GFS T574L64 (~ 25 km in horizontal over the tropics), adopted from National Centre for Environmental Prediction (NCEP), was implemented at IMD, New Delhi on IBM based High Power Computing Systems (HPCS; Durai et al., 2011). The assimilation system (for GFS T574) is a global 3-dimensional variational technique, based on NCEP Grid Point Statistical Interpolation (GSI 3.0.0; Kleist et al., 2009) scheme, which is the next generation of Spectral Statistical Interpolation (SSI; David et al., 1992). The details about model physics and dynamics are discussed in the recent study by Durai and Roy Bhowmik (2014).

2.2. The NCEP Global Forecast System (GFS) T1534

NCEP's global forecasts provide deterministic and probabilistic guidance out to 16 days. The atmospheric forecast model used in the GFS is a global spectral model (GSM) with spherical harmonic basis functions. The current operational horizontal resolution is T1534, or approximately 12 km at the equator for 0–10 day's forecasts. In the vertical there are 64 hybrid sigma pressure layers with the top layer centered around 0.27 hPa (approximately 55 km). The current operational dynamical core of the GFS / GSM is based on a two time level semi implicit semi Lagrangian discretization with three dimensional Hermite interpolation the dynamical core still supports three time level Eulerian approach. For the three time level Eulerian option for dynamics a positive definite tracer transport formulation (Yang, 2009) is used in the vertical.

The longwave (LW) and the shortwave (SW) radiation parameterizations in NCEP's operational GFS are both modified and optimized versions of the Rapid Radiative Transfer Models (RRTMG_LW v2.3 and RRTMG_SW v2.3, respectively) developed at AER Inc. To mitigate the unresolved sub grid cloud variability when dealing multi layered clouds, a Monte Carlo Independent Column Approximation (McICA) method is used in the RRTMG radiation transfer computations. In the operational GFS, a climatological tropospheric aerosol with a 5 degrees horizontal resolution is used in both LW and SW radiations. Concentrations of atmospheric greenhouse gases are either obtained from global network measurements, such as carbon dioxide (CO_2), or taking the climatological constants, such as methane, nitrous oxide, oxygen, and CFCs, etc. In the operational GFS, the actual CO_2 value for the forecast time is an estimation based on the most recent five year observations. In the lower atmosphere (< 3 km) a monthly mean CO_2 distribution in 15 degrees horizontal resolution is used, while a global mean monthly value is used in the upper atmosphere.

To improve day time planetary boundary layer (PBL) growth, a hybrid eddy diffusivity mass flux (EDMF) PBL parameterization has been developed and implemented into the NCEP GFS as of January 2015. Along with the hybrid EDMF parameterization, the heating by turbulent kinetic energy (TKE) dissipation is parameterized to reduce an energy imbalance in the GFS. Mountain blocking is incorporated from the Lott and Miller (1997) parameterization with minor changes, including their dividing streamline concept. Modest positive effects from using the parameterization are seen in the tropical upper troposphere and lower stratosphere.

A new mass flux shallow convection parameterization is developed based on the bulk mass flux parameterization of deep convection. The Simplified Arakawa Schubert (SAS) deep convection parameterization is revised to make cumulus convection stronger and deeper to reduce excessive grid scale precipitation. In early 2005 the land surface model (LSM) of GFS was upgraded from two soil layer (10 and 190 cm thick) Oregon State University model to four soil layer (10, 30, 60, and 100 cm thick) Noah model.

3. Data and methodology

The daily rainfall forecast data from the IMD GFS T574 and NCEP GFS T1534 models are extracted for Indian window (0 – 40° N and 60 – 100° E) at 25 km grid resolution for 122 days from 1st June to 30th September 2015. In this study rainfall forecast verification is carried out for IMD GFS T574 and NCEP GFS T1534 models run at 00 UTC against daily rainfall observations at the resolution of 25 km based on the merged rainfall data combining gridded rain gauge observations prepared by IMD Pune for the land areas and Global Precipitation Measurement (GPM) satellite estimated rainfall data for the Sea areas (Durai et al., 2010b). Models performance is evaluated for day-1 to day-5 forecasts of 24-hr accumulated precipitation in terms of several accuracy and skill measures.

For the Yes / No nature of the categorical rainfall forecast verification of the models at each grid point, Ratio Score (*RS*) and Hanssen and Kuiper's (*HK*) score (equations 1 and 2) are calculated using the 2 × 2 contingency table (Tab. 1). The term categorical refers to the Yes / No nature of the forecast verification at each grid point, then at each grid point, each verification time is scored as falling under one of the four categories of correct no-rain forecasts (D), false alarms (B), misses (C) or hits (A). For the quantitative rainfall verification at different thresholds (0.01, 3.5 and 12.5 cm / day), Hit Rate (*HR*) and Hanssen and Kuiper's score (*HKQ*) (eqs. 3 and 4) are calculated using 4 × 4 contingency table (Tab. 2)

Table 1. 2 × 2 contingency table for Yes/No forecast verification.

	Observed		
Forecast	Yes	No	Total
Yes	A	B	$A+B$
No	C	D	$C+D$
Total	$A+C$	$B+D$	$A+B+C+D=n$

A = Number of Hits (*YY*) (predicted and observed)
B = Number of False Alarms (*NY*) (predicted, but not observed)
C = Number of misses (*YN*) (observed, but not predicted)
D = Number of correct predictions of no rain (*NN*) (Neither predicted, nor observed)

at each grid point for monsoon season 2015. Following are the skill scores used for verification study (Bhardwaj et al., 2009; Kumar et al., 2000).

(a) Skill scores for Yes / No rainfall:

(1) Forecast Accuracy (*ACC*) or Ratio Score (*RS*) or Hit Score: It is the ratio of correct forecasts to the total number of forecasts.

$$RS = \frac{Correct\ forescast}{Total\ forrecast} = \frac{A+D}{N} = \frac{YY+NN}{YY+NN+YN+NY} \tag{1}$$

(2) Hanssen and Kuiper's Scores or True Skill Score (*HK*): It is the ratio of economic saving over climatology due to the forecast to that of a set of perfect forecasts.

$$HK = \left(ACC\right)_{events} + \left(ACC\right)_{non\text{-}events} - 1 = \frac{A \times D - B \times C}{\left(A+C\right) \times \left(B+D\right)} \tag{2}$$

Range: –1 to +1; Perfect: 1

(b) Skill scores for quantitative precipitation:

(3) Hit Rate (*HR*) for quantitative precipitation is defined as:

$$HR = \frac{n_{11} + n_{22} + n_{33} + n_{44}}{n_{tt}} \tag{3}$$

(4) Hanssen and Kuiper's score for quantitative precipitation (*HKQ*) is defined as:

$$HKQ = \frac{\dfrac{n_{11} + n_{22} + n_{33} + n_{44}}{n_{tt}} - \dfrac{n_{t1} \times n_{1t} + n_{t2} \times n_{2t} + n_{t3} \times n_{3t} + n_{t4} \times n_{4t}}{{n_{tt}}^2}}{1 - \dfrac{{n_{1t}}^2 + {n_{2t}}^2 + {n_{3t}}^3 + {n_{4t}}^4}{{n_{tt}}^2}} \tag{4}$$

Table 2. 4 × 4 contingency table for quantitative forecast verification.

	Observed				
Forecast	o_1	o_2	o_3	o_4	Total
f_1	n_{11}	n_{12}	n_{13}	n_{14}	n_{1t}
f_2	n_{21}	n_{22}	n_{23}	n_{24}	n_{2t}
f_3	n_{31}	n_{32}	n_{33}	n_{34}	n_{3t}
f_4	n_{41}	n_{42}	n_{43}	n_{44}	n_{4t}
Total	n_{t1}	n_{t2}	n_{t3}	n_{t4}	N_{tt}

Note: The quantitative precipitation is divided in the following four classes;
o_1, f_1: less than threshold (*Th*) is no rain (n_{11})
o_2, f_2: greater than *Th* and less than 3.5 cm is light to moderate rain (n_{22})
o_3, f_3: greater than 3.5 cm and less than 12.5 cm is heavy rain (n_{33})
o_4, f_4: greater than 12.5 cm is very heavy rain (n_{44})

The skill of both the models are also verified against IMD rainfall observations at 5 different homogeneous regions of India (Fig. 1) *i.e.*, North India (NI) (25 – 35° N; 70 – 85° E), West Coast India (WCI) (10 – 20° N; 70 – 78° E), North East India (NEI) (22 – 30° N; 85 – 100° E), Central India (CI) (22 – 28° N; 73 – 90° E) and Peninsular India (PI) (7 – 21° N; 74 – 85° E) and for whole of

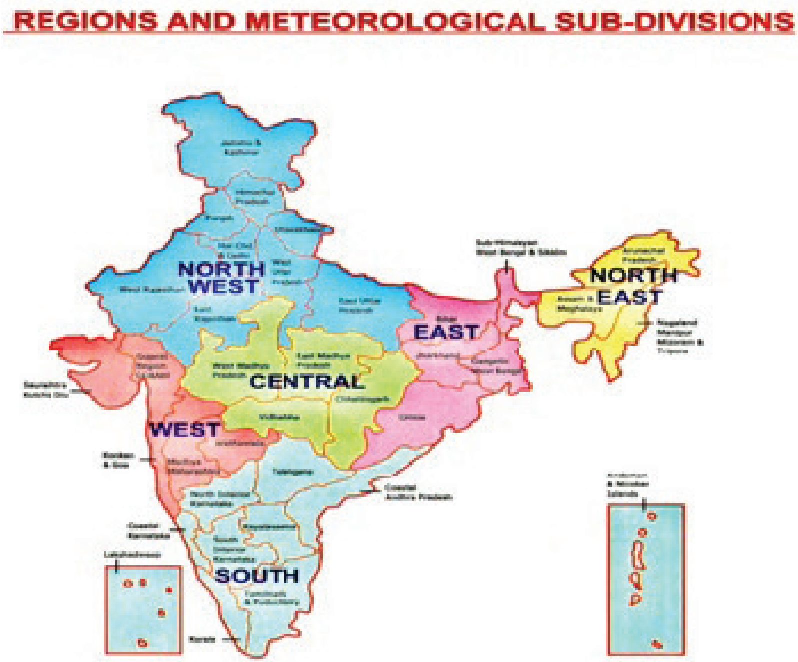

Figure 1. Distribution of meteorological subdivisions of India.

Indian window (AI) (0 – 40° N; 60 – 100° E). For regional verification also *RS* and *HK* scores calculated for Yes / No rainfall and *HR* and *HKQ* were calculated for rainfall amounts.

4. Results and discussion

4.1. Spatial distribution of rainfall forecast skill

The day-1 to day-5 forecast of GFS model run at IMD, *i.e.*, T574 and run at NCEP *i.e.*, T1534 are verified with observations and the above mentioned four skill scores were calculated for five days and the corresponding skill score plots are presented for day-1 (Figs. 2 and 3), day-3 (Figs. 4 and 5) and day-5 (Figs. 6 and 7). The observed and model forecasted rainfall values at the regular grid of 0.25° × 0.25° resolution for Indian window (0 – 40° N and 60 – 100° E) are considered and skill scores are calculated. For this *RS* and *HK* are calculated for Yes / No rainfall and *HR* and *HKQ* are calculated for different threshold rainfall amounts for summer monsoon season 2015. The scores are good and the highest value of *HK* score is 0.7, *HKQ* score is 0.3, *RS* for Yes / No rainfall forecast is 99 percent and *HR* is 0.9. If the RS is 100% then the forecast is perfect and is less than 50% then the forecast is poor. If the *HR* is closer to 1.0 then forecast is

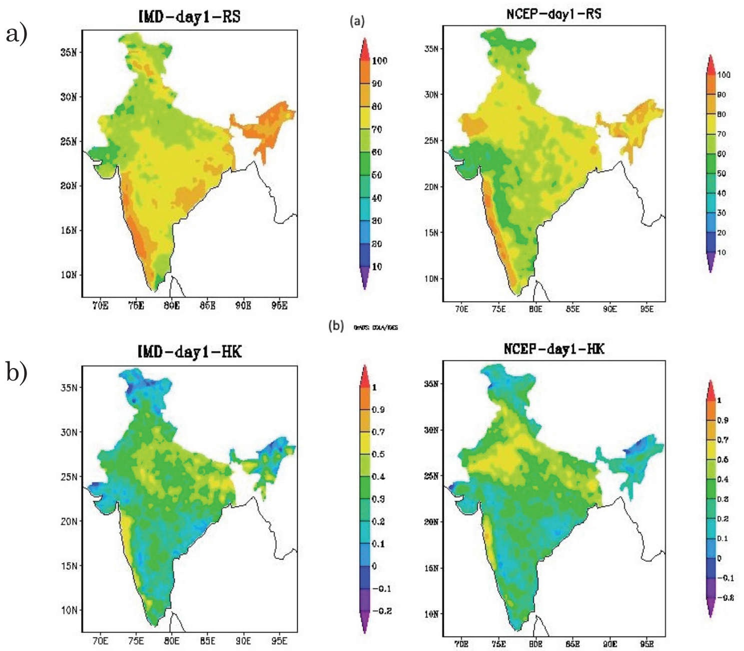

Figure 2. Spatial distribution of IMD GFS T574 and NCEP GFS T1534 day-1 rainfall categorical (Yes / No) skill scores (*a*) *RS* and (*b*) *HK* during summer monsoon 2015.

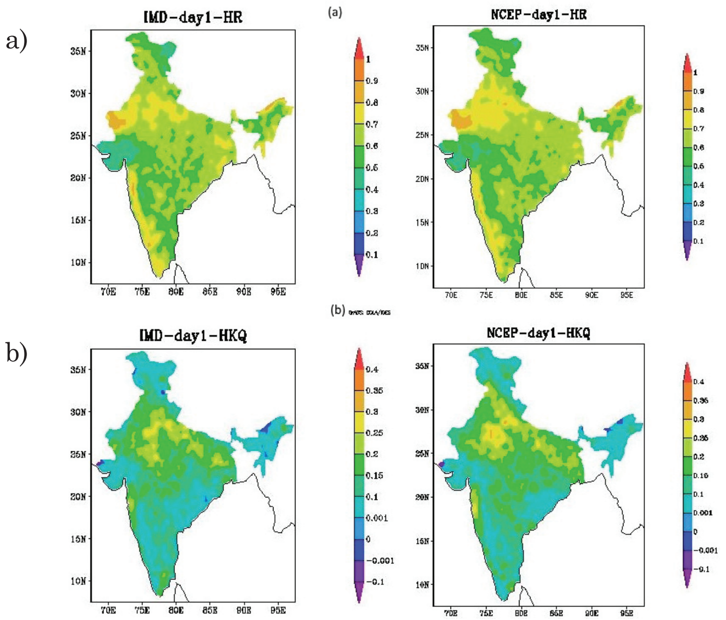

Figure 3. Spatial distribution of IMD GFS T574 and NCEP GFS T1534 day-1 rainfall quantitative skill scores (*a*) *HR* (*b*) *HKQ* during summer monsoon 2015.

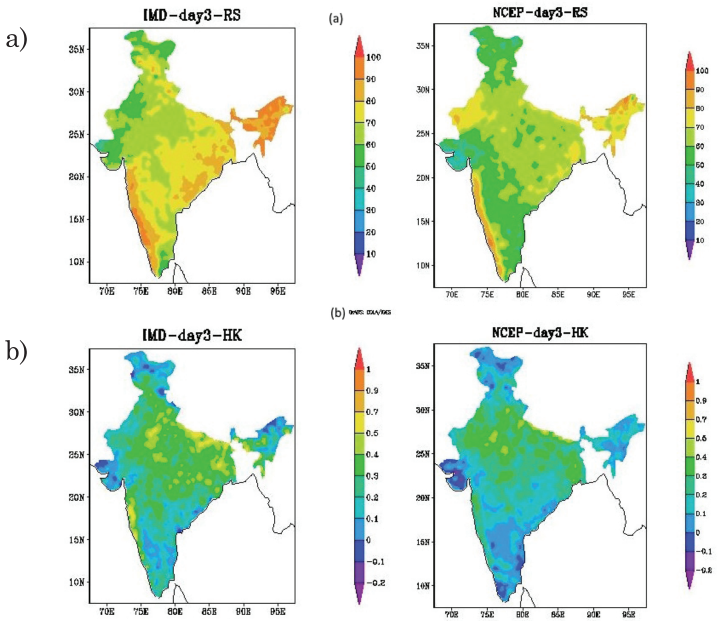

Figure 4. As in Fig. 2, but for day-3 rainfall forecast.

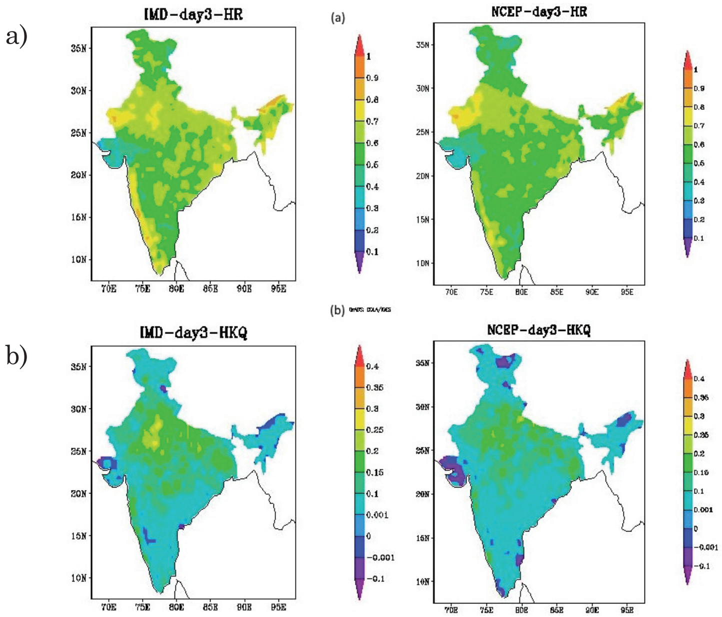

Figure 5. As in Fig. 3, but for day-3 rainfall forecast.

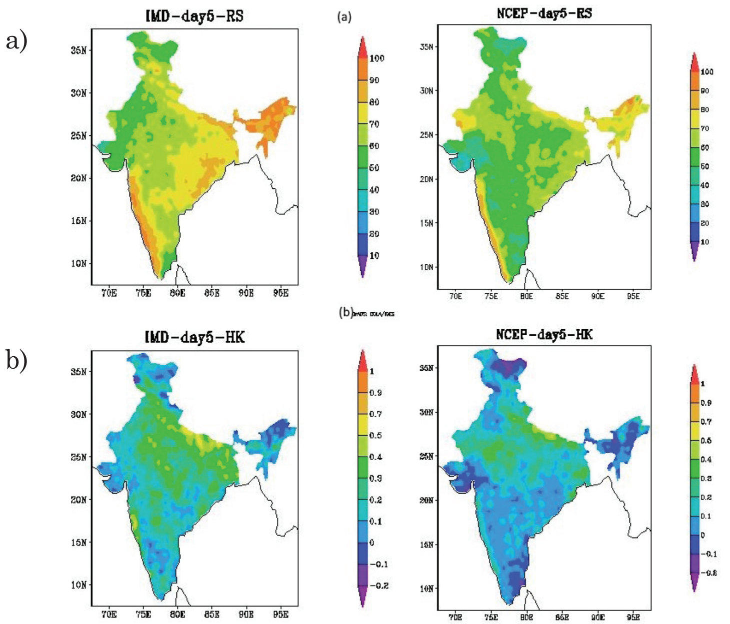

Figure 6. As in Fig. 2, but for day-5 rainfall forecast.

a)

b)

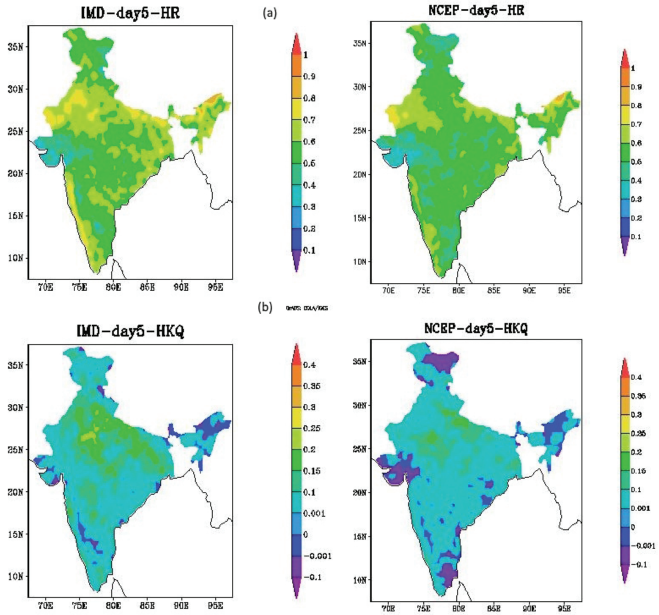

Figure 7. As in Fig. 3, but for day-5 rainfall forecast.

perfect and less than 0.5 then the forecast is poor. If *HK* & *HKQ* scores are closer to 1, the forecasts are good, and when the score is near or less than 0 then the forecasts are poorer. Here the skill of the rainfall forecast was found to be good for all parts of the country except high terrain regions.

The spatial verification of rainfall forecast for day-1 shows that the skill of both models for Yes / No rainfall (Fig. 2) forecast is very high, *i.e.*, 50 – 100% over all India. Both the models show positive *HK* score all the regions India, except very few parts of Jammu and Kashmir, Kutch and Northeast. In quantitative verification (Fig. 3) *HR* is also very high *i.e.*, 0.5 – 0.9 and *HKQ* score also positive over most parts of India, but models show negative *HKQ* over few parts of Jammu and Kashmir, Saurashtra and Kutch and Northeast India. However the skill of both models for day-3 Yes / No rainfall forecast (Fig. 4) *RS* is high *i.e.*, 40 – 100% and *HK* is also positive over all India, except few parts of south India, Jammu and Kashmir, Saurashtra and Kutch and Northeast India. Quantitative rainfall forecast (Fig. 5) also shows very high *HR i.e.*, 0.4 – 0.9 over all India, *HKQ* skill for both models is also good but negative skill observed over parts of south India, Jammu and Kashmir, Saurashtra and Kutch and North east India.

Similarly day-5 Yes / No rainfall forecast (Fig. 6) verification of both models show good skill *i.e.*, *RS* is 50 – 90% and *HK* score also positive over all India except parts of South India, Jammu and Kashmir, Saurashtra and Kutch and Northeast.

Quantitative rainfall forecast (Fig. 7) verification also shows high *HR i.e.*, 0.4 – 0.8 and *HKQ* score also positive except parts of south India, Jammu and Kashmir, Saurashtra and Kutch and Northeast India. In overall spatial verification result shows that the skill of both the models are high for day-1 and day-2 forecast and relatively low for day-3 onwards over most parts of Indian regions.

4.2. Skill of rainfall forecast over homogeneous regions of India

The five homogeneous regions over India selected for the study are shown in Fig. 1. The categorical, quantitative verification skill scores over five homogeneous regions along with all India during 2015 monsoon season is computed for day-1 to day-5 forecast. The day-1 forecast verification (Tab. 3) for Yes / No rainfall shows high Ratio Score *i.e.*, 65 – 87% and *HK* score also high *i.e.*, 0.17 – 0.38 over almost all the regions. In the Quantitative verification models show high *HR i.e.*, 0.52 – 0.63 and *HKQ* score are in the range of 0.1 to 0.14. In day-3 (Tab. 4) Yes / No rainfall forecast shows high Ratio Score *i.e.*, 60 – 87% and *HK* score are ranging from 0.1 to 0.33 over all the regions. Similarly the day-5 forecast verification (Tab. 5) for Yes / No rainfall shows RS 59 – 86% and *HK* score are in the range of 0.06 – 0.31, over almost all the regions. *HR* score is high *i.e.*, 0.45 – 0.55

Table 3. Skill scores RS, HK, HR and HKQ of IMD GFS & NCEP GFS for day-1 rainfall forecast during summer monsoon over 5 regions along with all India.

REGION	NCEP-*RS*	IMD-*RS*	NCEP-*HK*	IMD-*HK*	NCEP-*HR*	IMD-*HR*	NCEP-*HKQ*	IMD-*HKQ*
AI	71.11	77.29	0.22	0.2	0.54	0.54	0.09	0.08
NI	70.77	66.72	0.38	0.3	0.63	0.61	0.14	0.13
WCI	69.10	79.62	0.21	0.23	0.56	0.55	0.10	0.09
NEI	80.11	87.16	0.23	0.25	0.55	0.57	0.08	0.07
CI	71.59	73.48	0.37	0.37	0.56	0.57	0.14	0.14
PI	65.00	73.89	0.19	0.17	0.53	0.52	0.08	0.07

Table 4. Same as Tab. 3, but for day-3 forecast.

REGION	NCEP-*RS*	IMD-*RS*	NCEP-*HK*	IMD-*HK*	NCEP-*HR*	IMD-*HR*	NCEP-*HKQ*	IMD-*HKQ*
AI	66.77	76.04	0.13	0.15	0.5	0.53	0.04	0.06
NI	63.99	64.70	0.24	0.26	0.56	0.58	0.08	0.10
WCI	64.83	78.31	0.11	0.16	0.5	0.53	0.05	0.06
NEI	76.32	86.85	0.15	0.18	0.52	0.57	0.04	0.05
CI	66.23	72.95	0.26	0.33	0.51	0.56	0.09	0.11
PI	60.31	72.19	0.09	0.13	0.48	0.51	0.03	0.05

Table 5. Same as Tab. 3, but for day-5 forecast.

REGION	NCEP-*RS*	IMD-*RS*	NCEP-*HK*	IMD-*HK*	NCEP-*HR*	IMD-*HR*	NCEP-*HKQ*	IMD-*HKQ*
AI	65.08	74.92	0.08	0.11	0.47	0.51	0.03	0.04
NI	60.67	63.23	0.16	0.23	0.52	0.56	0.05	0.09
WCI	62.58	77.00	0.07	0.11	0.47	0.51	0.03	0.04
NEI	73.92	86.44	0.06	0.11	0.50	0.55	0.02	0.03
CI	62.78	71.59	0.17	0.27	0.48	0.53	0.06	0.09
PI	58.70	70.67	0.06	0.10	0.46	0.5	0.02	0.04

and HKQ score also good *i.e.*, 0.01 – 0.06 over all the regions. In overall regional verification for both the models shows high skill in day-1 and day-2, but from day-3 onwards skill is decreasing.

5. Summary and conclusions

The skill of Yes / No rainfall forecast verified in terms of *RS* and *HK* score and of rainfall amounts are verified in terms of *HR* and *HKQ* over Indian window (0 – 40° N and 60 – 100° E) during summer monsoon 2015. Both the model show good skill for almost whole country except for the high terrain regions. Results also indicate that the model forecast skill for rainfall are good for most parts of the country. The skill of the IMD GFS T574 and NCEP GFS T1534 shows that models are able to provide more realistic spatial distribution of rainfall during the Indian summer monsoon. In spatial verification both the models shows high skill, for day-1 and day-2 but from day-3 onwards models shows less skill. The skill of the IMD GFS T574 and NCEP GFS T1534 model verified over five homogeneous regions along with all India both the models shows high skill. In day-1, day-2 both the models shows almost same skill for all the regions, from day-3 onwards models show low skill. In overall the forecast skill decreasing with increasing forecast period. The evaluation of skill scores shows encouraging results and has a potential for forecasting rainfall with high accuracy in short to medium range. It can be concluded that if we add more Indian region data in the model analysis then the model skill will increase further.

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SAŽETAK

Vještina prognoze oborine iznad Indije tijekom ljetnog monsuna 2015. GFS modelom

Chollangi Sridevi, Kamalesh Kumar Singh, Pilli Suneetha, Vairamuthu Reval Durai i Ashok Kumar

Indijski ljetni monsun jedan je od najvažnijih fenomena koji donosi značajnu kišu Indiji. Stoga su prognoza indijskog ljetnog monsuna i njena verifikacija uvijek od velikog interesa, jer značajno utječe na indijsku poljoprivredu. U ovom je istraživanju provedena kategorijska (Da / Ne) i kvantitativna provjera prognoze oborine GFS (Global Forecasting System) modelom koji se koristi u Indijskom meteorološkom odjelu (IMD GFS T574, rezolucija 25 km) i Nacionalnom centru za predikciju okoliša (NCEP GFS T1534) na domeni koja pokriva Indiju s podacima mjerenja oborine u mreži od 0,25° tijekom ljetnog monsuna 2015. Detaljna verifikacijska studija za prognozu oborine za Indiju (prozor 0 – 40° N i 60 – 100° E) s mrežom 0,25° × 0,25° provedena je pomoću rezultata dvaju modela koji ukazuju da je vještina predviđanja oborine dobra za sve dijelove zemlje, osim za područja s visokim terenom. Regionalna provjera također je provedena na 5 homogenih indijskih regija: Sjeverna Indija, Zapadna Indija, Sjevernoistočna Indija, Srednja Indija i Južna Indija, pri čemu su korišteni rezultati oba modela. Rezultati pokazuju da su općenito i GFS T1534 i GFS T574 prognoze vješte u prognozi klimatološki jakih oborina. Međutim, točnost predviđanja lokacije i intenziteta oborine značajno varira. Za očekivati je da će dokumentirani rezultati studije biti korisni operativnim prognostičarima u svakodnevnoj vremenskoj prognozi iznad područja zahvaćenim indijskim monsunom.

Ključne riječi: GFS T1534L64, GFS T574L64, NWP, globalni model, analiza oborine, indijski ljetni monsun, vještina prognoziranja oborine, verifikacija prognoze

Corresponding author's address: Chollangi Sridevi, India Meteorological Department, Lodhi Road, New Delhi – 110 003, India; e-mail: srikhey@gmail.com