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ORIGINAL PAPER

A verification of spatio-temporal monsoon rainfall variability across Indian region using NWP model output

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Abstract Evaluation of weather forecasting systems and assessment of existing verification procedures are essential to achieve desirable seamless rainfall prediction. Prediction of wet and dry spells is quite useful in agriculture and hydrology but very few attempts have been made so far to resolve the issue using numerical model output. Performance of five state-of-the-art global atmospheric general circulation models and their ensemble mean has been examined in predicting the parameters of wet and dry spells (WSs/DSs) during monsoon period of 2008–2011 over seven subzones of the Indian region. The number of WSs across the region is found to be underestimated, while total duration and rainfall amount of WSs (DSs) overestimated (underestimated). Start of the first WS is late and ends of the last WS early in the model forecast. More uncertainty is noticed in the prediction of DS rainfall and its duration than that of the WS. The percentage area of India under wet conditions (rainfall amount over each grid is more than its daily mean monsoon rainfall) and rainwater over the wet area is overestimated by about 59 and 32 %, respectively, in all models.

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Abbreviations

AGCMs	Atmospheric global circulation models
AI	All India
BS_{dyn}	Dynamical Bias Score
CBS	Commission for Basic System
CC	Correlation coefficient
DIFF	Mean difference
DMR	Daily mean rainfall
DS	Dry spell
ECMWF	European Center for Medium Range Weather Forecasting
ETS_{dyn}	Dynamical Equitable Threat Score
FAR_{dyn}	Dynamical false alarm ratio
GDPFS	Global Data Processing and Forecasting System
GFS	Global Forecasting System
IMD	India Meteorological Department
JMA	Japan Meteorological Agency
MEAN	Simple ensemble mean
MME	Multimodel ensemble
MAPE	Mean absolute percentage error
NMSG	NCMRWF merged satellite-gauge dataset
NWP	Numerical weather prediction
NCEP	National Centers for Environmental Prediction
NCMRWF	National Centre for Medium Range Weather Forecasting
PAI	Percentage area of India
pe	Percentage error
POD_{dyn}	Dynamical probability of detection
RW	Rainwater
SMAPE	Symmetric mean absolute percentage error
SZ	Subzone
TMPA	TRMM Multi-satellite precipitation analysis
TRMM	Tropical rainfall measuring mission

UKMO	United Kingdom Meteorological Office
WMO	World Meteorological Organization
WS	Wet spell

1 Introduction

Reliable Rainfall prediction over tropical monsoonal region is exceptionally challenging task for the numerical modeling community. During boreal summer, Indian region receives maximum of its annual rainfall from the Asia-Pacific monsoon system. Secondary circulations (convergence of two or more large-scale flows, meander and cyclone/depression), local eddies, mid-latitude western disturbances and thunderstorm activities considerably affect the monsoon rainfall activities. These factors added complications in numerical rainfall prediction. Developments in the forecasting systems and observational networks consistently contributed to improve short-to-medium range weather forecasts (Mishra and Krishnamurti 2007; Mitra et al. 2011). Nowadays, many leading numerical weather prediction (NWP) centers across the world produce and deliver wide array of weather forecast products to the customers, generating from deterministic and ensemble NWP models. For scientific testing, upgradation and maintenance of the operational forecasting models, timely verification and evaluation of the forecast products is an imperative process. It helps to improve the individual model and facilitate comparison between different models. So the development of operational verification started in operational weather services of numerous countries (Casati et al. 2008). The verification process involves investigation of the properties of the joint distribution of the observations and the forecasts. The properties are characterized in terms of the relative frequencies of possible combinations of the observation-forecast values (Murphy and Winkler 1987). The nature and strength of the association between the forecast and observation are reflected in terms of skill scores. Based upon the method of analysis, the forecast can be deterministic, probabilistic or qualitative and assess accordingly by various verification procedures. For example, deterministic forecast are verified using visual, dichotomous, multi-category, continuous and spatial verification methods for assessment of nine different aspects of the qualities of forecasts (Murphy 1990, 1993). The forecasting centers are always looking for application of appropriate methods to measure forecast performance, analyze systematic forecast behavior and diagnose model errors. To provide consistent verification information on the NWP products by different forecasting centers, the World Meteorological Organization (WMO) led Centre for Deterministic NWP Verification defined CBS (Commission for Basic System) standard verification procedures. The standard set of CBS verification scores (categorical and continuous) are routinely produced and exchanged between the participating WMO Global Data Processing and Forecasting System (GDPFS) centers for the benefit of operational forecasters and to help the centers compare and improve their forecasts (WMO 2010, 2011).

Verification of quantitative precipitation forecast has been done over wide range of scales and for different regions across the globe (Mcbride and Ebert 2000; Tiziana et al. 2002; Kang et al. 2002; Accadia et al. 2005; Basu 2005; Mandal et al. 2007; Mohanty and Mahapatra 2008; Mitra et al. 2011 and many others). All studies have documented that the models have good skills in forecasting low-intensity rain events than heavy events but mostly the models overestimated the precipitation amounts. Roy Bhowmik and Durai (2010) have shown the superiority of the MME (multimodel ensembles) to individual NWP model for a district level forecast across India. The different verification studies indicated that the NWP model skills are dependent upon the region and rainfall threshold used in verification procedures.

Presently, atmospheric general circulation models (AGCMs) and coupled models provide rainfall forecasts on various spatial scales (country, state, subdivision, district and station) and temporal scales (from season to hour). But the models do not forecast the spatio-temporal features of the rainfall occurrences such as wet and dry spells (WSs and DSs), which are the genuine demand of agriculture, water resources and other water-related sectors. Majority of verification efforts have calculated the skill scores for location-specific precipitation forecast of various intensities. Limited attempts have been made to check model skills for the prediction of spatio-temporal characteristics of the rain events. Keeping in view requirement of different water-related sectors, it is felt imperative to evaluate performance of the operational AGCMs in simulating and predicting the wet and dry spells of the monsoonal period. Attempts have been made to evaluate simulation and prediction of wet/dry spells using Markov chain models and other statistical techniques (Chang et al. 1984; Moon et al. 1994; Sharma 1996; Wantuch et al. 2000; Mathuguma and Peiris 2011). Few attempted it by the NWP models. Huth et al. (2000) have studied characteristics of dry spells in area-averaged and station rainfall series of the Czech Republic. They found simulated dry spells are too long and annual cycle of their occurrences distorted. Higgins et al. (2008) examined the seasonal cycle of number of wet and dry spells in Climate Forecast System over the USA. Krishnamurti et al. (1990, 1992, 1995) have studied wet and dry spells in 1-month forecast of global models over India, China and Australia. respectively, and found rapid drop in skill during first 5 days of integration. They noticed slow rise in amplitude of high-frequency motions that contributed to error growth for the low-frequency modes and deterioration of the month forecasts. Large errors in rainfall spatio-temporal feature in short- and medium-range forecasts would lead to serious errors in extended range and seasonal forecasts. The high-resolution (horizontal and vertical) atmospheric global models that are used for operational weather forecasts can resolve high-frequency components more efficiently and lead to much faster growth of errors in forecast of the low-frequency modes.

Start, duration and rainfall amount of WSs and DSs are useful for rain-fed agriculture. In a generalized way, forecasting of persistent heavy rainfall that generates ample runoff is helpful for flood forecasting, disaster warning and water management purposes. Large-scale, long-period heavy rain events are important to understand complex hydrological processes. Present study deals with the errors and uncertainties in the simulation of wet and dry spell sequences and their eight characteristics parameters. The major objectives are as follows.

1. To study characteristics of wet and dry spells in numerical model outputs for seven subzones of Indian region;
2. To verify the skills of NWP models in predicting specified rainfall amounts using newly defined dynamical skill scores; and
3. To understand errors in predicting the area of the country under wet condition and rainwater over the area.

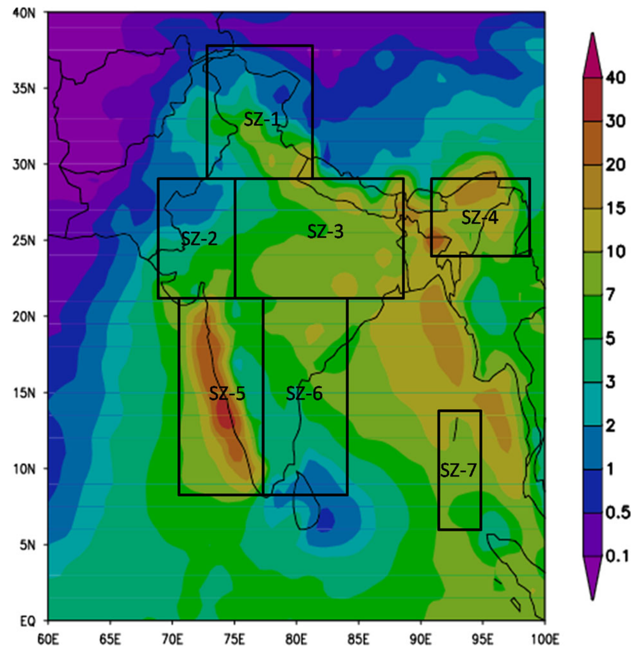


Fig. 1 The seven subzones of Indian subcontinent and distribution of daily mean monsoon rainfall (DMR)

2 Observed and model forecast data

National Center for Medium Range Weather Forecasting (NCMRWF) merged satellite-gauge (NMSG) daily rainfall product at 1° X 1° latitude–longitude resolution during 1998–2011 for the Indian monsoon region (0°–40°N and 60°–100°E) is used as the observed rainfall dataset in this study. The NMSG algorithm uses three hourly Tropical Rainfall Measuring Mission (TRMM), Multi-satellite Precipitation Analysis (TMPA) estimates accumulated for 24 h (daily) over land and ocean as the first guess (Mitra et al. 2009). Using successive-correction method, the mean biases in the TMPA estimates are corrected for each grid using India Meteorological Department (IMD) raingauge values over land-only areas. The details of the weights and interpolations are described in more details in Mitra et al. (2003). The NMSG data product has been checked qualitatively as well as quantitatively for its ability to capture large-scale monsoon rainfall pattern over and across India, Arabian Sea and Bay of Bengal (Mitra et al. 2009).

Medium range (1–5-day) rainfall forecast products from five state-of-the-art operational global forecasting models (European Centre for Medium Range Weather Forecasting (ECMWF), United Kingdom Meteorological Office (UKMO), National Center for Environmental Prediction-Global Forecasting System (NCEP-GFS), Japan Meteorological Agency (JMA) and National Centre for Medium Range Weather Forecasting (NCMRWF-GFS) during the period 2008–2011 are used. The NCMRWF global assimilation-forecast system is an adapted version of the NCEP-GFS system implemented in year 2007. The NCEP-GFS model data are from runs at 35 km horizontal grid and 64 vertical layers, the UKMO model data at 40 km horizontal grid and 50 vertical layers, the JMA model data at 40 km horizontal grid and 40 vertical layers and the NCMRWF-GFS model data at 50 km horizontal grid and 64 vertical layers. The model data have been interpolated on uniform 1-degree latitude–longitude grid cells to represent large-scale features of the monsoon rainfall. The model simulation was at finer resolution than the daily rainfall considered here in the analysis. In addition, a Simple (arithmetic) Ensemble Mean (MEAN) of all the five AGCMs forecasts is also used. Earlier works (Krishnamurthi et al. 1999, 2000; Mishra and Krishnamurti 2007) showed the concurrent use of various atmospheric global general circulation models for taking simple ensemble mean of the model outputs or by creating multimodel ensemble (MME) can reduce errors and increase skills of the forecasts.

Table 1 Mean of important parameters of wet and dry spells of monsoon period over All India (AI) and seven subzones of Indian region during 1998–2011

Subzones	Total no. of WSs	Total duration of WSs (days)	Total duration of DSs (days)	Total rainfall of WSs (mm)	Total rainfall of DSs (mm)	Start of first WS	End of last WS	Seasonal rainfall (mm)	% Contribution of WSs rainfall to seasonal total
SZ-1	4.6	53.1	27.3	313.1	57.2	23-Jun	10-Sep	434.0	70.1
SZ-2	4.1	42.6	38.4	417.2	46.3	17-Jun	4-Sep	499.6	81.7
SZ-3	5.3	63.3	29.1	702.4	142.6	16-Jun	15-Sep	937.2	74.4
SZ-4	5.9	54.7	43.4	813.2	293.5	9-Jun	14-Sep	1,252.9	63.6
SZ-5	4.6	50.7	38.2	1,039.3	250.8	8-Jun	5-Sep	1,482.2	68.7
SZ-6	5.2	50.0	45.4	462.6	138.2	14-Jun	16-Sep	684.0	64.5
SZ-7	6.9	50.4	55.9	725.9	217.1	7-Jun	20-Sep	1,059.5	68.0
AI	3.9	60.9	28.7	494.1	145.1	9-Jun	5-Sept	783.3	62.2

3 The division of the country into seven subzones

India covers large geographical area ($\sim$3.3 million km^2) between meridians of 67°–100°E and parallels of 7°–37°N. For effective use of model forecasts in agricultural and hydrological operations, the daily rainfall is considered over seven subzones (SZs) of the country. Topography, physiographic features, drainage pattern, annual/monsoon rainfall distribution, monsoon normal onset and withdrawal dates and rain-producing weather systems are considered qualitatively in this division (Fig. 1).

(i) Extreme North India (SZ-1: 29°–37°N; 73°–82°E): Rains occur mainly due to activation of line-cum-eddy convergences, troughs in the mid-latitude upper and mid-troposphere westerlies and the western disturbances in the lower troposphere.

(ii) Northwest India (SZ-2: 21°–29°N; 69°–75°E): Gets rainfall mostly from monsoon flows. Cyclonic circulation in mid-tropospheric level cause intense rain spells in the area.

(iii) Central India and Indo-Gangetic Plains (SZ-3: 21°–29°N; 75°–88°E): Rains occur from line-cum-meander convergence of monsoon flow with embedded small-scale eddies and low-pressure systems (or monsoon trough). Troughs in the mid-latitude upper and mid-tropospheric westerlies facilitate tropical–extratropical interactions in a complex manner and affect rainfall activities over the Indo-Gangetic plains. The synoptic systems that develop over the head Bay of Bengal travel north-northwestward along with large-scale monsoon flow contribute to intensification of the monsoon flows and rainfall activities.

(iv) Northeast India (SZ-4: 24°–29°N; 91°–99°E): Heavy rains frequently occur due to moist convergence caused by westward turning of the monsoon flows and orographic effect. Cherrapunji and Mawsynram stations in this area are among the highest rainfall recording stations (>10,000 mm) in the world.

(v) West Coast of India (SZ-5: 8°–21°N; 72°–77°E): A trough frequently develop in the monsoon flow off the west coast of Indian peninsula which produces longer period heavy rain spells. Some of the stations record 5,000–7,000 mm of rainfall during monsoon.

(vi) Eastern Peninsula (SZ-6: 8°–21°N; 77°–84°E): Rainfall activities are weak due to rain-shadow effect. Rains occur from extended north–south trough in the low-level westerly monsoon flows along the East Coast and/or intensification of easterly waves of the northeast trades.

(vii) Andaman Nicobar Islands (SZ-7: 6°–14°N; 92°–94°E): Rainfall occur from circular convergence that develop due to convergence of low-level return flows from the deep subtropical highs over North Pacific, South Pacific, Australia and Mascarene.

4 Results and discussion

4.1 Characteristics of wet and dry spells in NWP model output

Time distribution of monsoon rainfall is characterized by wet and dry spells. Frequency, intensity, areal spread and duration of the spells exhibit large variations. Some areas of the country (western and eastern Himalayas, West Coast, extreme southern peninsula and bay islands) receive considerable rains during pre- and post-monsoon periods. Normally, during wet spell persistent rainfall occurs over relatively large areas, while it is subdued and isolated during dry spell. Singh and Ranade (2010) have studied

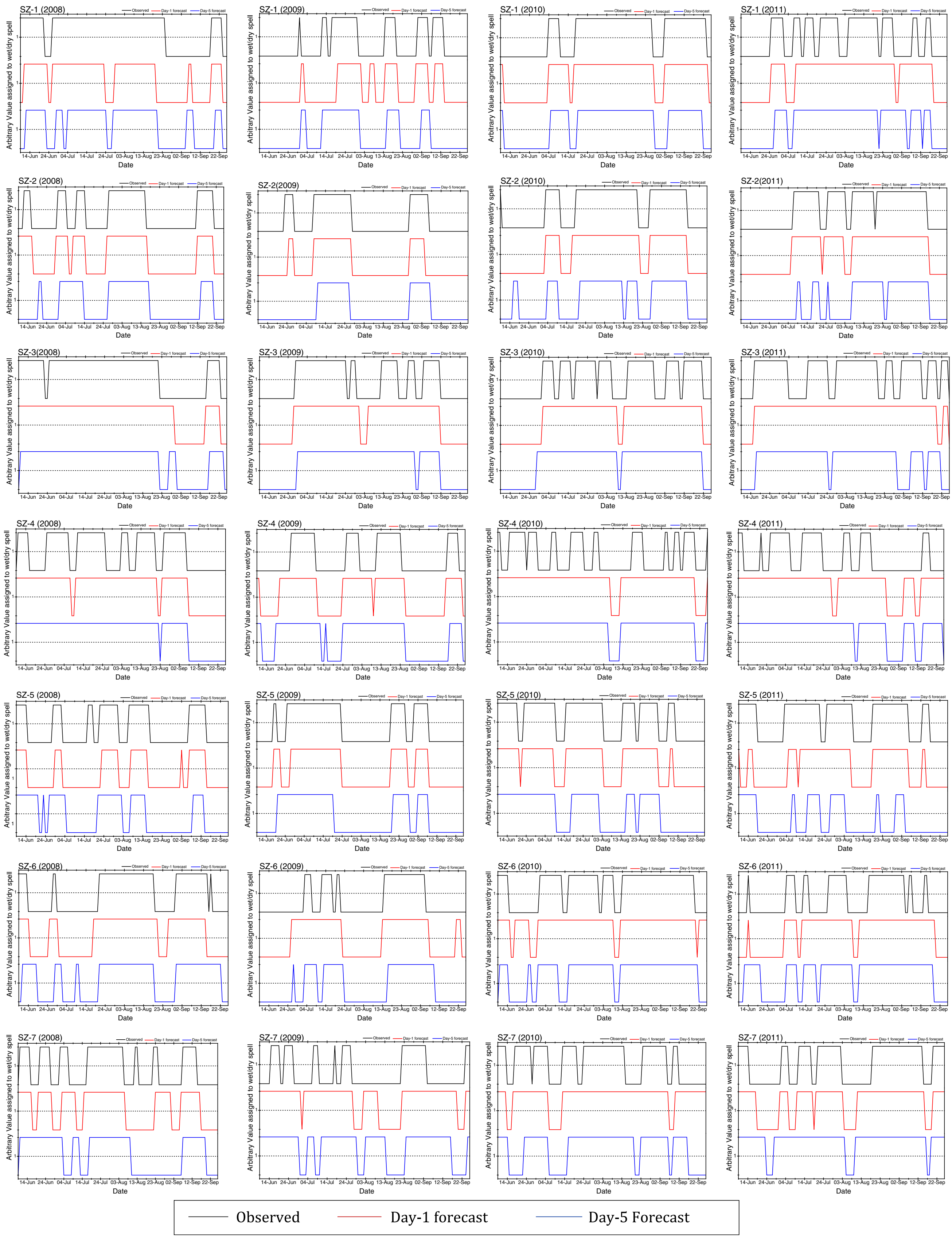


Fig. 2 The NMSG observed and model simulated wet/dry spell sequences over the seven subzones during 2008–2011

Table 2 Mean of important parameters of wet and dry spells in observed and day-1 MEAN model forecast over All India (AI) and seven subzones of Indian region during 2008–2011

Subzones	Total No. of WSs		Total duration of WS (days)		Total duration of DSs (days)		Total rainfall of WS (mm)		Total rainfall of DS (mm)		Start of first WS		End of last WS		Seasonal rainfall (mm)		% age contribution of Ws rains to seasonal total	
	Observed	MEAN forecast	Observed	MEAN forecast	Observed	MEAN forecast	Observed	MEAN forecast	Observed	MEAN forecast	Observed	MEAN forecast	Observed	MEAN forecast	Observed	MEAN forecast	Observed	MEAN forecast
SZ-1	5.0	4.5	59.8	67.0	28.3	27.3	353.1	393.8	54.2	63.0	23-Jun	17-Jun	18-Sep	18-Sep	444.3	501.5	78.0	76.8
SZ-2	4.0	3.8	51.5	54.5	35.8	32.8	496.2	478.7	43.7	56.8	18-Jun	18-Jun	12-Sep	12-Sep	569.5	570.5	86.6	83.3
SZ-3	5.5	2.0	66.8	86.0	25.0	6.5	758.1	1,040.5	127.8	35.7	20-Jun	19-Jun	18-Sep	18-Sep	957.5	1,158.1	78.6	89.6
SZ-4	7.0	3.8	47.5	89.3	50.8	18.8	665.5	1,347.3	340.3	148.6	11-Jun	4-Jun	16-Sep	19-Sep	1,157.2	1,619.8	57.3	82.8
SZ-5	5.5	5.5	59.3	55.5	39.3	42.0	1,213.5	924.5	265.9	361.4	5-Jun	5-Jun	10-Sep	10-Sep	1,626.1	1,456.6	74.3	63.0
SZ-6	5.3	4.0	52.8	74.3	38.5	25.3	443.5	626.0	122.7	92.2	14-Jun	13-Jun	12-Sep	19-Sep	657.0	803.8	65.0	76.8
SZ-7	7.0	5.3	57.0	87.3	49.0	24.0	820.2	1,208.5	207.0	129.0	5-Jun	4-Jun	18-Sep	22-Sep	1,121.4	1,432.9	72.4	84.0
AI	4.3	2.5	70.0	98.8	31.3	24.0	564.4	894.1	157.6	37.2	5-Jun	4-Jun	13-Sep	16-Sep	807.9	1,016.0	69.0	87.8

Fig. 3 Spatial distribution of the dynamical probability of detection ▶ in forecasting the rainfall amount equivalent to DMR in day-1, day-3 and day-5 by the AGCMs

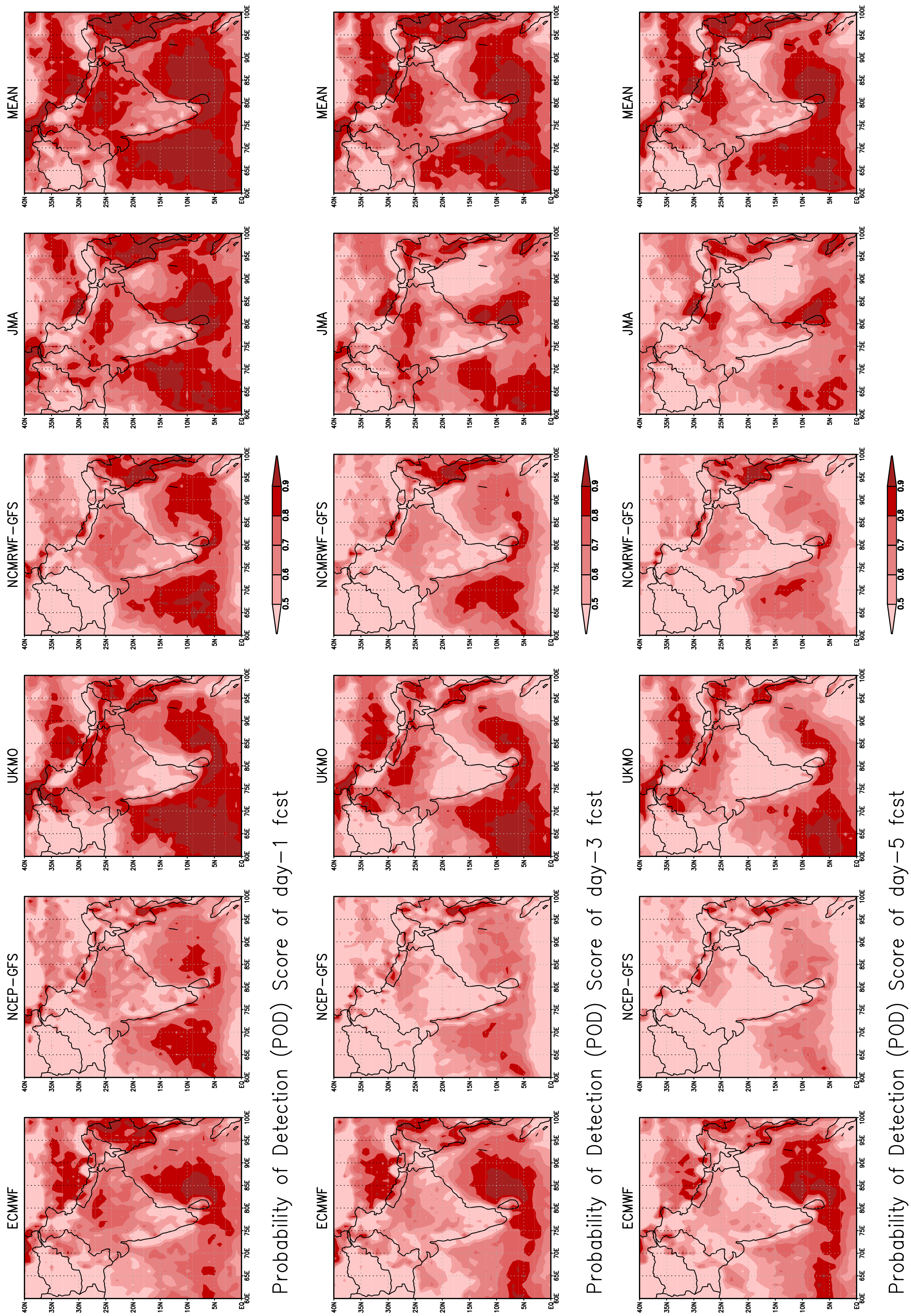
climatological and fluctuation features of 40 parameters of wet and dry spells and their extremes over 19 subregions of India during 1951–2007. They have applied local rainfall climatology as the rainfall threshold for the delineation of wet/dry spells. According to their studies, on an average, number of WSs (DSs) varies from 11 (10) over extreme south peninsula to 4 (3) over north-west India. Total duration of WSs (DSs) decreases from 101 (173) to 45 (29) days, and the duration of individual WS (DS) from 12 (18) to 7 (11) days. Across the country, the rainfall associated with wet and dry spells contributes 68 and 17 % to the annual total, respectively. A tendency was noticed for the first WS to start about 6 days earlier across the country and the last WS to end about 2 days earlier, giving rise to longer duration of rainfall activities by approximately 4 days, however, a spatially coherent robust long-term trend was not seen in any of the parameters of spells. With the continuation of this exhaustive study of WSs/DSs, an attempt has been made to study them using current generation NWP model outputs for their reliable prediction.

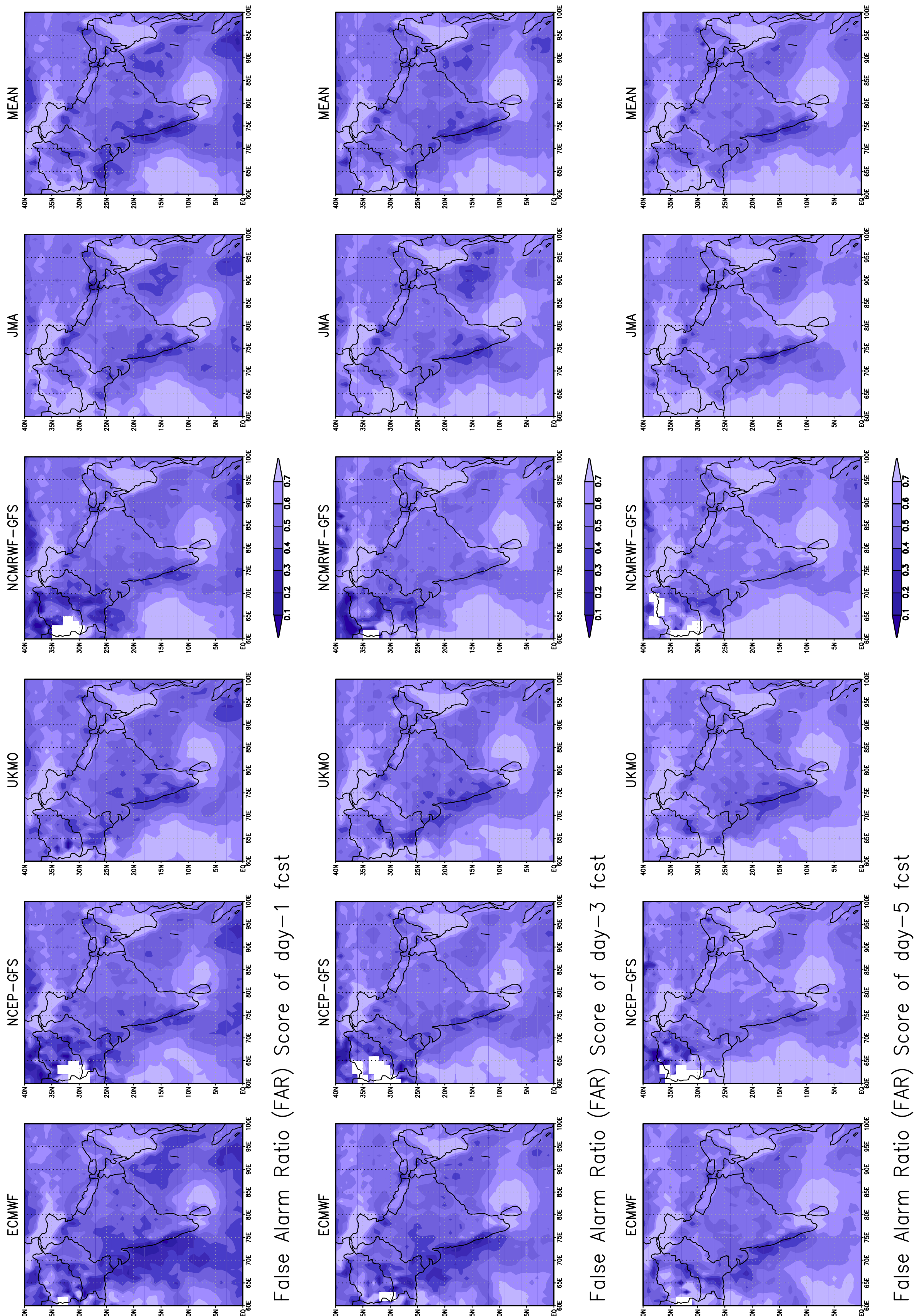
A wet spell is defined as continuous period with daily rainfall more than daily mean monsoon rainfall (DMR) of the area under consideration (Singh and Ranade 2010). The criterion has been applied on daily NMSG 1-degree gridded rainfall of June through September to understand features of wet and dry spells over the seven subzones during 1998–2011. The DMR used is the daily mean rainfall of the fixed monsoon period across the country (June to September) based upon the data 1998–2011 (Fig. 1). It varies from ~2 mm (SZ-2) to ~40 mm (SZ-4 and SZ-5). Yearwise area-averaged daily rainfall sequence of each subzone during monsoon period has been prepared by simple arithmetic mean of NMSG data of that particular subzone. The computational steps to demarcate yearwise wet and dry spells in the area-averaged rainfall sequence are as follows (Singh and Ranade 2010).

(i) Normalize daily monsoon rainfall sequence by diving it with DMR of respective subzone
(ii) Apply nine-point Gaussian low-pass filter
(iii) Identify continuous period in the filtered sequence with the value greater than or equal to 1.0 as wet spell (WS) and less than 1.0 as dry spell (DS).

Features of the following eight parameters of actual wet and dry spells have been described.

(i) Number of wet spells
(ii) Total duration of wet spells
(iii) Total duration of dry spells


ECMWF
NCEP-GFS
UKMO
NCMRWF-GFS
JMA
MEAN
0.5 0.6 0.7 0.8 0.9
Probability of Detection (POD) Score of day-1 fcst
Probability of Detection (POD) Score of day-3 fcst
Probability of Detection (POD) Score of day-5 fcst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False Alarm Ratio (FAR) Score of day-1 fcst
False Alarm Ratio (FAR) Score of day-3 fcst
False Alarm Ratio (FAR) Score of day-5 fcst
0.1 0.2 0.3 0.4 0.5 0.6 0.7

◀**Fig. 4** Spatial distribution of the dynamical false alarm ratio in forecasting the rainfall amount equivalent to DMR in day-1, day-3 and day-5 forecasts

(iv) Total rainfall of wet spells
(v) Total rainfall of dry spells
(vi) Start of the first wet spell
(vii) End of last wet spell and
(viii) Percentage contribution of wet spells rainfall to the seasonal total

The mean of the parameters of the wet and dry spells for seven subzones and All India (AI) during 1998–2011 is given in Table 1. For the country as whole, 4 WSs (3 DSs) occurs with the duration of 60.9 days (28.7 days) and total rainfall of 494.1 mm (145.1 mm). The first WS started around 9th June and ends around on 5th September by contributing 62.2 % to the seasonal total (783.3 mm). On subzonal scale, number of WSs varies from four over the SZ-2 to about seven over the SZ-7. Total duration of the WSs is 42.6 days (minimum) over the SZ-2 and the 63.3 days (maximum) over the SZ-3, while that of DSs from 29.1 days over the SZ-3 to 55.9 days over the SZ-7. Total rainfall of the WSs is highest (1,029.3 mm) over the SZ-5 and lowest (313.1 mm) over the SZ-1. Contribution of the DSs is lowest (46.3 mm) over the SZ-2 and highest (293.5 mm) over the SZ-4. The start of the first monsoonal WS is the earliest (8 June) over the SZ-5 and latest (23 June) over the SZ-4. The last WS ends earliest (4 September) from the SZ-2 and latest (20 September) from the SZ-7. The start and end dates of the WS are well matched with the normal summer monsoon onset and withdrawal, respectively, across Indian region. The percentage contribution of the WSs to the seasonal total varies from 63.6 % (SZ-4) to 81.7 % (SZ-2).

The objective criterion with the same DMR (1998–2011) as threshold has been applied to identify wet and dry spells in the forecasted rainfall of day-1, day-3 and day-5 lead times by the five models during 2008–2011. Figure 2 presents schematic of yearwise wet and dry spells of MEAN forecast of five models for day-1 and day-5 lead times over seven subzones along with their observed spells. In the schematic, an arbitrary value 0.5 is assigned for each day of the dry spell and 1.5 for the wet spell. The wet and dry spells forecasted by the individual models matched qualitatively with the actual pattern over the different subzones. However, the MEAN wet and dry spells forecasted by the five models showed a satisfactory match with the observed pattern (Fig. 2). Error in the parameter of the forecasted MEAN wet and dry spells has been examined by calculating symmetric mean absolute percentage error (SMAPE) which is based upon the formula of mean absolute percentage error (MAPE).

$$\mathrm{MAPE} = \frac{1}{n\sum|\mathrm{PE}|}; \quad \text{in which} \quad \mathrm{PE} = \frac{(F-O)}{O} * 100 \qquad (1)$$

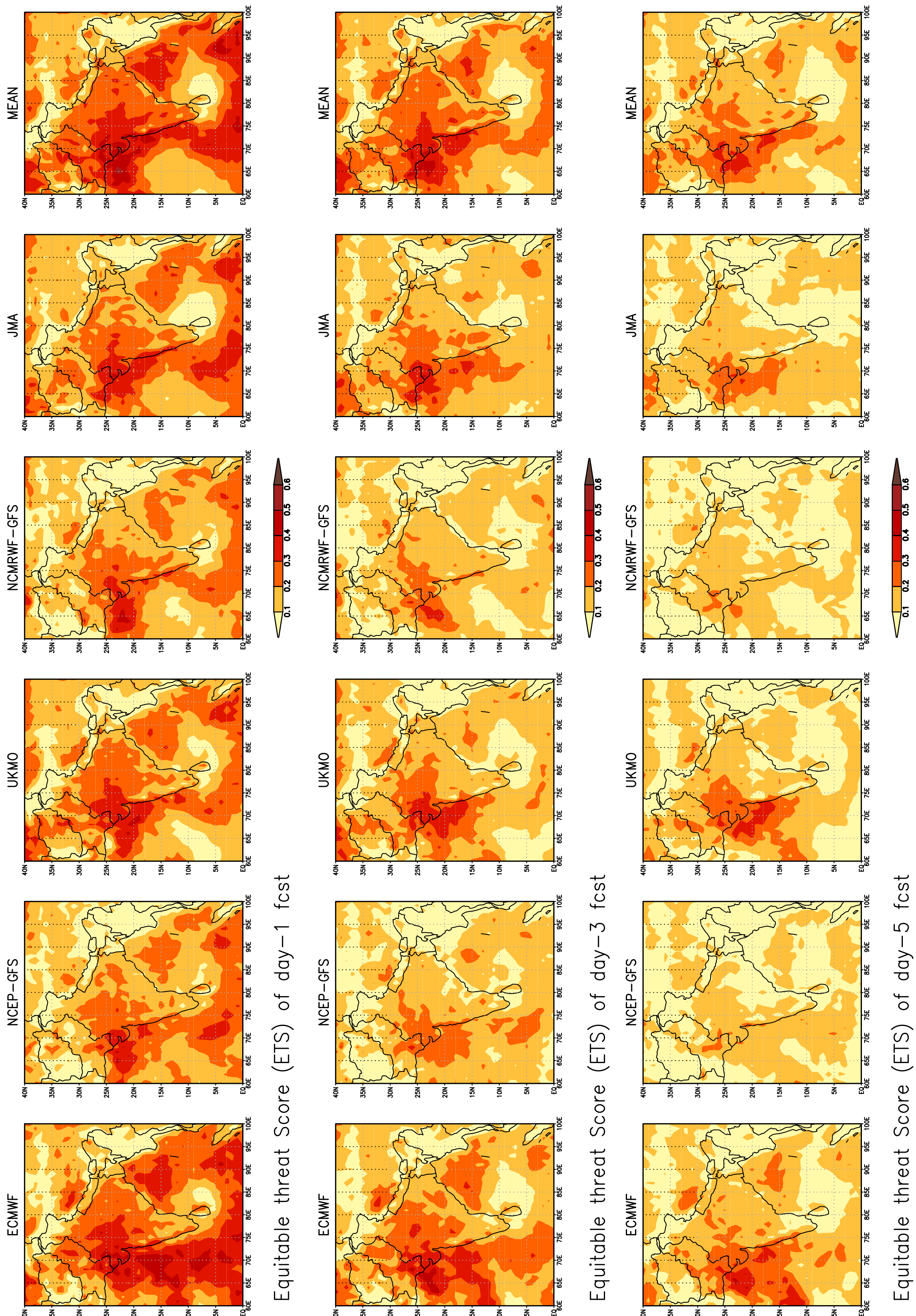
where F is forecasted value, O observed value and n number of observations. In SMAPE, the percentage error (PE) is calculated differently.

$$\mathrm{SMAPE} = 1/n\sum|\mathrm{PE}|; \quad \text{in which} \quad \mathrm{PE} = \frac{(F-O)}{\left(\frac{F+O}{2}\right)} * 100 \qquad (2)$$

This measure is adopted because it is scale-independent. Major disadvantage of equation (2) is that the PE and the MAPE are infinite or undefined for O = 0. In addition, these measures have only positive values and no upper binds, and the PEs possess highly right-skewed asymmetry (Smith and Sincich 1988). However, the symmetric MAPE (SMAPE) can deal with some of the limitations of the MAPE (Makridakis 1993). The SMAPE has an upper limit of 200 % providing a wide range to judge the level of accuracy and not severely influenced by extreme values. Further, it corrects the computational asymmetry of the PE.

During 2008–2011, on an average four wet spells (three intervening dry spells) occurred over the country with total duration 70 days (31.3 days) and total rainfall 564.4 mm (157.6 mm). The first wet spell was started on 5th June and ended around 13th September. The WSs contributed 69 % to total monsoon rainfall of 807.9 mm. In day-1 forecast, only two WSs occurred over the country with total duration of 98.8 days and one DS of 24 days. The WS started on 4th June and ended on 16th September. The total rainfall of the WSs is 894.1 mm which contributed 87.8 % to the monsoon total rainfall of 1,016 mm (Table 2). A brief account of the errors in selected parameters of the MEAN wet and dry spells forecasted by the five models for day-1, day-3 and day-5 lead time over the seven Indian subzones is in order (Table 2).

- *Number of WSs:* Number of WSs in the day-1 forecast varies from two over the SZ-3 to five over the SZ-5. The average SMAPE for the seven subzones for day-1 and day-5 forecast is 40 % with lowest error for the SZ-1 (~16.7 %) and highest for the SZ-3 (~2.6 %). The number of wet spells is underestimated in the SZ-3 and the SZ-4. Overall, number of wet spells is often under forecasted across the country.
- *Total duration of WSs:* Total duration of WSs in day-1 forecast is shortest (54.5 days) over the SZ-2 and longest (89.3 days) over the SZ-4. The average SMAPE for the country for day-1 and day-5 forecasts is 27.9 % with lowest error (~11.2 %) for the SZ-2 and highest (~60.8 %) for the SZ-4. The duration is longer in day-1 forecasts but shorter in day-3 forecasts.


ECMWF
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Equitable threat Score (ETS) of day-1 fcst
Equitable threat Score (ETS) of day-3 fcst
Equitable threat Score (ETS) of day-5 fcst
0.1
0.2
0.3
0.4
0.5
0.6

◀**Fig. 5** Spatial distribution of the dynamical ETS score in forecasting significant amount of rainfall in day-1, day-3 and day-5 forecasts

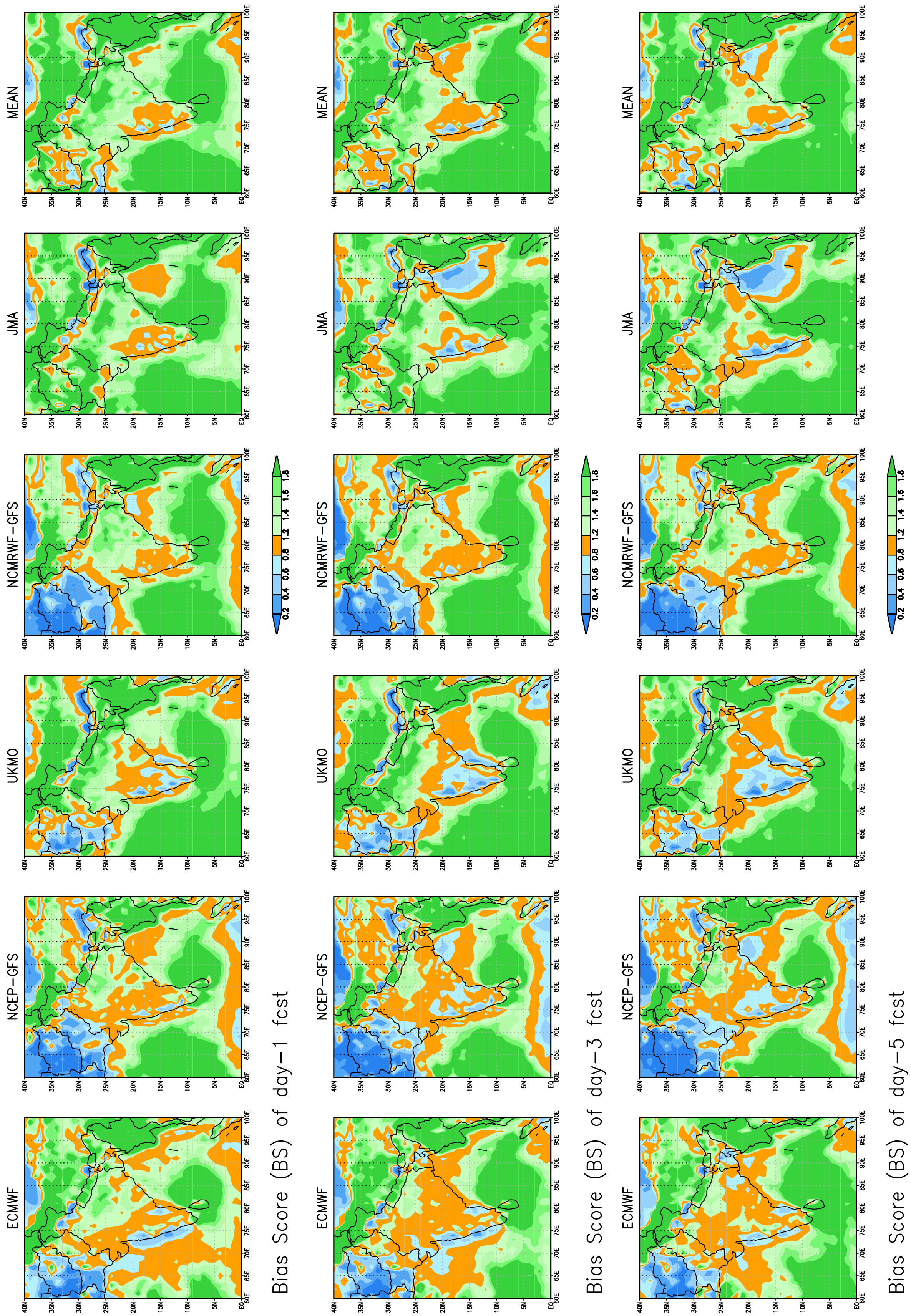
- *Total duration of DSs:* Total duration of DSs is shortest (6.5 days) over the SZ-3 and longest (42 days) over the SZ-5. The average SMAPE for the country for day-1 and day-5 forecasts is 69.1 %, least error (~16.6 %) is for the SZ-5 and most (~117.7 %) for the SZ-3. Total duration of DSs is shorter in day-1 forecasts but longer in day-3 forecasts.
- *Total rainfall of WSs:* Total rainfall of WSs in day-1 forecasts varies from 393 mm (SZ-1) to 1,347 mm (SZ-4). The average SMAPE is about 32.9 %. The least error is ~12.2 % for the SZ-1 and most ~67.2 % for the SZ-4. The total rainfall is lower in day-1 forecasts (except over subzones SZ-5 and SZ-2) and higher in day-3 forecasts.
- *Total rainfall of DSs:* Total rainfall of DSs for day-1 forecasts is highest 361 mm for the SZ-5 and lowest 35.7 mm for the SZ-3. The average SMAPE is 67.5 % with least error (~24.7 %) for the SZ-5 and highest error (~111.2 %) for the SZ-4. The total rainfall is lower in day-1 forecasts over most of the subzones and higher in day-3 forecasts.
- *Start of first WS:* In day-1 forecasts, start of first wet spell is earliest (4 June) over the SZ-4, the SZ-6 and the SZ-7 and latest (19 June) over the SZ-3. The average error in day-1 to day-5 forecasts is 2.2 % with least error (~0.4 %) over the SZ-3 and highest (~ 5.3 %) over the SZ-1. Start of the first WS is marginally late in day-1 forecasts and early in day-3 and day-5 forecasts.
- *End of last WS:* End of last wet spell is earliest (10 September) from the SZ-5 and latest (22 September) from the SZ-7 in day-1 forecasts. The average error is 1.0 %, the minimum is ~0.3 % for the SZ-3 and the SZ-2 and maximum ~2.1 % for the SZ-6. End of last WS is normally earlier in day-1 forecasts but later in day-3 forecasts.
- *Percentage contribution of WSs to seasonal total:* Monsoon total rainfall in day-1 forecasts varies from 501.5 mm (SZ-1) to 1,456.6 mm (SZ-5). The average SMAPE noticed in day-1 to day-5 forecasts is 18.2 % with least error (~9.6 %) for the SZ-1 and most (~32.9 %) for the SZ-4. Seasonal rainfall is lower in day-1 forecasts (except SZ-5) and higher in day-3 and day-5 forecasts. Percentage contribution of the WS rainfall to seasonal total in day-1 forecasts is highest (89.6 %) over the SZ-3 and lowest (63 %) over the SZ-5. The average error (SMAPE) in the percentage contribution is 16.6 % error. It is least (~5.8 %) for the SZ-2 and highest (~36.4 %) for the SZ-4. The percentage contribution is higher in day-1 forecasts for most of the subzones and lower in day-3 forecasts.

On subzonal scale, start of first WS and end of last WS is better forecasted for the SZ-3 (central Indo-Gangetic plains). Uncertainty is large in forecast of total duration of WSs over the SZ-4 (northeast India) and that of DSs over the SZ-3. Forecast of total rainfall during WSs and that during DSs and total monsoon rainfall is more uncertain over the SZ-4 than the other subzones. More uncertainty is seen in forecast of rainfall and duration of DSs than those of WSs. Uncertainty is least in forecast of start of first WS and end of last WS and most number of WSs. Further, forecast of rainfall during WS or DS is more uncertain than total rainfall during whole season.

4.2 Prediction of area under wet condition and rainwater

It is well known that skills of NWP models drastically reduce higher rainfall amounts. In the verification of NWP forecasts, generally few arbitrary rainfall amounts are uniformly used across entire area of interest as threshold. Significance of any rainfall amount varies drastically across different climatic regions (desert, arid, semiarid, dry subhumid, moist subhumid and perhumid). Rainfall over particular area depends upon type, intensity and frequency of weather systems (line convergence, trough-meander, cyclone, eddies, thunderstorm etc.) given the role of orography, ocean, continent and Coriolis force. Numerical models are expected to take into account these factors. Local rainfall climatology as DMR values (Ranade and Singh 2014) has been used to verify forecast of the area of country under wet condition and rainwater over it by five-selected NWP models and their ensemble MEAN for day-1, day-3 and day-5 lead times. The DMR for 1-degree grid cells is based on observed NMSG dataset for the period 1998–2011.

During monsoon period (June through September) of 2008–2011, a grid cell is identified under wet condition if actual rainfall equaled or exceeded its DMR. Well-known dichotomous skill scores such as Bias Score (BS), Probability of Detection (POD), False Alarm Ratio (FAR) and Equitable Threat Score (ETS) have been calculated using spatially variable rainfall threshold (DMR) rather than fixed rainfall amount. For the sake of differentiation, the skill scores are referred to as dynamic and denoted as BS_{dyn}, POD_{dyn}, FAR_{dyn} and ETS_{dyn}. The spatial distribution of the skill scores suggests mismatch between observed and forecasted daily rainfall equal to the DMR. Spatial distribution of POD_{dyn} and FAR_{dyn} are as shown in Figs. 3, 4 respectively, for day-1, day-3 and day-5 forecasts by the five NWP models and their MEAN. These scores determine the proportion of observed 'yes' events forecasted correctly and proportion of forecasted events that failed, respectively. They complement each other and


ECMWF
NCEP−GFS
UKMO
NCMRWF−GFS
JMA
MEAN
Bias Score (BS) of day−1 fcst
Bias Score (BS) of day−3 fcst
Bias Score (BS) of day−5 fcst
0.2 0.4 0.6 0.8 1.2 1.4 1.6 1.8

◀**Fig. 6** Spatial distribution of the Dynamical Bias Score in forecasting the significant amount of rainfall in day-1, day-3 and day-5 forecasts

therefore considered simultaneously. For perfect prediction, the POD_{dyn} should be 1.0 and the FAR_{dyn} zero. The POD_{dyn} for the five models is higher (>0.8) over oceanic areas and 0.6–0.8 over the land areas. Most of the models raise false alarms (>0.4) over most part of the country, but lesser FAR_{dyn} (<0.2) is seen over the West Coast. The POD_{dyn} decreases and the FAR_{dyn} increases with increase in the lead time indicating poorer performance of the models in correctly predicting observed yes/no events for longer lead time. The skill is more for the MEAN forecast than the individual models indicating reduction in uncertainties in prediction of observed 'yes' events and false alarms in the ensemble MEAN. The ETS_{dyn} represents percentage improvement over reference forecast (here threat score). It is shown in Fig. 5 calculated for the five models and their MEAN. The variation in ETS_{dyn} across the country is between 0.2 and 0.4. However, it is impractical to assess skill of the forecasting systems with the ETS score alone but in conjunction with the bias score. The forecasts with larger bias tend to have higher ETS (Hamill 1999; Mesinger 2008). We have calculated the BS_{dyn} (Fig. 6) in order to correctly judge the performances of the models. The BS_{dyn} represents number of events correctly predicted from the number of events actually realized, and it is a measure of relative frequency of rainfall forecasts and observations. Its value greater than 1.0

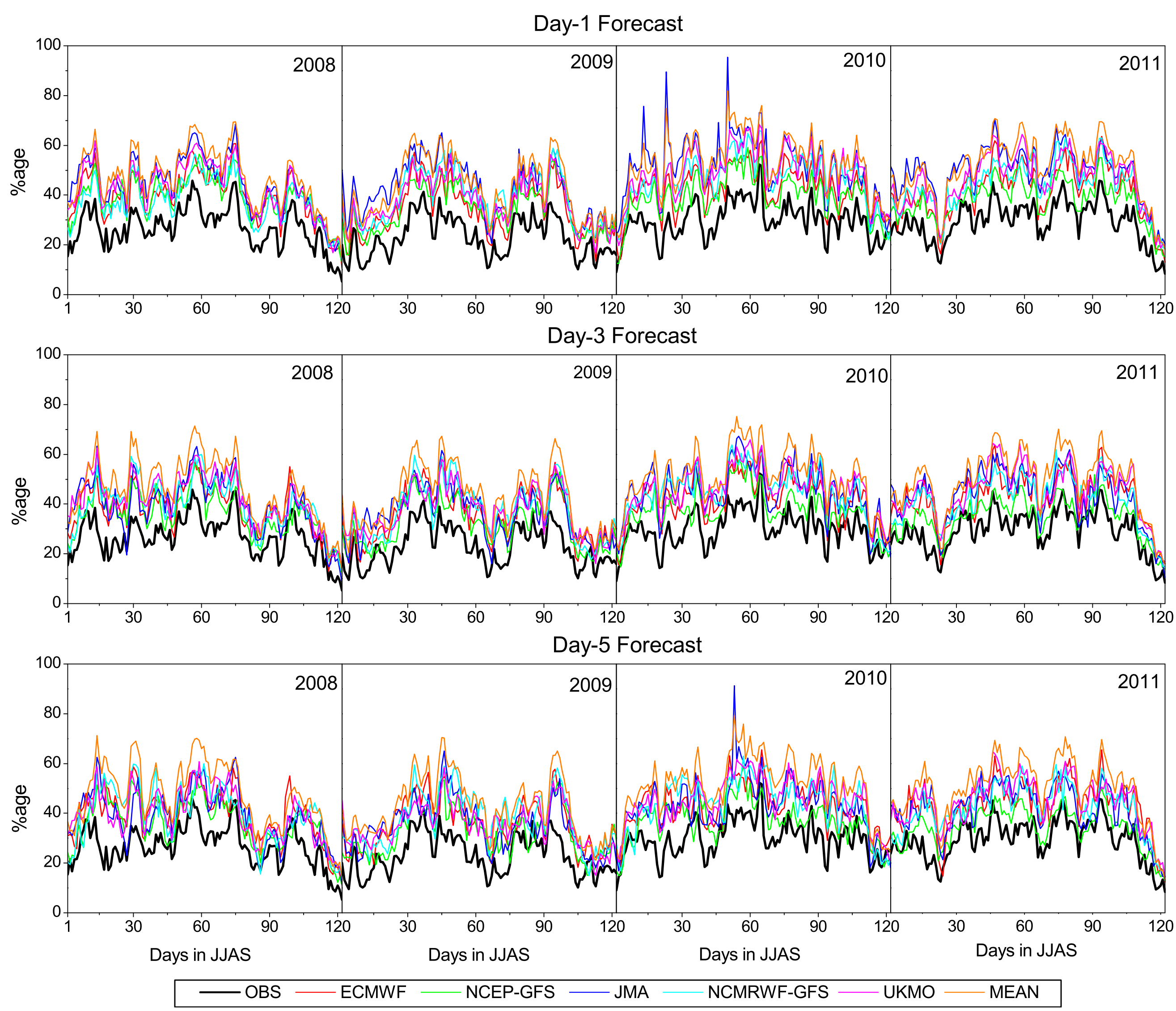


Fig. 7 Daily variation in PAI calculated from the NMSG observed precipitation and day-1, day-3 and day-5 forecasts of the five AGCMs and the MEAN during 2008–2011

Table 3 The difference (DIFF) between forecasted and observed percentage area of India under wet condition (PAI) by different models; and their MEAN, the mean absolute percentage error (MAPE) and the correlation between observed and forecasted PAI during 2008–2011

Models	Day-1 forecast			Day-3 forecast			Day-5 forecast		
	DIFF (%)	MAPE (%)	CC	DIFF (%)	MAPE (%)	CC	DIFF (%)	MAPE (%)	CC
ECMWF	12.01	47.75	0.92	12.26	49.72	0.87	13.24	54.20	0.82
NCEP-GFS	10.29	43.66	0.86	7.74	34.96	0.79	7.75	36.85	0.71
JMA	19.65	78.03	0.86	13.74	55.34	0.83	12.44	51.93	0.76
NCMRWF-GFS	14.46	59.41	0.83	13.64	56.91	0.77	13.62	58.77	0.66
UKMO	16.51	65.98	0.88	15.39	62.94	0.83	14.11	59.07	0.78
MEAN	21.28	83.18	0.90	20.11	79.14	0.85	20.70	82.53	0.80

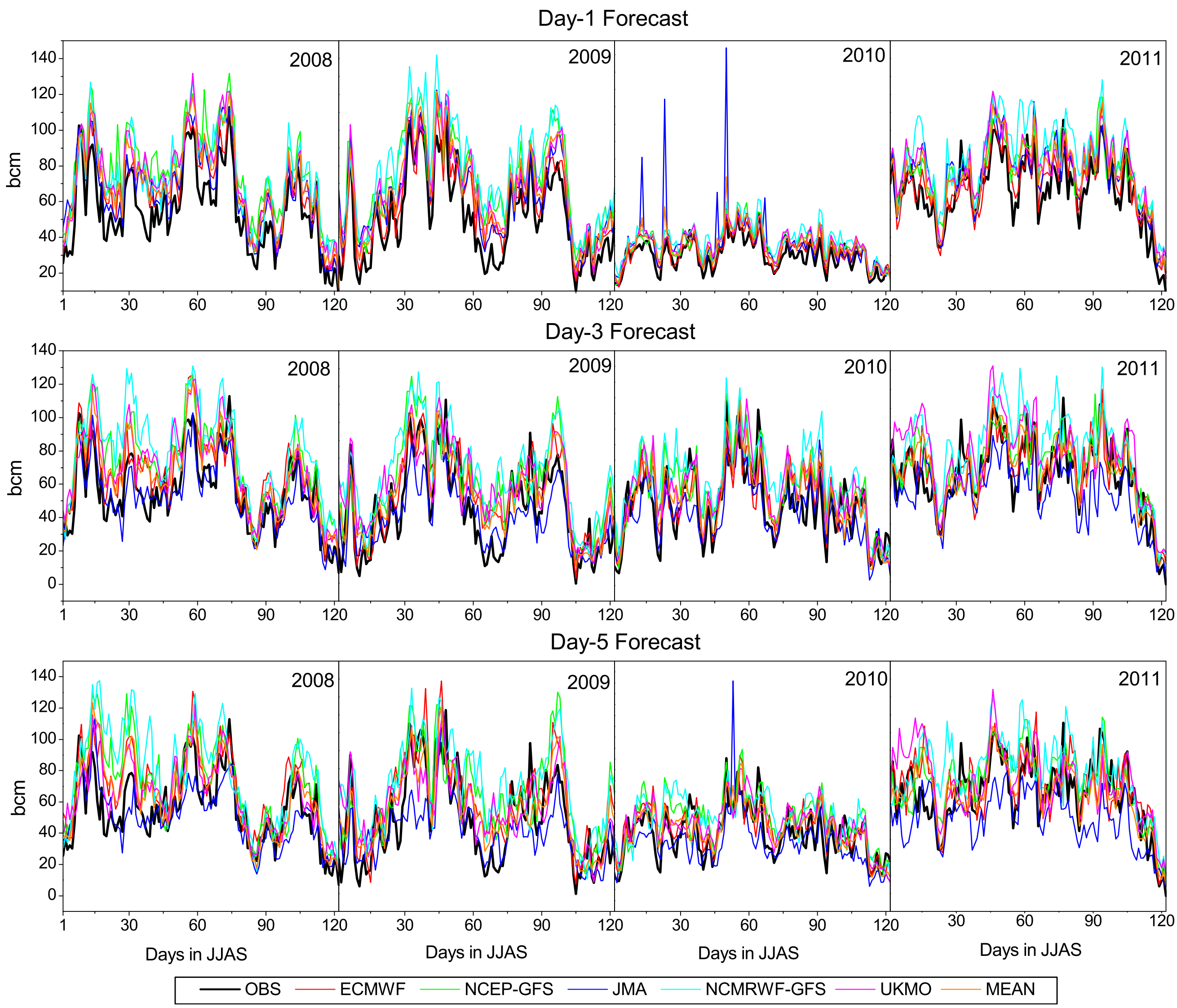


Fig. 8 Daily variation in RW calculated from the NMSG observed precipitation and day-1, day-3 and day-5 forecasts of the five AGCMs and MEAN during 2008–2011

indicates over forecast by the model and lowers than 1.0 under forecast. Most of the models overpredicted the rainfall frequency particularly over extreme north and northeast India, Myanmar and major part of the oceanic region, but a few models under predicted over Pakistan, Afghanistan region. Forecasted frequency of significant

Table 4 The difference (DIFF) between forecasted and observed rainwater (RW) by the models; and their MEAN, the mean absolute percentage error (MAPE) and the correlation between observed and forecasted RW during 2008–2011

Models	Day-1 forecast			Day-3 forecast			Day-5 forecast		
	DIFF (bcm)	MAPE (%)	CC	DIFF (bcm)	MAPE (%)	CC	DIFF (bcm)	MAPE (%)	CC
ECMWF	6.92	20.94	0.91	5.23	22.36	0.85	7.90	27.81	0.79
NCEP-GFS	17.37	39.72	0.87	11.83	34.04	0.79	12.43	37.42	0.72
JMA	12.33	28.76	0.77	5.25	20.93	0.82	9.02	25.70	0.69
NCMRWF-GFS	20.72	45.73	0.86	18.24	45.65	0.75	16.84	47.49	0.62
UKMO	14.52	33.28	0.90	10.77	32.17	0.80	7.41	30.76	0.74
MEAN	12.68	28.97	0.91	5.97	24.02	0.85	4.38	25.47	0.78

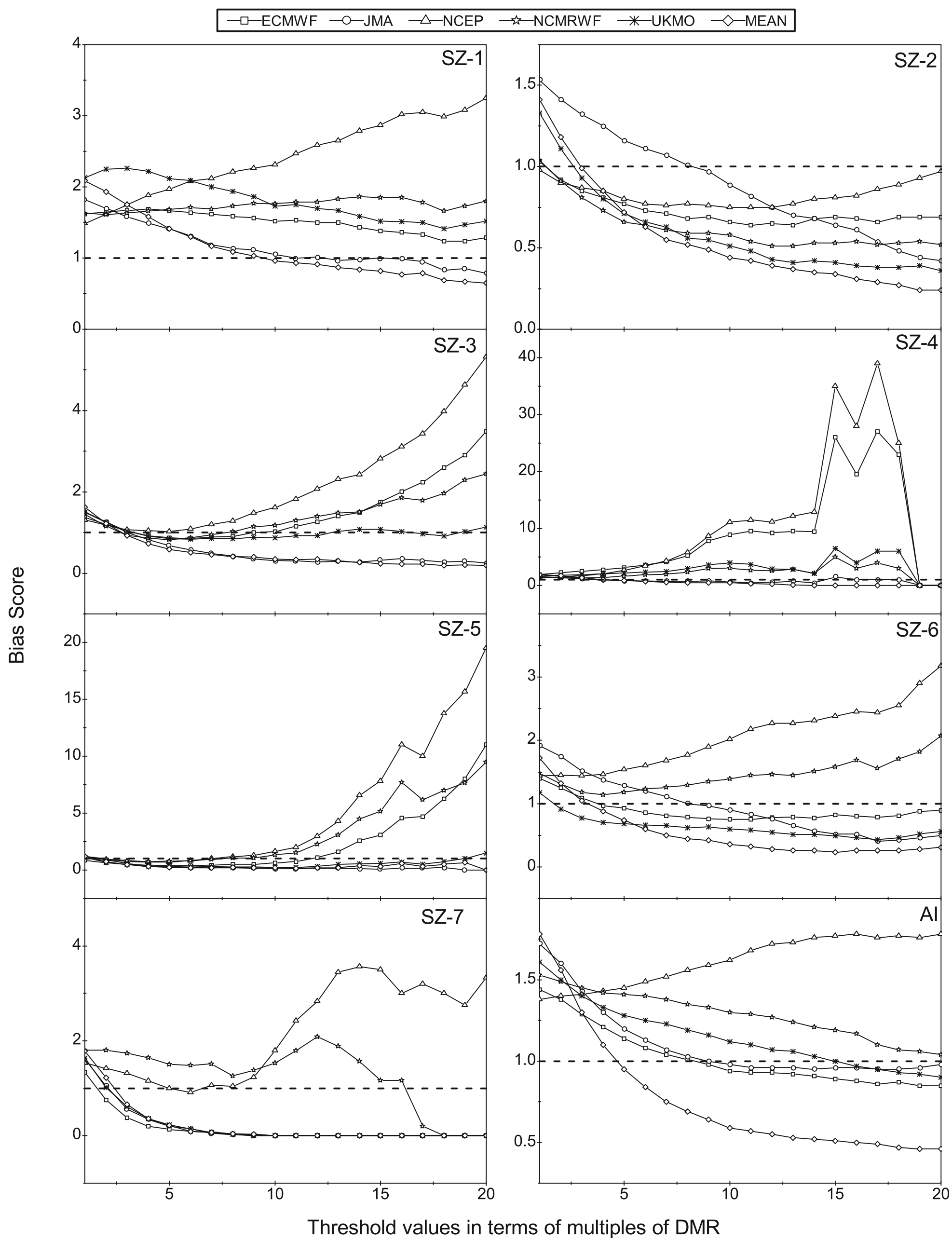


Fig. 9 The Dynamical Bias Scores in day-1 forecast calculated for specified rainfall thresholds over the seven subzones

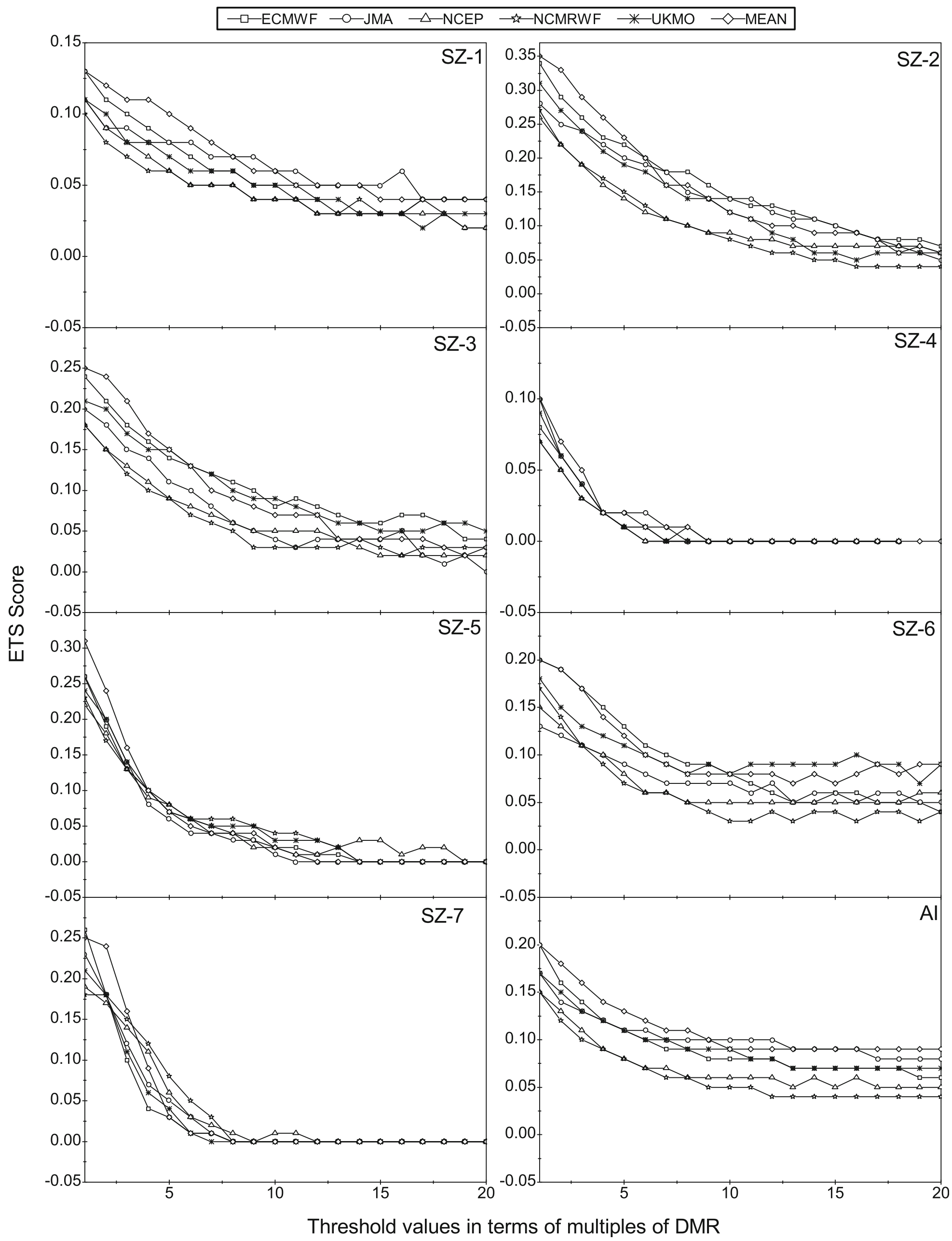


Fig. 10 The dynamical ETS scores in day-1 forecast calculated for specified rainfall thresholds over the seven subzones

rainfall is in close agreement with observed value over most part of peninsula and some part of northwest India. Different models show higher ETS_{dyn} over oceanic areas (Fig. 5) but simultaneously biases are also higher. In addition, the NMSG observed rainfall over oceanic regions are only multi-satellite estimates. In such situation, any conclusion regarding accuracy of the models in predicting rainfall over oceanic areas would be ambiguous. For the ECMWF model, the ETS_{dyn} is higher and the BS_{dyn} is lower especially over northwest India for all the forecast lead times. The performance of the ECMWF is better compared to others. In general, the ETS_{dyn} decreases with lead time. The skill scores computed above jointly provide the qualities of the models for rainfall forecast. The ensemble MEAN showed better skill in the prediction of significant amount of rainfall than any individual model.

Ranade and Singh (2014) have studied percent area of India (PAI) under wet condition during 1951–2007 to understand spatial features of rainfall occurrences over the country. They documented that, normally each day only 26.3 % (SD = 2.5 %) area of the country occurs under wet condition with the intensity 26.3 mm/day (SD = 1.2 mm/day), during the main monsoon wet spell (18 June–16 September). In this study the PAI calculated from forecasted rainfall is verified with the observed value during 2008–2011. Area of the grids with forecasted daily rainfall greater than or equal to the respective DMR has been totaled and expressed as percentage of total geographical area of the country to obtain PAI. The observed PAI during 2008–2011 varied from 5.3 to 52.3 % with mean and standard deviation being 27.25 and 7.95 %, respectively. The forecasted daily PAI by the five models and their MEAN for day-1, day-3 and day-5 lead times is considerably higher than the observations (Fig. 7). The mean absolute percentage error (MAPE) for the difference (DIFF) between forecast and observation is given in Table 3. The mean MAPE (2008–2011) is 43.66 to 83.18 % for day-1, 34.96 to 79.14 % for day-3, and 36.85 to 82.53 % day-5 forecasts. The minimum error is for the NCEP-GFS forecast and maximum for the ensemble MEAN. The observed and forecasted daily PAI is, however, highly correlated. The correlation coefficient (CC) is 0.83–0.92 for day-1, 0.77–0.87 for day-3 and 0.66–0.82 for day-5 forecasts (Table 3), which in general shows decrease with lead time. The highest CC is for the ECMWF model and lowest for the NCMRWF-GFS.

Rainwater (RW: rainfall multiplied by the area) is directly useful information in hydrology and water resources. During 2008–2011, daily RW over the country varied from 6.9 bcm (billion cubic meters) to 130.8 bcm with mean 58.77 bcm and standard deviation 22.2 bcm. The forecasted RW is higher in all the cases compared with observation (Fig. 8). The mean difference between forecast and observation and the MAPE is given in Table 4. The mean MAPE is from 20.94 to 45.73 % for day-1, 20.93 to 45.65 % for day-3 and 25.47 to 47.49 % for day-5 forecasts. Least error is for the ECMWF model and most for the NCMRWF-GFS. However, the forecasted and observed daily RW is highly correlated, the CC is 0.86–0.91 for day-1, 0.75–0.85 for day-3 and 0.62–0.79 for day-5 forecast (Table 4). The highest CC is for the ECMWF and lowest the NCMRWF-GFS model. It seems overprediction of RW is essentially due to overprediction of area of the country under wet condition. Though moderate and heavy rainfall are under predicted by the models (Ebert and McBride 2000; Mandal et al. 2007; Roy Bhowmik and Durai 2010), light rains are frequently predicted over larger dry areas of the country.

4.3 Sensitivity to rainfall threshold

Heavy precipitation events can affect model performances drastically. This is demonstrated by calculating skill scores for a range of rainfall thresholds over the seven subzones. The standard statistical skill scores especially defined for the areal coverage (Anthes 1983; Schaefer 1990) analogous to that defined for precipitation amount are used. The rainfall thresholds considered are of multiples of the DMR of the individual grids. The BS_{dyn} is the ratio of forecasted area to observed area for specified rainfall threshold. The ETS_{dyn} measures the skill in predicting the area with specified rainfall amount to a random (no skill) control forecast. The BS_{dyn} and ETS_{dyn} for variable rainfall threshold in day-1 forecast over seven subzones are shown in Figs. 9, 10 respectively. The biases are larger for higher rainfall intensities for all the subzones. In general the models have a tendency to overpredict the rainfall frequency for higher rainfall thresholds. Overprediction is higher for NCEP-GFS especially for higher rainfall intensities (more than 15 times of DMR) compared with other models. The ETS_{dyn} scores of the models drastically reduce and become zero for higher thresholds (more than seven times of DMR). The models show similar variations in the ETS_{dyn} scores with change in rainfall threshold. The scores decrease gradually for day-3 and day-5 compared with day-1 forecasts (figures are not shown). For lower rainfall thresholds, bias scores of different models are analogous compared with that of higher rainfall thresholds. Thus, the models can be more accurate at lower rainfall thresholds. The ETS_{dyn} is higher for the ECMWF model and the MEAN followed by the JMA and the UKMO models for forecasts of different lead times.

The AGCMs are developed independently using different assimilation systems and physical parameterization schemes. But uncertainties in representing the dry and wet spells and other spatio-temporal features of rainfall variability are comparable to the models. Therefore, it is rather difficult to attribute the errors and inaccuracies to any specific physical process or data assimilation technique. Since precipitation is computed in the models from the atmospheric water vapor, adequate modeling of different components of water cycle is an essential in order to improve the results. Incorporation of proper coupling scheme for land-surface models is an important requirement. Cumulus convection plays a central role in most of the interactions between physical processes (dynamical processes, hydrological processes, radiation and chemical processes, boundary layer processes etc.). Krishnamurti et al. (2007, 2008) have attempted numerous cloud radiative transfer algorithm and cumulus parameterization schemes in different models in order to assess the best algorithm. They found large systematic errors in all schemes. This occurs not only due to the scheme itself but because of interaction of the scheme with the model structure. In addition to parameterization of physical processes, Arakawa (2004) suggested statistical behavior of small-scale processes to be formulated in order to understand large-scale phenomenon. Day to day fluctuations of rainfall seem to depend on interaction of cloud processes with the large-scale flows, but predictability of intraseasonal components are part of large-scale low-frequency oscillations.

5 Conclusions

The medium rainfall forecasts (1- to 5-day) during 2008–2011 by five AGCMs and their ensemble MEAN have compared against the TRMM-gauge-merged data to understand skills of models in forecasting parameters of wet and dry spells, area under wet condition and rainwater over and across the Indian region. The main findings of the study are as follows.

1. During 1998–2011, on an average four wet spells (three intervening dry spells) with duration $\sim$61 days ($\sim$29 days) with total rainfall 494.1 mm (145.1 mm) occurred over the country. The first wet spell started on 9 June and ended around 5 September. The wet spells contributed 62.2 % monsoon total rainfall (783.3 mm).
2. Number of wet spells is under predicted (40 % less) by MEAN forecast of five models. While start of the first WS is marginally late and end of the last WS marginally early in day-1 forecasts while opposite is true in day-3 and day-5 forecasts. The start of the first WS and end of the last WS are better simulated over the Central Indo-gangetic plains (SZ-3).
3. Total duration and total rainfall of WSs (DSs) and seasonal rainfall are overestimated (underestimated) in day-1 forecasts but opposite situation found in day-3 forecasts. Uncertainty is larger in the prediction of the DS rainfall and its duration compared with the WS rainfall and its duration. The percentage contribution of WSs rainfall to the seasonal total is predicted by models with the mean error of 16.6 %.
4. The ensemble MEAN shows better skill in the prediction of rainfall amount equivalent to the respective area (grid) DMR.
5. The observed daily PAI under wet condition during 2008–2011 is 27.25 %. The forecasted PAI by the different models is considerably higher ($\sim$59 %). The error is least in the NCEP-GFS forecasts and most in the ensemble MEAN. However, the observed PAI shows high correlation of 0.86 with corresponding day-1 forecasts that of 0.82 with corresponding day-3 forecasts and that of 0.76 with corresponding day-5 forecasts. The CC deteriorates with lead time.
6. The observed daily mean RW (2008–2011) over the area of the country under wet condition is 58.77 bcm. The forecasted RW by different models is considerably higher ($\sim$32 %). The error is least in ECMWF forecasts and most in NCMRWF-GFS. However, the correlation coefficient between observed and forecasted RW for day-1 is 0.87, day-3 0.81 and day-5 CC = 0.72.
7. Most of the models show tendency to overpredict rainfall frequency for higher thresholds. The skill of different models drastically reduces and becomes negligible with increase in rainfall threshold. The ECMWF and ensemble MEAN show higher ETS_{dyn} followed by the JMA and the UKMO models. However, performance of all the models deteriorates with the forecast lead time.

Critical examination and real-time monitoring of the global distribution of the anomalies in atmospheric and oceanic parameters is essential to understand the intensity of monsoon circulation, formation of rain-producing systems and localized weather systems. Verification of model forecasted atmospheric circulations, particularly type, location and intensity of rain-producing weather systems, seems essential to understand overprediction of area under wet condition and rainwater and errors in the parameters of the wet and dry spells which can be done in separate research program.

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