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Prediction of occurrence of daily summer monsoon precipitation over Karnataka

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ABSTRACT: Karnataka, a State in south peninsular India, receives 73% of its annual rainfall during the southwest monsoon season. Because of the complex physiographical features, the rainfall pattern over the State shows large spatial variation from 50 to 350 cm. The co-efficient of interannual variation of the monsoon rainfall is about 15% over coastal Karnataka (CK) and between 20 and 30% over interior Karnataka. It is, therefore, a difficult task to predict the location specific daily rainfall over Karnataka. In this study, an attempt has been made to develop an objective tool for forecasting the occurrence and non-occurrence of precipitation during a 24 h period for the 19 stations in Karnataka during the monsoon season. The probability of precipitation (POP) model is developed using forward stepwise regression with the available surface and upper air parameters from synoptic and radiosonde and radio wind stations in and around Karnataka as potential predictors. The POP model has been developed based on the data from 1981 to 1996 and verified with the data from 1997 to 2002. Different skill scores are computed using a yes/no contingency table. The POP model performs very well, with percentages of correct (PC) forecasts for occurrence/non-occurrence of precipitation being 57–91% for the independent data. Comparing the results of the POP model with that of the conventional method of forecast for Bangalore City, the PC forecasts improves from 44 to 56% with the use of the POP model. Copyright © 2011 Royal Meteorological Society

KEY WORDS monsoon precipitation; forward stepwise regression; Karnataka

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1. Introduction

The monsoon rainfall over India is of critical importance in agricultural production and industrial usages. India receives nearly 75% of its annual rainfall during the monsoon season (June–September). This daily monsoon rainfall over India shows large scale spatial and temporal variations. Considering the importance of the daily rainfall prediction in various fields, a number of methods are used by forecasters. A review of the synoptic analogues developed by various authors for different regions of India for prediction of precipitation is given by Mohanty and Mohapatra (2007). The dynamical numerical models are used by many centres for predicting the rainfall and other weather elements, but these are highly dependent on the initial data, parameterization schemes and numerical techniques used for solving the governing equations. These models are capable of simulating large-scale features, but the rainfall is highly under-predicted and is available only at the model grid point, not at the station location. Considering the above, statistical models still have a use in predicting the location specific daily rainfall. Kruzinga (1989) has compared forecasting of probability of precipitation (POP) over the Netherlands using an analogue technique and logistic regression: the regression technique performed better than the analogue technique. Mohanty *et al.* (2001) developed an objective technique to forecast POP over Delhi and provide the quantitative precipitation forecast (QPF) using a classical multivariate regression technique. Mohanty and Mohapatra (2007) have developed a statistical model for POP based on forward stepwise regression for Orissa State. Their results show that the POP model performs very well, with the percentage correct (PC) forecast as 73 and 65% respectively for the developmental and the independent data.

Karnataka, a State in south peninsular India (Figure 1(a)) is confined within the 11.5 and 18.5 °N latitudes and 74 and 78.5 °E longitudes (IMD, 1984). The southwest monsoon is the principal rainy season, during which it receives 73% of its annual rainfall. It has basically four physiographical regions: (1) coastal plains comprising Uttar Kannada, Dakshin Kannada and Udipi districts, (2) the Western Ghat region which comprises Shimoga, Chikmangalur, Hassan and Kodagu districts, (3) the south interior plateau region, and (4) the north interior plateau region. According to the classification of the India Meteorological Department (IMD) there are three meteorological subdivisions: coastal Karnataka (CK), south interior Karnataka (SIK) and north interior Karnataka (NIK) (Figure 1(b)). The orography plays a very important role in the rainfall pattern over the coastal and Ghat regions of the State. The monsoon rainfall over the State varies from 50 to 350 cm. CK, which lies on the windward side of the Western Ghats, receives very heavy rain, amounting to 317 cm during the monsoon period due to interaction between the orography and the monsoon flow. The normal rainfall over NIK and SIK are 47 and 66 cm respectively. The northern interior districts of the State are comparatively dry and have large co-efficient of variability of rainfall as compared to the south interior districts. The co-efficient of interannual variation of the monsoon rainfall is about 15% over CK and between 20 and 30% over interior Karnataka (IK).

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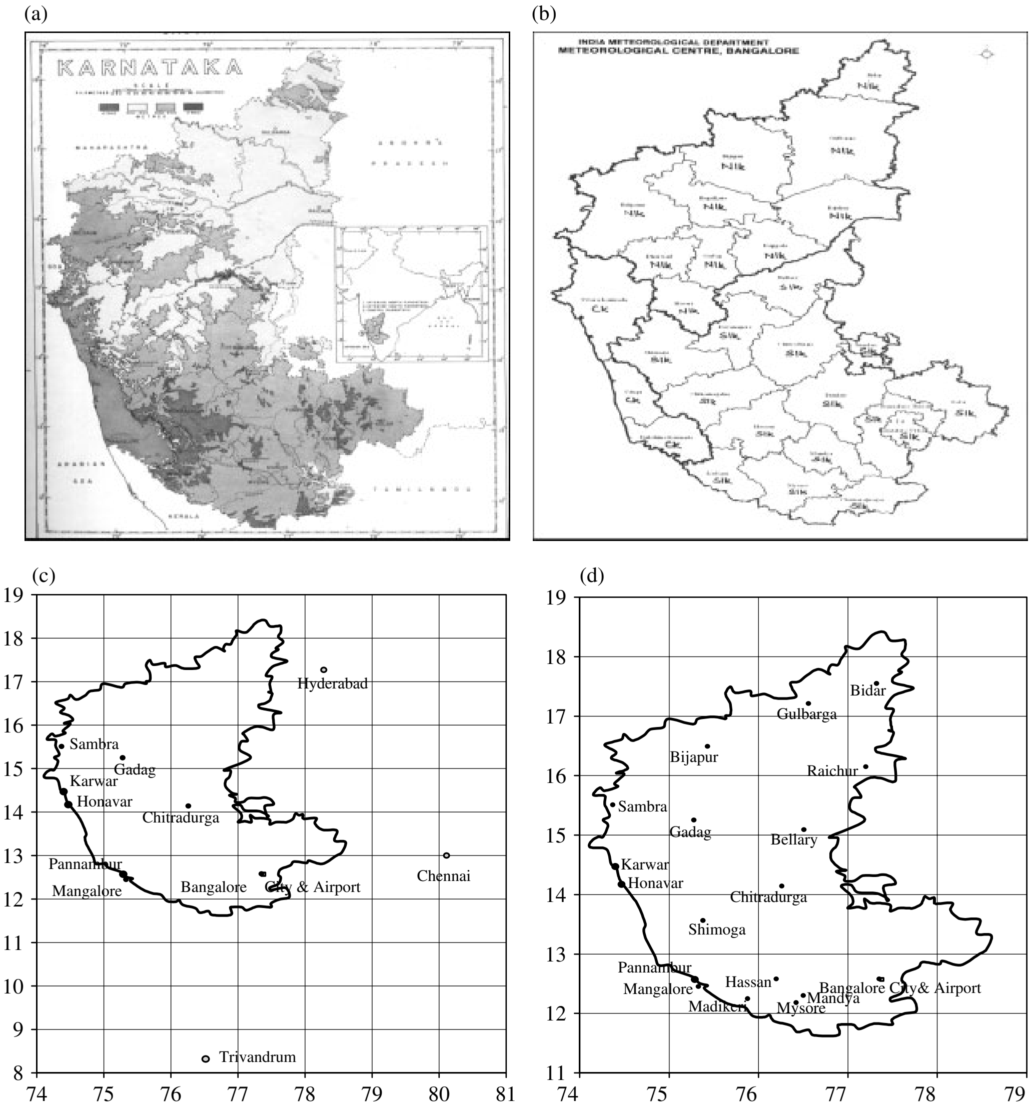

Figure 1. (a) Physiographical regions of Karnataka (b) Meteorological subdivisions of Karnataka (c) Stations whose data are used for developing the probability of precipitation (POP) models (d) Stations under consideration for prediction of precipitation based on POP model. Figure 1(a) is reproduced from India Meteorological Department (1984).

The monsoon precipitation over Karnataka is dominated by the offshore trough running along the west coast and the strengthening of westerlies/southwesterlies along the coast. The other synoptic scale systems that affect this State are the depressions that form in the west-central (WC) and northwest (NW) Bay of Bengal and move in a west to northwesterly direction during the monsoon season (Mooley and Shukla, 1989; Jadhav, 2002). These systems enhance the southwesterly monsoon current over the State leading to the increased interaction with the orography and hence rainfall. During the break monsoon conditions the monsoon trough shifts to the foothills of the Himalayas and the strength of the westerlies over south peninsular India decreases (Ramamurty, 1969) leading to a decrease in rainfall over the CK and Ghat areas of SIK. On some of these occasions, a north–south trough or wind discontinuity develops over the south of the peninsula, such as that during pre-monsoon months (March–May), which cause thunderstorm activity over IK. Sometimes troughs in easterlies with an embedded cyclonic circulation or low pressure area pass through the extreme south of the peninsula, causing good rainfall over IK (Rao, 1976).

Considering the complexity in the rain formation processes over Karnataka, it is a challenging task for a forecaster to predict location-specific daily precipitation. Hence, an attempt has been made to develop an objective tool for forecasting the occurrence and non-occurrence of precipitation during the next 24 h using a POP model for the representative stations over Karnataka during the monsoon season. This study will be helpful in understanding the physical mechanism of occurrence of daily precipitation over Karnataka.

2. Data and methodology

The station rainfall depends on various surface and upper air parameters (Mohanty and Mohapatra, 2007). However, the relationship varies with respect to the location of the rain gauge station due to the varied physiography of Karnataka. Hence, the available surface and upper air parameters observed from synoptic and radiosonde/radio wind stations in and around Karnataka during 1981–1996 have been considered as potential predictors for development of the multiple regression equation-based POP model. The model has been tested based on the data of 6 years from 1997 to 2002. As the monsoon season (June–September) consists of 122 days, the data samples of 1936 days (121 days *per* year × 16 years; starting from 2 June to 30 September) for developmental period and 726 days (121 days *per* year × 6 years; starting from 2 June to 30 September) are considered to be reasonable for the development of the POP model. However, the data could have been extended up to 2007 which were available at IMD recently. This is a limitation of this study. To address this issue, the developed model will be upgraded with the inclusion of latest data in future work. The details of the POP model are discussed in Section 2.1.

The interaction of synoptic and mesoscale processes are taken into account by considering the surface and upper air observations of IMD in and around Karnataka. According to Nigam (1994), the El Niño related persistent (spring-summer) heating anomalies over the tropical Pacific and Indian Ocean basins mostly regulate the low level westerly monsoon flow intensity over equatorial Africa and the north Indian Ocean. The lower tropospheric flow by the persistent El Niño related tropical Pacific and Indian Ocean heating anomalies counteracts the climatological monsoon flow and thereby reduces the moisture flux into the Indo-China region. The weakening of the tropical easterly jet during the pre-monsoon months of rainfall deficit years (Webster and Yang, 1992) reflects the impact of the persistent El Nino related heating anomalies that force upper tropospheric westerlies over the tropical Indian Ocean. Hence, the El-Niño and sea surface temperature anomaly over the north Indian Ocean influence the monsoon circulation over Indian region. However, according to Webster and Yang (1992), the lack of significant correlation across the spring suggests a distinct limitation to the use of southern oscillation index based prediction schemes. However, the influence of ENSO on lower and upper tropospheric wind has been taken care by considering the wind data over the region.

The surface and upper air stations selected for finding out the potential predictors are shown in Figure 1(c). The upper air stations are marked in light circles and the synoptic stations marked in dark circles. The meteorological parameters considered for selection of potential predictors are shown in Table 1. The observations recorded at 0300 UTC from the surface observatories and observations recorded at 0000 UTC from the upper air stations for the period

1981–1996 are considered as developmental data for the POP model. These parameters include mean sea level pressure (MSLP), maximum (T_x) and minimum (T_n) temperature, dry bulb temperature (T), wet bulb temperature (T_w) and dew point (T_d), relative humidity (RH), vapour pressure (V_p) and zonal (u) and meridional (v) winds at surface level. The maximum temperature considered on the day of forecast is actually the maximum temperature observed on the previous day and the minimum temperature on the day of forecast is observed on the same day morning. The actual wind is resolved into zonal (u) and meridional (v) components. The u and v are taken as positive for zonal westerly and meridional southerly winds and negative for zonal easterly and meridional northerly winds respectively. The upper air data includes geopotential height (Z), T, T_d, u and v at standard isobaric levels up to 200 hPa.

The stations in Karnataka for which the prediction of daily precipitation is attempted are shown in Figure 1(d). It is seen from Figure 1(c) that CK is represented well by four observatories. The interior part of the State is not fully represented as continuous long period data were not available for these stations.

All these data are quality checked and missing values are filled up by the daily mean values calculated based on the data from 1981 to 2002. As monsoon season consists of 122 days, the sample size of 2684 days over a period of 22 years taken for calculation of daily mean is considered to be reasonable. If only one missing value is present then the gap is filled using the mean of the previous and the next day values. The parameter having minimum 80% data out of the 2684 days is taken as one of the potential predictor for the development of the POP model.

2.1. Development of the probability of prediction model (POP)

The available surface and upper air parameters selected through the procedure as mentioned above have been considered as potential predictors for development of the POP model by forward step-wise regression.

In the development of the POP model, the value of predictand (precipitation) is taken as 1 if the precipitation occurs and has a value of 1 mm or more in 24 h ending at 0300 UTC of

Table 1. Surface and upper air meteorological variables used as potential predictors of precipitation over Karnataka.

S. no.	Surface and upper air stations	Index number	Meteorological variables
1.	Sambra (BLG)	43198	$MSLP$, T_x, T_n, T, T_w, T_d, RH, V_p, u, v
2.	Gadag (GDG)	43201	$MSLP$, T_x, T_n, T, T_w, T_d, RH, V_p, u, v
3.	Karwar (KWR)	43225	$MSLP$, T_x, T_n, T, T_w, T_d, RH, V_p, u, v
4.	Honavar (HNV)	43226	$MSLP$, T_x, T_n, T, T_w, T_d, RH, V_p, u, v
5.	Chitradurga (CHT)	43233	$MSLP$, T_x, T_n, T, T_w, T_d, RH, V_p, u, v
6.	Mangalore (MNG)	43284	$MSLP$, T_x, T_n, T, $\mathrm{T_w}$, T_d, RH, V_p, u, v
7.	Pannambur (PNB)	43285	$MSLP$, T_x, T_n, T, T_w, T_d, RH, V_p, u, v
8.	Bangalore City (BNG CO)	43295	$MSLP$, T_x, T_n, T, T_w, T_d, RH, V_p, u, v
9.	Bangalore Airport (BNG AP)	43296	$MSLP$, T_x, T_n, T, T_w, T_d, RH, V_p, u, v
10.	Hyderabad (HYD)	43128	Z, T, T_d, u and v at 1000, 850, 700, 500, 400, 300, 200 hPa
11.	Chennai (CHN)	43279	Z, T, T_d, u and v at 1000, 850, 700, 500, 400, 300, 200 hPa
12.	Mangalore (MNG)	43284	Z, T, T_d, u and v at 1000, 850, 700, 500, 400, 300, 200 hPa
13.	Bangalore City (BNG CO)	43295	Z, T, T_d, u and v at 1000, 850, 700, 500, 400, 300, 200 hPa
14.	Trivandrum (TRV)	43371	Z, T, T_d, u and v at 1000, 850, 700, 500, 400, 300, 200 hPa

MSLP is mean sea level pressure, maximum (T_x) and minimum (T_n) temperature, dry bulb temperature (T), wet bulb temperature (T_w) and dew point (T_d), relative humidity (RH), vapour pressure (V_p) and zonal (u) and meridional (v) winds, and Z is geopotential height.

the day. It is taken as 0 if the precipitation does not occur or is less than 1 mm. Hence, the value of predictand varies from 0 to 1. The sigma restricted parameterization and forward stepwise procedure are used to select the predictors from the set of potential predictors as mentioned above. In this criterion, the potential predictors showing 99% level of confidence with the predictand are selected for all the specific locations under consideration (Figure 1(d)). Further screening is done by removing those parameters which do not show significant correlations with the predictand, as they may not explain any significant amount of variance and rather introduce the noise in the multiple regression model. The parameters thus selected have been used to develop the multiple regression model for each station under consideration. The values of predictand are estimated for all observations of the developmental data set using the multiple regression equation. The estimated value of the predictand may be even more/less than 1 depending upon the values of the selected predictors. While the higher value of the predictand favours occurrence, the lower value indicates non-occurrence of precipitation in probabilistic form. The critical threshold value of the estimated predictand is taken as 0.5 to convert the probability forecast into a deterministic forecast of occurrence/non-occurrence of precipitation for each station. For this purpose, if the estimated value of the predictand is greater than 0.5 occurrence of precipitation is considered and if it is less than 0.5, non-occurrence of precipitation is considered.

The statistical POP model has been developed based on data of the summer monsoon season (June–September) during 1981–1996 and data during 1997–2002 have been used for testing the skill of the models. The statistical software, Statistica Utility (1994) has been applied for the forward stepwise regression.

2.2. Forecast verification procedure

The rainfall data for a period of 6 years from 1997 to 2002 is selected for testing the POP model. The rainfall is considered as dichotomous variable and there are numerous threat scores which are the measures of accuracy of forecast for such a variable. The performance of the regression model for the developmental and test datasets has been evaluated following a 2 × 2 contingency table. This procedure uses the contingency table given in Table 2 following Wilks (1995). In this table, the threshold value of 1 mm day^{-1} is chosen to distinguish a rain event from a non-rain event. 'A' signifies the number of correct precipitation prediction events, 'B' is the number of misses, 'C' is number of false alarms and 'D' signifies the occurrence of correct non-precipitation events. The performance of the POP model is evaluated by calculating various threat scores and percentage correct as mentioned in Table 3.

Table 2. Contingency table for verification of forecast for occurrence/non-occurrence of precipitation.

Observed	Forecast	
	Yes	No
Yes	A	B
No	C	D

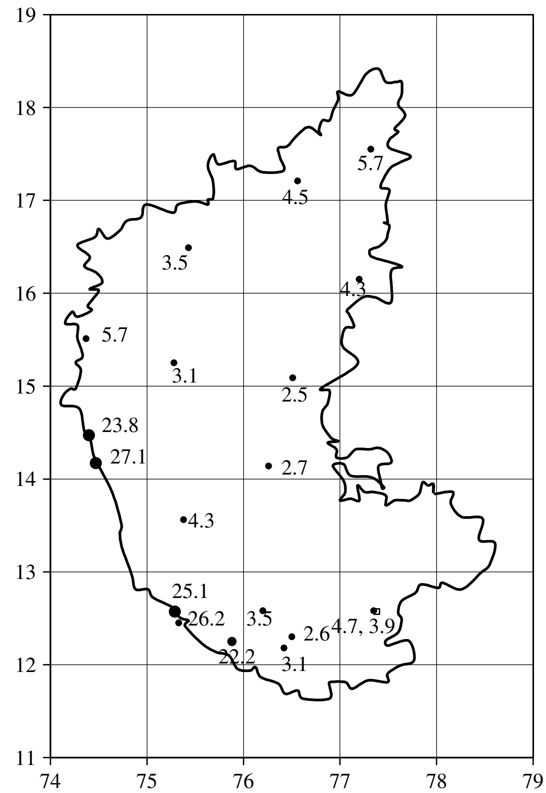

Figure 2. Mean daily rainfall (mm) during monsoon season (June–September) over stations in Karnataka under consideration based on data from 1981 to 2002.

3. Results and discussion

The mean daily rainfall based on data from 1981 to 2002 over different stations in Karnataka is shown in Figure 2. It is seen from this figure that the mean daily rainfall varies from less than 5 mm day^{-1} over the eastern parts of the State to more than 25 mm day^{-1} over the western part of the State. This large spatial variation in daily rainfall over Karnataka is mainly due to the large variation in the physiographic features of the State (Figure 1(a)).

Table 3. Skill scores used for evaluation of the probability of precipitation (POP) model.

S. no	Scores used	Formula
1.	Probability of detection (POD)	$A/(A+B)$
2.	False alarm rate (FAR)	$C/(C+A)$
3.	Correct non-occurrence (CNON)	$D/(C+D)$
4.	Percentage correct (PC)	$((A+D)/(A+B+C+D)) \times 100$
5.	Bias for occurrence (BIAS)	$(A+C)/(A+B)$
6.	Critical success index (CSI)/threat score	$A/(A+B+C)$
7.	Heidke Skill Score (HSS)	$2(AD-BC)/((B^2+C^2+2AD+(B+C)\ (A+D))$

Table 4a. Correlation co-efficients (CC) of the selected predictors with the precipitation over selected stations in coastal Karnataka (CK).

Region	Station	Predictors	CC	Station	Predictors	CC
Coastal Karnataka	1. Sambra	BLG *RH*	0.34	Honavar	MNG T_{d850}	0.15
		HYD u_{850}	0.34		GDG *RH*	0.12
		MNG u	0.28		CHN T_{200}	0.10
		BNG CO v	0.21		BNG CO T_w	−0.15
		BNG AP v	0.20		HYD u_{200}	−0.15
		CHN T_{d500}	0.20		KWR T_x	−0.18
		BLG T_n	0.19		PNB T_n	−0.18
		GDG T_d	0.19		CHN Z_{700}	−0.19
		HYD v_{850}	0.11		HYD v_{200}	−0.26
		CHN v_{850}	−0.11		BLG T_x	−0.32
		TRV v_{200}	−0.20	4. Mangalore	TRV u_{700}	0.36
		GDG T_x	−0.37		BLG T_n	0.32
	2. Karwar	TRV u_{700}	0.4		MNG *RH*	0.30
		MNG *RH*	0.34		BLG V_p	0.28
		HNV *RH*	0.27		BNG u	0.27
		BLG T_d	0.26		BLG T_d	0.23
		BLG T_n	0.25		MNG T_{d700}	0.22
		CHT u	0.23		MNG v	0.17
		CHN T_{d500}	0.22		CHN v_{700}	0.12
		TRV u_{1000}	0.21		BNG T_{d850}	0.12
		MNG v	0.19		CHN v_{1000}	−0.12
		CHN v_{700}	0.17		HYD T_{850}	−0.14
		GDG *RH*	0.16		CHN v_{850}	−0.14
		BNG CO T_{d500}	0.10		BLG T_x	−0.27
		BNG CO V_p	−0.10		BLG *MSLP*	−0.40
		HYD u_{300}	−0.11	5. Pannambur	HYD u_{850}	0.32
		TRV v_{850}	−0.11		BLG T_n	0.31
		KWR TT	−0.12		BLG T_d	0.29
		KWR T_x	−0.21		HNV *RH*	0.26
		HYD v_{200}	−0.27		MNG T_{d700}	0.20
		BLG T_x	−0.35		MNG v	0.16
	3. Honavar	TRV u_{700}	0.39		BNG T_{d500}	0.16
		HYD u_{850}	0.37		CHN v_{700}	0.11
		MNG *RH*	0.33		HYD T_{850}	−0.13
		BLG T_n	0.27		CHN v_{850}	−0.14
		HNV *RH*	0.26		BNG T_{850}	−0.16
		BLG T_w	0.20		BNG T	−0.20
		MNG v	0.20		GDG *MSLP*	−0.40

The relationship between selected predictors and predictand for each station are discussed in Section 3.1. The salient features of the developed POP models and their performance for the independent dataset are discussed in Sections 3.2 and 3.3 respectively. The broad conclusions of the study are presented in Section 4.

3.1. Relationship between selected predictors and the predictand

The correlation co-efficients (CC) between predictors selected for the regression model and the predictand (precipitation), for different stations in CK, SIK and NIK are shown in Tables 4(a–c), 5 and 6 respectively.

3.1.1. Rainfall over CK

The daily rainfall over Sambra in north CK increases with the increase in the *RH* and T_n over Sambra. The increase in T_n indicates increase in cloudiness over the station. The rainfall also increases with the increase in T_d and decrease in T_x over Gadag which lies to the south of it. The decrease in T_x reflects the increase in the cloudiness over the region. Increase in surface westerlies over Mangalore and southerlies over Bangalore are favourable for rainfall over Sambra as they indicate strong south-west monsoon current. Stronger south-westerlies over Hyderabad and a weaker southerly over Chennai at 850 hPa are favourable for rainfall over Sambra. The stronger monsoon circulation over the peninsular region is associated with westerly-southwesterly wind along the coast and northeasterly wind along the east coast, including Chennai. The rainfall over Sambra is more favourable with the increase in the northerly component of wind at 200 hPa over Trivandrum. Hence, if the tropical easterly jet (TEJ) is oriented from northeast to southwest over the extreme south of the peninsula, it is favourable for the occurrence of rainfall over Sambra. Climatologically the axis of the TEJ passes through Chennai-Trivandrum latitude during normal and active monsoon conditions (Rao, 1976).

Almost similar is the case with rainfall over other stations in north CK such as Karwar and Honavar. The rainfall over Karwar increases with increase in T_d and T_n over Sambra, decrease in T_x over Sambra, increase in RH over Honavar and Mangalore and increase in T_d at 500 hPa over Chennai, respectively. The rainfall increases with increase in south-westerlies in lower level along the west coast and increase

Table 4b. Correlation co-efficients (CC) of the selected predictors with the precipitation over selected stations in south interior Karnataka (SIK).

Region	Station	Predictors	CC	Station	Predictors	CC
South interior Karnataka	1. Mandya	BNG T_d	0.23	BNG AP	HNV T_x	−0.10
		BNG CO T_{d700}	0.16		BLG v	−0.12
		CHT RH	0.14		HYD v_{850}	−0.13
		CHN u_{200}	0.11	6. Hassan	MNG u	0.25
		MNG v	−0.10		CHT RH	0.25
		BNG AP u	−0.19		BLG RH	0.21
		HYD u_{850}	−0.19		BNG CO T_{d500}	0.20
		CHT u	−0.25		CHN u_{400}	0.18
	2. Mysore	BNG CO RH	0.23		TRV u_{1000}	0.15
		CHN T_{d500}	0.19		HYD v_{850}	0.14
		MNG u	0.10		BNG AP u	0.12
		GDG u	−0.14		BNG AP RH	0.11
		BNG CO Z_{1000}	−0.16		PNB T_n	−0.12
		CHT u	−0.17	7. Shimoga	CHN u_{850}	0.29
		PNB $MSLP$	−0.18		BLG RH	0.23
		BNG AP T_x	−0.18		HNV RH	0.21
		HYD Z_{850}	−0.20		BNG AP RH	0.21
					PNB u	0.20
	3. Chitradurga	CHT RH	0.36		TRV u_{500}	0.19
		CHN u_{850}	0.30		CHN u_{1000}	0.17
		MNG u	0.29		BNG AP v	0.16
		GDG RH	0.29		GDG RH	0.14
		BNG CO RH	0.29		HYD T_{d850}	0.14
		MNG T_{d700}	0.19		HYD Z_{850}	−0.17
		BNG CO T_{d700}	0.17		MNG Z_{850}	−0.18
		TRV u_{1000}	0.17		KWR T_x	−0.24
		BNG AP v	0.16	8. Madikeri	MNG RH	0.28
		MNG Z_{1000}	−0.18		BLG T_n	0.25
		KWR T_n	−0.21		HYD u_{850}	0.25
	4. BNG City	CHT RH	0.23		BNG CO RH	0.24
		BNG T_d	0.21		MNG T_{d700}	0.23
		MNG T_{d700}	0.20		TRV u_{1000}	0.16
		CHN T_{d500}	0.15		BNG CO T_{d850}	0.11
		HYD u_{850}	−0.12		TRV T_{d700}	0.11
		KWR T_x	−0.13		HYD T_{850}	−0.12
	5. BNG AP	BNG RH	0.22		BNG CO T_{850}	−0.15
		CHT RH	0.21		BLG $MSLP$	−0.33
		BNG u	0.21			

in north-easterlies over Hyderabad in the upper tropospheric levels. The rainfall over Honavar increases with the increase in surface RH over Honavar and Mangalore and with an increase in T_n and decrease in T_x over Sambra. Rainfall further increases with increase in surface southwesterlies over the region and with increase in northeasterlies over Hyderabad at 200 hPa.

In the case of Mangalore, the relationship between the rainfall and the predictors is similar to that of north coastal Karnataka. However, unlike the north coastal stations, the rainfall does not depend significantly on the upper tropospheric parameters.

3.1.2. Rainfall over Western Ghat areas of SIK

The four districts of Chikmangalur, Shimoga, Hassan and Madikeri constitute the western Ghat section of SIK and receive maximum rainfall during the monsoon season. Considering Hassan, its rainfall is more probable with higher moisture content and stronger southwesterlies in lower and middle levels over the coastal regions in association with strong monsoon current. The case with Madikeri and Shimoga districts is similar: as with the south coastal districts, the rainfall is least dependent on the upper tropospheric parameters.

3.1.3. Rainfall over SIK

The relation between rainfall over Bangalore City and the predictors indicates that higher moisture content in lower and middle levels over the region is favourable for rainfall. The rainfall over Bangalore City increases with increase in the easterlies over Hyderabad at 850 hPa. During the weak monsoon conditions, an east-west shear zone develops over the south peninsula in the lower levels which is indicated by the easterlies over Hyderabad. Hence, the weak monsoon conditions with high moisture content in the lower and middle levels are favourable for the occurrence of rainfall over Bangalore City. Considering Bangalore Airport, there is a similar case, though there is variation in the surface based predictors. The case is also similar for stations such as Mandya and Mysore in SIK. However, the rainfall over Mandya increases with decrease in easterly or increase in westerly components of the wind at 200 hPa over Chennai, which occurs during weak monsoon conditions. Chitradurga receives more rainfall during the strong monsoon conditions as its rainfall increases with increase in lower level westerlies over Mangalore and Trivandrum. However, it also increases with the increase of westerlies over Chennai in the lower levels, indicating the

Table 4c. Correlation co-efficients (CC) of the selected predictors with the precipitation over selected stations in north interior Karnataka (NIK).

	Station	Predictors	CC	Station	Predictors	CC
North interior Karnataka	1. Bijapur	GDG *RH*	0.25	Gadag	BLG *MSLP*	−0.23
		HYD T_{d500}	0.17			
		CHN u_{200}	0.15	4. Bellary	BNG CO *RH*	0.19
		TRV u_{500}	0.12		CHT *RH*	0.18
		HYD u_{500}	−0.11		CHN T_{d850}	0.12
		TRV v_{200}	−0.15		TRV v_{200}	−0.14
		BNG AP T_x	−0.21		HYD u_{850}	−0.16
	2. Raichur	GDG *RH*	0.20	5. Bidar	GDG *RH*	0.21
		HYD T_{d500}	0.18		HYD T_{d500}	0.21
		HYD T_{d850}	0.16		HYD T_{d400}	0.19
		HYD u_{400}	−0.13		CHT *T*	−0.15
		PNB T_n	−0.15		HYD u_{400}	−0.15
		CHN T_{1000}	−0.15		PNB T_n	−0.16
	3. Gadag	GDG *RH*	0.27		CHN T_{1000}	−0.18
		CHT *RH*	0.26	6. Gulbarga	HYD T_{d500}	0.21
		MNG *u*	0.21		HYD T_{d700}	0.19
		BLG *RH*	0.19		CHN T_{300}	0.12
		HYD T_{d500}	0.18		GDG *T*	−0.16
		BLG T_n	0.17		TRV v_{200}	−0.16
		HYD Z_{700}	−0.21		CHT *T*	−0.18

Table 5. Main features of the multiple regression equation based probability of precipitation (POP) model for prediction of occurrence/non-occurrence of rainfall.

S. no.	Station	MCC	Variance (%)	F ratio (calculated value)
1.	Sambra	0.57 032	33	71.27 173
2.	Karwar	0.61 201	37	60.39 133
3.	Honavar	0.60 011	36	63.49 975
4.	Mangalore	0.58 284	34	58.04 439
5.	Pannambur	0.57 932	34	64.65 685
6.	Mandya	0.39 431	16	29.50 364
7.	Mysore	0.43 270	19	29.48 579
8.	Chitradurga	0.53 187	28	42.0 128
9.	Bangalore City	0.40 501	16	31.44 346
10.	Bangalore Airport	0.42 391	18	30.05 812
11.	Hassan	0.49 587	25	34.72 527
12.	Shimoga	0.44 228	20	31.1 275
13.	Madikeri	0.49 356	24	47.61 423
14.	Bijapur	0.35 171	12	30.20 856
15.	Raichur	0.37 159	14	23.68 492
16.	Gadag	0.44 211	20	33.33 617
17.	Bellary	0.37 144	14	21.96 085
18.	Bidar	0.40 851	17	32.09 864
19.	Gulbarga	0.38 119	15	27.24 458

Table 6. Skill scores of location specific forecast of daily precipitation over Bangalore city based on the conventional method and probability of precipitation (POP) model.

S. no.	Score parameters	Conventional method	POP model
1.	Probability of detection (POD)	93	65
2.	False alarm rate (FAR)	65	55
3.	Correct non-occurrence (CNON)	21	51
4.	Percentage correct (PC)	44	56
5.	Bias for occurrence (BIAS)	261	144
6.	Critical success index (CSI)/threat score	34	36
7.	Heidke Skill Score (HSS)	10	14

fact that Chitradurga may receive good rainfall during weak monsoon conditions also.

3.1.4. Rainfall over NIK

Rainfall over Bellary is more probable during weak monsoon conditions as it increases with the increase in easterlies over Hyderabad in the lower levels. Such a type of flow is possible with the east–west shear zone over the south peninsula in lower levels over south-west and adjoining west-central Bay of Bengal. However, it also increases with increase in the northerlies over Trivandrum in the upper tropospheric level. The condition is similar in the drought-prone districts of Bijapur, Raichur, Bidar and Gulbarga, which receive good rainfall in weak monsoon condition.

Considering Gadag, a lower thickness of the atmosphere over Hyderabad in the lower levels, lower MSLP over Sambra, stronger surface westerlies over Mangalore are favourable for rainfall over Gadag. Hence, strong monsoon condition favours rainfall over Gadag, unlike other stations of NIK.

Comparing the predictors for different stations and summarizing the results, the strong monsoon condition with stronger south-westerlies in lower and middle levels and higher relative humidity up to 500 hPa are favourable for the occurrence of rainfall over CK and Ghat areas of SIK. In addition, strong northeasterly wind in association with the TEJ favours the occurrence of rainfall over the northern part of CK. Weak monsoon conditions leading to development of the east–west shear zone across the south peninsula in the lower levels, along with the high moisture content in the lower and middle levels, are favourable for occurrence of rainfall over the remaining parts of Karnataka. However, the upper tropospheric north-easterlies along the Hyderabad latitude in association with TEJ favour the occurrence of rainfall over the drought-prone districts of NIK, confirming the earlier findings (Rao, 1976). The rainfall over

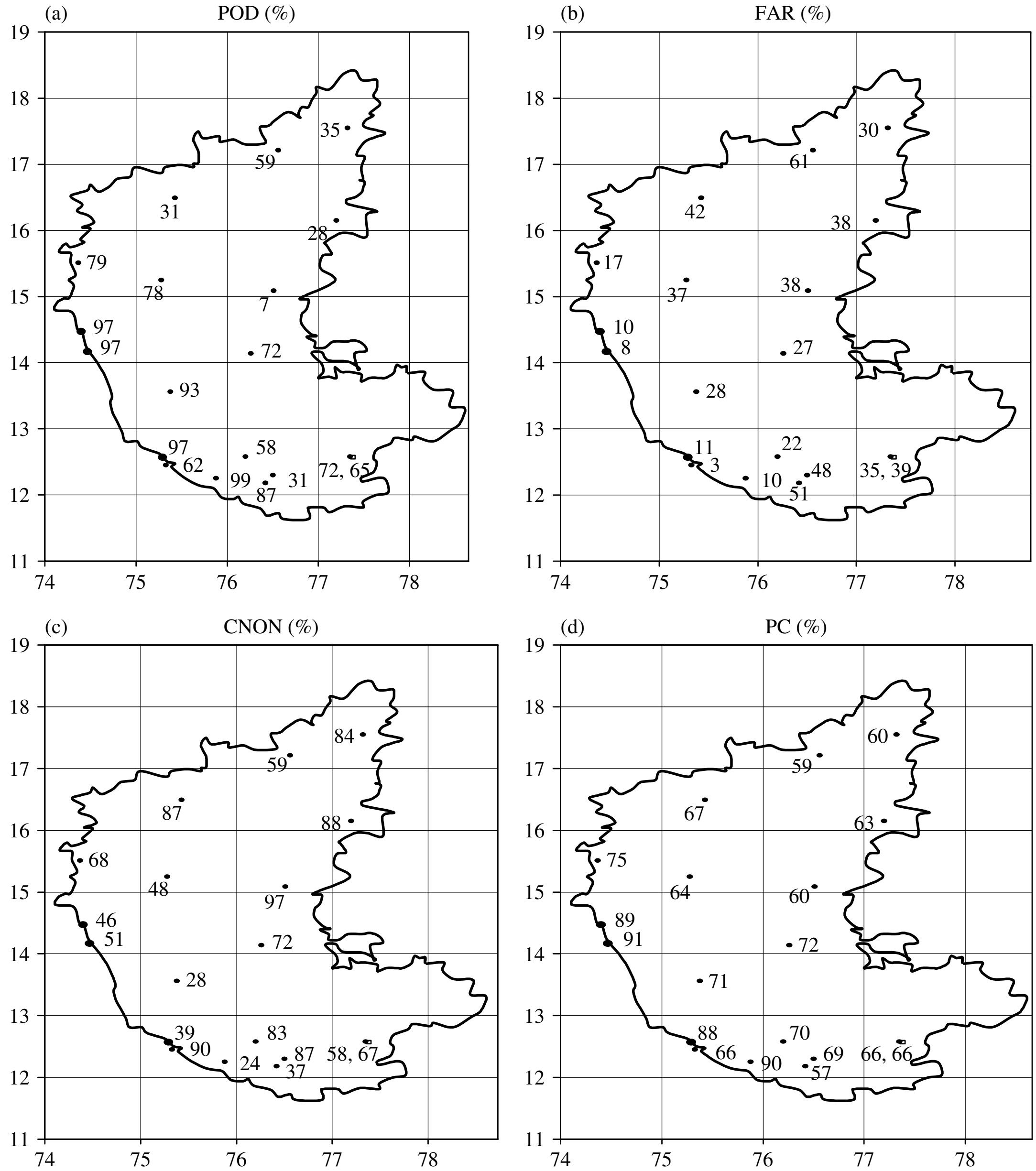

Figure 3. (a) Probability of detection (POD). (b) False alarm rate (FAR). (c) Correct non-occurrence (CNON). (d) Percentage correct (PC). (e) Bias for occurrence (BIAS). (f) Critical success index (CSI)/Threat score (CSI). (g) Heidke Skill Score (HSS) (%) of forecast rainfall over different stations under consideration during test period based on probability of precipitation (POP) model.

any station depends on both the thermodynamic and dynamic parameters. The dynamic parameters are more dominant for the rainfall over CK and the adjoining Ghat areas of SIK. The role of dynamic parameters is less and the rainfall is more dependent on the thermodynamic parameters for the remaining parts of the state. This may be due to the fact that the rainfall over the interior part is mainly convective and hence depends on the thermodynamic instability and moisture availability over the region. Considering the number of predictors required for the predictions of rainfall over different stations under consideration, the number of predictors is significantly higher for the stations in CK and the Ghat areas of SIK (more than 10). It gradually decreases over the south interior districts and is significantly less, ranging from five and seven, over the stations in NIK. It indicates that the rainfall over the orographically dominant region of CK and Ghat areas of SIK are more complex in nature. The rainfall over northern part of CK and NIK depends on upper tropospheric parameters in addition to lower and middle tropospheric parameters, whereas the rainfall over other stations is least dependent on upper tropospheric parameters.

3.2. Salient features of the POP model

The main features of the POP model for prediction of occurrence/non-occurrence of rainfall are given in Table 5. It is seen from this table that multiple correlation co-efficient (MCC) of the selected predictors with the predictand is significant at the 95% confidence level. The variance accounted by the selected predictors is less than 15% over Bellary, Gulbarga, Raichur, Bijapur which are the drought-prone districts. It is more than 30% over coastal stations. The calculated F ratio is significant for all the stations at the 95% confidence level. However, it is higher over coastal stations.

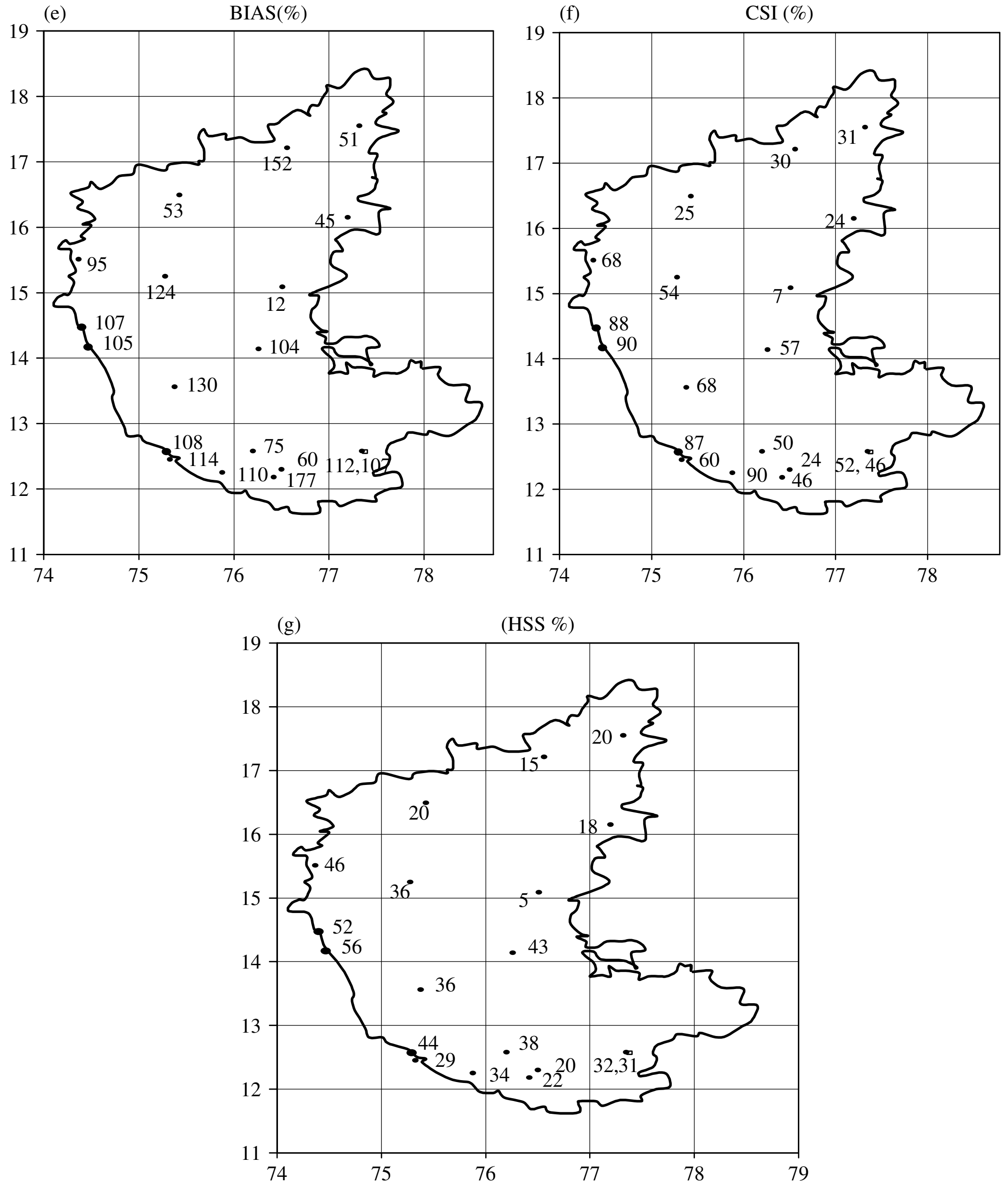

Figure 3. (*Continued*).

3.3. Performance of the POP model

Different skill scores, as mentioned in Table 3, are calculated based on the developmental and independent datasets. However, the results are presented in Figure 3 for independent data set only, as scores will obviously be higher for the developmental period. Considering the probability of detection (POD) (Figure 3(a)), it is more than 95% over the coastal areas and less than 50% over the northeastern part of the State. It is seen that the POD is higher over the high rainfall region and low over the drought prone regions in northeastern part of the State. Hence, the developed model, as any other model, is biased towards the climatology of the region. As the missing rate (MR) is opposite to POD, it is very high (>50%) over the eastern parts of NIK in both the developmental and test periods but is less along the coast (not shown). Considering the false alarm rate (FAR), it is higher (>30%) over the drought-prone regions of NIK and low rainfall region of SIK (Figure 3(b)).

The correct non-occurrence (CNON) of rainfall is relatively less (<50%) over CK and adjoining Ghat areas (Figure 3(c)). Considering both occurrence and non-occurrence of rainfall together, the percentage correct (PC) is higher along the west coast and less over the interior parts of the State (Figure 3(d)).

The bias score measures the ratio of the frequency of forecast events to the frequency of observed events. Bias score more or less than 1 implies that the model has a tendency to over forecast (bias >1) or under forecast (bias <1) the rainfall events. It is seen from the Figure 3(e) that the rainfall is over predicted along the west coast and under predicted over the drought prone areas of NIK.

The critical success index (CSI) or the threat score refers refer to the accuracy when the correct negatives have been removed from consideration and is shown in Figure 3(f). This figure also shows higher values of CSI along the west coast and lower in interior part of the State. The Hiedke Skill Score

(HSS), which compares the forecast with the random forecast also shows similar spatial variation (Figure 3(g)).

In Karnataka State, the location specific forecast is issued by IMD for Bangalore city only during the period of study. Hence, the results of the POP model have been compared with the local forecast issued by the IMD for Bangalore City only. To verify the efficiency of the regression model for Bangalore city, its forecast was verified against the local forecast issued by the Meteorological Centre, Bangalore, using conventional synoptic and upper air charts during 1999–2002. Table 6 gives the values of different score parameters based on the conventional method and the POP model for Bangalore city. It is seen from Table 6 that the FAR, CNON, CSI, PC and HSS are higher for the POP model which indicates that the developed POP model is skillful and can be used operationally for location specific forecast of daily precipitation over Karnataka during the monsoon season.

4. Conclusions

The following broad conclusions can be drawn from the above results and discussion.

1. The strong monsoon condition with stronger southwesterlies in the lower and middle levels and higher relative humidity up to 500 hPa are favourable for the occurrence of rainfall over the coastal Karnataka (CK) and Ghat areas of south interior Karnataka (SIK). In addition, strong north-easterly in association with the Tropical; Easterly Jet (TEJ) favours the occurrence of rainfall over northern part of CK.
2. Weak monsoon conditions leading to development of the east–west shear zone across the south of the peninsula in the lower levels along with the high moisture content in the lower and middle levels are favourable for the occurrence of rainfall over the remaining parts of Karnataka. However the upper tropospheric northeasterlies along the Hyderabad latitude in association with TEJ favour the occurrence of rainfall over the drought prone districts of north interior Karnataka (NIK).
3. Comparing the role of dynamic and thermodynamic predictors, the dynamic parameters play a more significant role over the CK and Ghat areas of SIK, whereas the thermodynamic parameters play a more significant role for the remaining parts of the state, indicating the dominant role of convection for rainfall over this region.
4. The POP model performs very well with percentages of correct forecasts for occurrence/non-occurrence of precipitation being 57–91% for the independent data. Comparing the results of the developed model with that of the conventional method of forecast for Bangalore City, there is an improvement of PC from 44 to 56%. However, the performance of the developed POP model needs further improvement with respect to the stations in the interior parts of Karnataka as the skill scores are relatively less for the independent dataset. This may be possible with the inclusion of numerical model outputs and non-conventional datasets over south peninsula, Bay of Bengal and Arabian Sea region in the mesoscale network as potential predictors for the selection of actual predictors.

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References

India Meteorological Department (IMD). 1984. Climate of Karnataka State.

Jadhav SK. 2002. Summer monsoon low pressure systems over the Indian region and their relationship with subdivisional rainfall. *Mausam* **53**: 177–186.

Kruzinga S. 1989. Statistical interpretation of ECMWF products in Dutch weather service. *ECMWF Seminar/Workshop on Interpretation of NWP Products*. ECMWF: Reading, United Kingdom; 360–365.

Mohanty UC, Mohapatra M. 2007. Prediction of occurrence and quantity of daily summer monsoon precipitation over Orissa (India). *Meteorological Applications* **14**: 95–103.

Mohanty UC, Ravi N, Madan OP. 2001. Forecasting precipitation over Delhi during southwest monsoon season. *Meteorological Applications* **8**: 11–21.

Mooley DA, Shukla J. 1989. Main features of the westward moving low pressure systems which form near the Indian region during the summer monsoon season and their relation to the monsoon rainfall. *Mausam* **40**: 137–152.

Nigam S. 1994. Dynamical basis for the Asian summer monsoon rainfall – El Nino relationship. *Journal of Climate* **7**: 1750–1771.

Ramamurty K. 1969. Some aspects of break in the Indian Southwest Monsoon during July and August. FMU Report No. IV-18.3, India Meteorological Department: Pune.

Rao YP. 1976. *Southwest Monsoon*, *Meteorological Monograph Synoptic Meteorology*, 1/1976. India Meteorological Department: Pune.

Statistica Utility. 1994. *Statistica for Windows*, Vol. III. Statistics II, Statsoft: Tulsa, OK; 958.

Webster PJ, Yang S. 1992. Monsoon and ENSO: selectively interacting systems. *Quarterly Journal of the Royal Meteorological Society* **118**: 877–900.

Wilks DS. 1995. *Statistical Methods in Atmospheric Sciences*. Academic Press: San Diego, CA; 466.

