Meteorol. Appl. 11, 189–199 (2004) DOI:10.1017/S1350482704001306

Prediction of southern Indian winter monsoon rainfall from September local upper-air temperatures

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An attempt is made to establish a probable link between mean September upper-air temperatures at Indian stations and the ensuing winter monsoon rainfall over eight individual meteorological subdivisions of southern India where the winter monsoon accounts for a large percentage of mean annual rainfall. For this purpose, linear correlations between the winter monsoon rainfall of the subdivisions and the mean September upper-air temperatures and vertical temperature differences at the Indian stations have been evaluated using the data set for the period 1959 to 1988. The inter-correlations between the significant parameters were calculated and then tested to derive multiple linear regression equations containing the best combination of predictor variables. There is a significant positive relationship between the winter monsoon rainfall over Tamilnadu and the mean temperature difference at 500–300 hPa levels at Nagpur in September. Secondly, the winter monsoon rainfall over Coastal Andhra Pradesh is significantly negatively correlated with the mean September temperature over Visakhapatnam at 700 hPa. The most significant inverse relationship exists between the winter monsoon rainfall over Rayalaseema and the mean September temperature over Visakhapatnam at 850 hPa. By using significant parameters, algorithms have been formulated and tested for each subdivision for six succeeding years, 1989–94. These results assisted to some extent in the prediction of winter monsoon rainfall over subdivisions of South India. Finally, stationarity is tested by evaluating another set of multiple linear regression equations using the data set for the period 1965–94 and then testing the algorithms on the preceding six years.

1. Introduction

The winter monsoon is also known as the northeast (NE) monsoon over South India during October through December, and rainfall is highly variable both spatially and temporally. In this paper, the authors assess spatial variations in the predictability of winter monsoon rainfall over southern India following the studies conducted for the prediction of Indian summer monsoon rainfall (Murakami 1977; Banerjee et al. 1978; Joseph 1978; Parthasarathy & Panth 1985; Mooley et al. 1986; Hastenrath 1987; Mooley & Shukla 1987; Bhanu Kumar 1988; Gowariker et al. 1989, 1991; Parthasarathy et al. 1990; Bhalme et al. 1990; Thapliyal & Kulshrestha 1992; Bhaskara Rao et al. 2001; Thapliyal & Rajeevan 2003). Rainfall in the winter monsoon season over south peninsular India is considerably large in general and particularly crucial in Tamilnadu. For example, mean seasonal rainfall for the 129 years used in this study reveals that the subdivisions of Kerala, Tamilnadu and Coastal Andhra Pradesh received 48 cm, 45 cm and 37 cm respectively. The rainfall during this season is due to synoptic/sub-synoptic systems like tropical cyclones, depressions, easterly waves, north–south trough activity and coastal convergence (India Meteorological Department 1973, 1979, 1987, 1996; Srinivasan & Ramamurthy 1973b).

Eight meteorological subdivisions of South India are influenced by these weather systems from the Bay of Bengal, and necessary water is stored in this season for hydroelectric power production, irrigation of crops through dams, and in tanks for drinking purposes. Hence these rainfall amounts are very significant in this season over South India. Any prediction of winter monsoon rainfall is of paramount importance for the economy of the study region. De et al. (1992) pointed out that spells of above normal rainfall occurred in only two or three weeks of the winter monsoon season over South India even during years of normal or above normal rainfall. Adequate steps have to be taken for storing such occasional high amounts of rainfall. There have been several studies on the winter monsoon circulation and statistical properties (Rao 1953; Rao 1963; Thiruvengadathan 1965; Srinivasan & Ramamurthy 1973a, 1973b; Dhar et al. 1982a, 1982b; De et al. 1992; Sontakke 1993; Singh & Sontakke 1999; Nageswara Rao 1999; Bhanu Kumar et al. 2003a, 2003b; Naga Ratna et al. 2003).

The synoptic circulation changes observed with the onset of the Indian winter monsoon are: (i) the retreat of summer monsoon rains from India during September–October; (ii) the reversal of lower-level winds from southwesterlies to northeasterlies; and (iii) an increase in rainfall over parts of south peninsular India (Rao 1963; India Meteorological Department 1973). The Winter Monsoon Experiment 1979 revealed several important features: summer monsoon semi-permanent systems over India and neighbouring regions – the Mascerene high, Somali jet, Tibetan anticyclone, easterly jet stream over south India and monsoon trough along the Ganges valley, etc. – are replaced by the Siberian anticyclone, cold surges from the Siberian high, Western Pacific high, subtropical jet stream over north India and monsoon trough over Indonesia during the winter monsoon season. Jayanthi & Govindachari (1999) noticed an all-time record of NE monsoon rainfall over Tamilnadu in 1997 and this also happened to be in the year of an intense El Niño event. During this season, the general wind flow in the lower levels was predominantly easterly with strong westerlies aloft, and this situation generated a strong vertical wind shear over the study region for excess rainfall. Secondly, significant easterly waves are also associated with excessive rainfall in Tamilnadu. They also evaluated a statistical relationship between El Niño and rainfall over Tamilnadu, and commented on the fact that in more than 80% of El Niño years Tamilnadu received above normal rainfall. According to De & Mukhopadhyay (1999), the frequency of cyclonic systems formed is lower during the ENSO years compared to that during Anti ENSO years. However, during ENSO years these cyclonic systems follow a more westerly path and cross Tamilnadu and the south Andhra coast, thus giving enhanced precipitation. During Anti ENSO years, these cyclonic systems move in a more northerly direction and often recurve and hit either West Bengal or the Bangladesh coast. During ENSO years, the mean ridge line at 200 hPa level in the NE monsoon is around 13° N, while it is situated at 16° N during Anti ENSO years.

There have been few attempts to predict winter monsoon rainfall. Doraiswamy Iyer (1941) studied the forecasting of NE monsoon rainfall over south Chennai. Later, Rao & Jagannathan (1953) observed large rainfall amounts over Tamilnadu due to depressions or cyclonic storms in the Bay of Bengal that were moving westwards and striking the Coromandel coast. Deficient winter monsoon rainfall occurs when these systems move in a northerly direction without striking the Coromandel coast. Further, Sen Gupta (1960) pointed out that the northward location of the subtropical circulation, which appears in the sunspot minimum, favours disturbances hitting the Madras coast, thus causing large amounts of rainfall. Rao (1963) noted the following favourable atmospheric circulations for excess winter monsoon rainfall: (i) the absence of a blocking high in the European portion of the former USSR; (ii) the location of the westward portion of the subtropical high at a level of 500 hPa near the eastern coast of the country; (iii) a weak northerly wind component at lower levels over Tamilnadu; and (iv) a strong southerly component at higher levels. Further, Subbaramayya (1976) found that the NE monsoon rainfall over the Coromandel coast is associated with the equatorial trough, and the disturbances in the equatorial trough and the adjoining easterlies.

Raj (1989) screened several upper-air and surface parameters of representative stations in India, and derived linear regression equations to predict winter monsoon rainfall in four subdivisions of South India. Later, Raj et al. (1993) continued the above study with six zonal and meridional wind predictors in August and September from Chennai and Thiruvanthapuram, and developed a prediction algorithm for NE monsoon rainfall by adopting a technique of stepwise screening. The developed multiple linear regression equation explained 48.5% of the variation with a standard error of 18%. More recently, Raj (1998) used wind data for 10 stations and evaluated a prediction algorithm for rainfall in Tamilnadu using six local predictors: (i) 200 hPa zonal wind in April at Mumbai, Chennai, Minicoy, Trivandrum and Hyderabad; (ii) 150 hPa meridional wind in April at Mumbai and Ahmedabad; (iii) 150 hPa temperature in June–September at Port-Blair and Hyderabad; (iv) 850 hPa wind speed in August and September over Trivandrum; (v) 150 hPa zonal wind in August over Trivandrum; and (vi) 300 hPa zonal wind in September over Trivandrum. By using the linear regression technique, he formulated an equation with each predictor and calculated predicted values of rainfall from each individual regression equation. Thus the final forecast is the weighted mean of individual forecasts of several parameters, the weights being the squares of the respective correlation coefficients. The above system of equations explained between 65 and 75% of the variation in rainfall with a standard error of 13–15%. The predictors used in the above study differ from those used in the present study. Our approach here is simpler and covers eight meteorological subdivisions by using local upper-air temperatures in September only. Increasing the number of predictors will definitely improve the forecast, as shown by Raj et al. (1993; 1998).

There are also several studies relating to the prediction of NE monsoon rainfall using predictors such as El Niño, Southern Oscillation, Indian Ocean Dipole, etc. (Ropelewski & Halpert 1987; Sridharan & Muthuswamy 1990; Singh & Chattopadhyay 1998; Jayanthi & Govindachari 1999; De & Mukhopadhyay

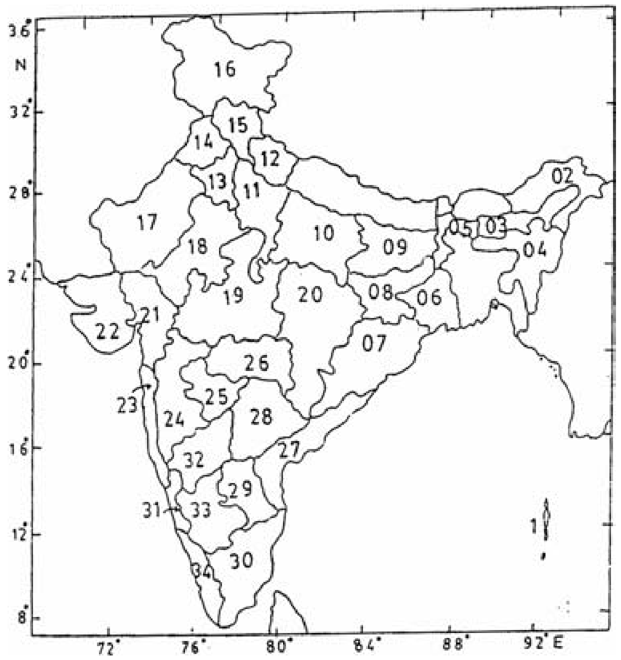

Figure 1. *Meteorological subdivisions affected by winter monsoon: Coastal Andhra Pradesh (27), Telangana (28), Rayalaseema (29), Tamilnadu (30), Coastal Karnataka (31) North Interior Karnataka (32), South Interior Karnataka (33) and Kerala (34).*

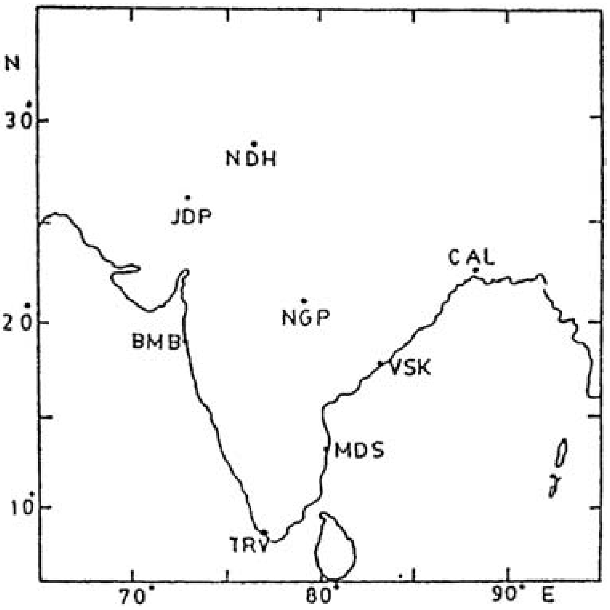

Figure 2. *Locations of the stations: Thiruvananthapuram – TRV, Chennai – MDS, Mumbai – BMB, Visakhapatnam – VSK, Nagpur – NGP, Kolkata – CAL, New Delhi – NDH and Jodhpur – JDP.*

1999; Medha Khole & De 2003; Bhanu Kumar et al. 2003b). El Niño generally appears in the months of December, January and sometimes February, and it persists even in later months and influences the Indian summer as well as winter monsoon activity. Secondly, there is an inverse relationship between NE monsoon rainfall over Tamilnadu and the preceding March–April–May SOI (Singh & Chattopadhyay 1998). A significant positive relationship with SSTs of Niño-4 region during June, July and August is also detected. Thus an El-Niño/ENSO episode generally enhances NE monsoon rainfall.

The utility of forecasts for large areas is less though the forecast skill is high in a statistical sense. Long-range forecasts shall be attempted for a homogeneous region in the sense that the temporal variations in the region are similar. On the other hand, if the forecasts are made for a large area in which the rainfall variations are similar, the total variability of the rainfall in the whole region would be less and the forecast skill could be high. However, the accuracy of the forecast in different parts of region would be less.

The main aim of this paper is to investigate the extent to which local upper-air temperatures and vertical temperature differences at different stations over India in September could be used to predict winter monsoon rainfall over eight meteorological subdivisions of south peninsular India separately (Figure 1) using linear correlation and regression techniques. This is based on the premise that the vagaries of the ensuing winter monsoon should be linked to temperature parameters over India in September. Important circulation as well as thermal changes, which begin in the second week of September, lead to winter type conditions over India. September temperature parameters over Indian stations act as precursors for winter monsoon activity over south peninsular India.

2. Data and methods

This study will utilise two main data sets: mean September upper-level temperatures for a number of Indian stations, and winter monsoon rainfall over south peninsular India. Mean upper-air temperature data from 850, 700, 500, 300, 200, 150 and 100 hPa for September of eight Indian stations for the 36-year period 1959–94 were used: Thiruvananthapuram-TRV (8.29° N, 76.57° E), Chennai-MDS (13.00° N, 80.11° E), Mumbai-BMB (19.07° N, 72.51° E), Visakhapatnam-VSK (17.42° N, 83.18° E), Nagpur-NGP (21.06° N, 79.03° E), Kolkata-CAL (22.39° N, 88.27° E), New Delhi-NDH (28.35° N, 77.12° E) and Jodhpur-JDP (26.18° N, 73.01° E). Many of above stations (Figure 2) are situated under the influence of the subtropical ridge in the middle and upper levels over south India, which reaches its peak intensity during the winter monsoon. These data were extracted from the monthly climatic means published by the NOAA/World Meteorological Organization. The reason for taking the September mean upper-air temperature as an indicator is that the influence of the upper-air temperature at the end of the Indian summer monsoon season may exercise some influence on the Indian winter monsoon also. This is similar to the influence of April/May upper-air temperature on Indian summer minsoon rainfall (Bhaskara Rao et al. 2001). Furthermore, September mean upper-air temperatures mark the transition from the summer monsoon to the winter monsoon over India.

Parthasarathy et al. (1995) prepared monthly rainfall data for 29 subdivisions by considering 306 well-distributed stations (one from each of the districts in the plain regions) by giving appropriate weightings for each station in the calculation of subdivisional rainfall. In order to maintain the continuity of the series, they considered 90% of the country's total area, but excluded hilly regions (four subdivisions) owing to the sparse rain gauge network, and islands in the Arabian Sea and Bay of Bengal (two subdivisions). For the present purpose, the rainfall data for the October–December season for the years 1959–94 were taken from the published report of Parthasarathy et al. (1995) for the following eight meteorological subdivisions shown in Figure 1: Coastal Andhra Pradesh (27), Telangana (28), Rayalaseema (29), Tamilnadu (30), Coastal Karnataka (31), North Interior Karnataka (32), South Interior Karnataka (33) and Kerala (34).

The antecedent upper-air mean monthly temperatures at Indian stations in September may provide some important signals to predict winter monsoon rainfall over the above-mentioned meteorological subdivisions. For the eight stations, the mean upper-air temperatures at the levels 850, 700, 500, 300, 200, 150 and 100 hPa and mean upper-air temperature differences between 850 and 700 hPa; 700 and 500 hPa, 500 and 300 hPa, 300 and 200 hPa, 200 and 150 hPa, 150 and 100 hPa, 850 and 500 hPa and 500 and 200 hPa were calculated. The linear correlations (Pearson product moment correlation coefficients) between these parameters and the winter monsoon rainfall of each of the eight subdivisions for the 30-year period 1959 to 1988 were evaluated separately. The intercorrelations between the parameters were calculated to determine the interdependency of the parameters, but these results are not presented. The significance of the correlations and the intercorrelations were tested by using the Student's t-test. Correlations with values of 0.57, 0.46, 0.36 and 0.31 are significant at the 0.1%, 1%, 5% and 10% levels respectively. The significant parameters are highlighted for different subdivisions (Table 1). Upper-air temperatures at Visakhapatnam strongly influence the winter monsoon rainfall of six subdivisions. This may be due to its geographical location and the fact that it is under the influence of the subtropical ridge. First, the winter monsoon influences this station more than most of the other south Indian stations. The parameters, which are showing statistically insignificant intercorrelations between themselves and statistically significant correlations with winter monsoon rainfall, are considered in formulating regression equations. Multiple regression equations were evaluated for many sets of parameters; each set consists of two or three parameters. In this study of the forecasting of rainfall over each meteorological subdivision, the algorithms developed by the authors contain two or three parameters. The model's multiple correlation coefficients (MCC) were calculated and their significance was determined; a coefficient of determination (COD) was also calculated for all the equations. The equation with the most significant MCC was taken as the forecasting equation. This type of analysis was extended to the eight subdivisions in the winter monsoon region of India. The forecasting equations were then tested using independent data for the six years 1989 to 1994.

To establish the stationarity of the relationships between the winter monsoon rainfall and the September temperature parameters, the period 1965 to 1994 is also considered for formulating the linear multiple regression equation for winter monsoon rainfall of each meteorological subdivision with the corresponding temperature parameters. These equations are then tested over the years 1959 to 1964.

Atmospheric stability/instability in the troposphere is considered in terms of temperature differences at different levels for different stations and this process enhances the number of significant parameters for forecasting of winter monsoon rainfall. Further, the rate of temperature change with height is as equally valid a predictor of rainfall as temperature at specified levels.

So far, there have been no attempts to assess the predictability of winter monsoon rainfall over eight subdivisions, and hence the authors attempted this in view of the importance of mean upper-air temperature of September over India on winter monsoon rainfall south of 20° N in India.

3. Results and discussion

3.1. Coastal Andhra Pradesh (27)

Figure 1 shows the location of the Coastal Andhra Pradesh (CAP) meteorological subdivision. The rainfall of Coastal Andhra Pradesh during 1959 to 1988 is significantly related to 17 mean upper-air September temperature parameters (Table 1). Many regression equations were evaluated with different sets of parameters which were not significantly intercorrelated. It was found that the mean temperature at 700 hPa at Visakhapatnam ($T_{vsk\ (700)}$), the 300–200 hPa temperature difference at Nagpur ($T_{ngp(300-200)}$) and the mean 850–500 hPa temperature difference at Chennai ($T_{mds(850-500)}$) have significant correlations of –0.46, 0.42 and 0.38 respectively with Andhra Pradesh rainfall. The first temperature parameter has an inverse relationship with the monsoon rainfall, while the second and third parameters show a positive relationship. The decrease in the mean September 700 hPa temperature at Visakhapatnam favours above-normal winter monsoon

Table 1. *Parameters (significant at more than 10% level) for winter monsoon rainfall of different subdivisions (Coastal Andhra Pradesh – CAP, Telangana – TL, Rayalaseema – RS, Tamilnadu – TN, North Interior Karnataka – NIK, South Interior Karnataka – SIK, Coastal Karnataka – CK and Kerala – KL. The parameters used in the forecasting model are indicated by bold font).*

Parameter	CAP	TL	RS	TN	NIK	SIK	CK	KL	No. of times parameter repeated
trv850							0.38		1
trv700							**0.39**		1
trv100		−0.37			−0.30				2
trv300-200	0.36								1
mds850			−0.30		**−0.36**				2
mds850-700	0.36				**−0.42**				2
mds850-500	**0.38**			0.35					2
mds300-200		0.40							1
bmb850		**−0.36**						**0.35**	2
bmb100		−0.39					0.35		2
bmb850-700	0.42								1
bmb850-500						−0.30			1
bmb700-500						**−0.34**	**−0.38**		2
bmb200-150		0.40							1
bmb150-100	−0.37						−0.32		2
vsk850		**−0.41**	**−0.53**		−0.44		**−0.40**	**−0.33**	5
vsk700	**−0.46**		−0.47						2
vsk500	−0.30		−0.32				−0.30		3
vsk300								−0.31	1
vsk200			−0.32						1
vsk150		−0.37	−0.33						2
vsk100		−0.56	−0.46		−0.52				3
vsk200-150		**0.52**							1
vsk150-100		0.42			0.41				2
ngp300				−0.31					1
ngp200				−0.32			0.36		2
ngp150							0.34		1
ngp500-300				**0.43**					1
ngp500-200	0.38			0.38					2
ngp300-200	**0.42**						−0.30		2
ngp150-100				−0.30					1
cal200	−0.30								1
cal150	−0.30								1
cal500-300	0.38								1
cal500-200	0.35		0.31						2
cal300-200			0.32						1
cal200-150	0.39		0.30						2
cal150-100	−0.54								1
ndh850			**−0.36**	−0.37	**−0.33**				3
ndh100							0.30		1
ndh150-100	−0.46								1
jdp850				−0.30					1
jdp500				**−0.37**				**−0.32**	2
jdp300				−0.33					1
jdp500-300					−0.34				1
jdp500–200							−0.31		1
jdp200-150				**0.35**					1
jdp150-100	−0.51							−0.41	2
Total number of parameters	17	10	11	11	8	2	12	5	

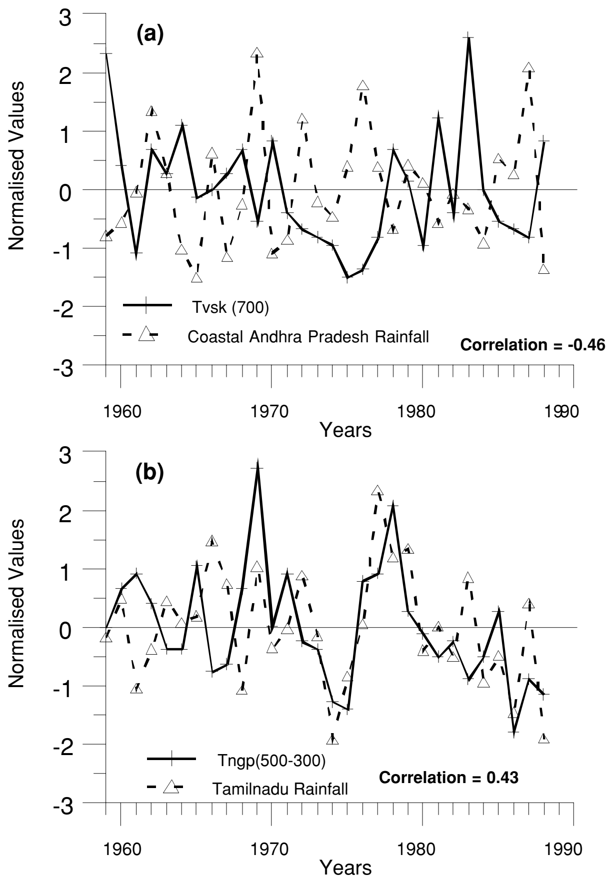

Figure 3. *Time series of normalised values of (a) winter monsoon rainfall of Coastal Andhra Pradesh and the parameter,* $T_{vsk(700)}$*; and (b) winter monsoon rainfall of Tamilnadu and the parameter,* $T_{ngp(500-300)}$.

rainfall in the above region. Figure 3a clearly indicates this inverse relationship; through the entire 30-year period (1959–88), the relationship holds well in 22 of those years. Secondly, higher values of the latter two parameters tend to result in above average rainfall. The MCC for the regression model containing these three parameters is 0.63, which is significant at the 0.1% level. The coefficient of determination is 100*(MCC)^2. Here COD is 40% and the standard error of the observed totals (SE) is 2.64 cm. The significant MCC suggests the following algorithm for the prediction of winter monsoon rainfall over Coastal Andhra Pradesh (R_{CAP} in cm):

$$R_{CAP} = -136.62 - 7.28\ T_{vsk(700)} + 5.21\ T_{ngp(300-200)} + 5.52\ T_{mds(850-500)} \tag{1a}$$

The above equation was tested over the period 1989 to 1994 and the actual rainfall (AR), predicted rainfall (PR) and errors (E) are presented in Table 2.

The model estimate is good for 1992. The errors in 1989, 1991 and 1993 are similar. Data are not available for 1994. However, the estimated value in 1989 is far from the actual value. The same is also true of 1990, 1991 and 1993. The reason for this needs to be investigated. However, the winter monsoon in 1989 for this subdivision is poor and an extreme event according to the India Meteorological Department.

The above three parameters showed significant relationships with the rainfall of Coastal Andhra Pradesh during the period 1965 to 1994 with the following forecasting equation:

$$R_{CAP} = -178.65 - 7.71\ T_{vsk(700)} + 6.82\ T_{ngp(300-200)} + 5.97\ T_{mds(850-500)} \tag{1b}$$

The equation is slightly improved with MCC of 0.73 and COD of 53% when compared with equation 1a. The SE is 2.71 cm. PR values are good in the years 1964, 1963 and 1959 (Table 2). The model performs poorly over the remaining years.

Deriving the regression equation over a different time period did not change the sign of the regression coefficients.

3.2. Telangana (28)

There are 10 significant thermal parameters (Table 1) for this division's winter monsoon rainfall (TL). Out of these, the parameters $T_{vsk\ (200-150)}$, $T_{vsk\ (850)}$ and $T_{bmb\ (850)}$ yielded the best fit. These parameters show significant correlations 0.52, −0.41 and −0.36 respectively – with winter rainfall. These correlation coefficients indicate a positive relation between $T_{vsk\ (200-150)}$ and rainfall; inverse relationships exist between the last two parameters and rainfall. The model's MCC of 0.63 is significant at the 0.1% level with a COD of 40%, leading to the following regression equation:

$$R_{TL} = 46.24 + 2.9\ T_{vsk(200-150)} - 2.90\ T_{vsk(850)} - 0.94\ T_{bmb(850)} \tag{2a}$$

The PR and AR amounts over Telangana are tabulated (Table 2). The SE is 1.3 cm. The PR value is good for 1993. The errors in predicted values in 1991 and 1992 are relatively low. In 1994 the data are not available. As for Coastal Andhra Pradesh, however, this equation does not predict the low rainfall observed in 1989. This reveals that the above equations (1a and 1b) and (2a) have some limitations.

The above three parameters revealed stationarity when a rainfall prediction equation for Telangana was derived over the period 1965–94. The equation of prediction is

$$R_{TL} = 46.46 + 3.13\ T_{vsk(200-150)} - 3.35\ T_{vsk(850)} - 0.71\ T_{bmb(850)} \tag{2b}$$

The relationship between the parameters and rainfall in the period 1965–94 is relatively enhanced compared with that of the period 1959 to 1988. The MCC and the COD are 0.66 and 44% respectively. The SE is 1.3 cm. The PR values agreed well with AR values in 1959 and

Table 2. *Actual winter monsoon rainfall (AR), predicted rainfall (PR) and error (E) in cm for different subdivisions (SE standard error) (Numbers in bold font indicate the errors less than or equal to one SE.)*

	Equation (1959–1988)						Equation (1965–1994)					
	1989	**1990**	**1991**	**1992**	**1993**	**1994**	**1959**	**1960**	**1961**	**1962**	**1963**	**1964**
Coastal Andhra Pradesh												
			(SE = 2.64 cm)						(SE = 2.71 cm)			
AR	13.2	47.3	48.8	49.1	39.8	70.3	25.0	28.3	35.7	55.7	40.5	21.6
PR	20.3	32.6	41.6	49.4	47.1	—	30.5	42.2	50.9	30.3	37.1	22.1
E	−7.1	14.7	7.2	**−0.3**	−7.3	—	−5.5	−13.9	−15.2	25.4	3.4	**−0.5**
Telangana												
			(SE = 1.3 cm)						(SE = 1.3 cm)			
AR	5.0	17.1	7.4	12.6	12.4	18.6	7.0	7.8	21.4	16.2	13.1	6.7
PR	10.0	11.6	9.9	11.8	11.6	—	7.1	10.8	15.0	5.9	8.5	6.8
E	−5.0	5.5	−2.5	−1.7	**0.8**	—	**−0.1**	−3.0	6.4	10.3	4.6	**−0.1**
Rayalaseema												
			(SE = 1.5 cm)						(SE = 1.6 cm)			
AR	9.7	24.3	31.1	19.4	36.9	31.5	11.5	20.3	18.7	28.1	10.3	15.4
PR	11.9	13.6	18.4	23.4	22.2	18.0	11.5	13.6	17.6	20.2	22.4	23.1
E	−2.2	10.7	12.7	−4.0	14.7	13.5	0	6.7	**1.1**	7.9	−12.1	−7.7
Tamilnadu												
			(SE = 2.3 cm)						(SE = 2.4 cm)			
AR	31.2	38.9	45.4	48.8	74.4	44.8	44.4	52.6	33.8	42.1	52.1	47.6
PR	44.9	47.0	49.0	45.0	47.7	37.8	46.8	42.0	45.0	44.3	42.5	41.4
E	−13.7	−8.1	−3.6	3.8	26.7	7.0	**2.4**	10.6	−11.2	**−2.2**	9.6	6.2
North Interior Karnataka												
			(SE = 1.2 cm)						(SE = 1. 3 cm)			
AR	5.5	12.2	7.8	23.4	29.9	23.6	9.8	7.5	14.7	20.7	19.7	16.3
PR	12.3	9.7	14.3	12.8	16.5	—	5.0	5.4	7.9	13.6	15.1	19.4
E	−6.8	2.5	−6.5	10.6	13.4	—	4.8	2.1	6.8	7.1	4.6	−3.1
South Interior Karnataka												
			(SE = 1.37 cm)						(SE = 1.37 cm)			
AR	15.9	19.8	30.1	29.2	30.4	30.2	12.5	20.6	20.5	32.6	24.9	25.5
PR	20.8	21.0	15.2	22.8	17.0	29.4	17.7	15.1	—	23.5	21.4	20.1
E	−4.9	**−1.2**	14.9	6.4	13.4	**−0.8**	−5.2	5.5	—	9.1	3.5	5.4
Coastal Karnataka												
			(SE = 2.14 cm)						(SE = 2.28 cm)			
AR	3.7	27.6	13.3	34.4	44.4	29.9	10.8	18.4	39.3	37.7	25.8	29.1
PR	25.8	26.0	15.0	40.3	28.8	31.1	18.9	20.5	24.6	21.0	20.9	23.3
E	−22.1	**1.6**	**−1.7**	−5.9	15.6	**−1.2**	−8.1	**−2.1**	14.7	16.7	4.9	5.8
Kerala												
			(SE = 3.02 cm)						(SE = 3.1 cm)			
AR	42.7	50.3	37.4	62.8	74.2	54.4	36.9	61.5	34.7	50.5	33.3	48.4
PR	41.7	31.0	47.7	47.9	46.6	37.9	50.0	59.3	44.6	36.0	44.3	42.5
E	**1.0**	19.0	−10.3	14.9	27.6	16.5	−13.1	**2.2**	−9.9	14.5	−11.0	5.9

1964; but the PR values in 1961, 1962 and 1963 are not encouraging. In 1960 the error is smaller.

The signs of the regression coefficients in the above equation were the same as equation (2a).

3.3. Rayalaseema (29)

In Rayalaseema subdivision (RS) (Figure 1), there are 11 significant parameters (Table 1). All but two of the parameters are intercorrelated. These two, $T_{vsk(850)}$ and $T_{ndh(850)}$, are inversely related to rainfall with correlation coefficients of −0.53 and −0.36 respectively. Using these two parameters resulted in a significant MCC of 0.59, which is significant at the 0.1% level, which was also the case for Coastal Andhra Pradesh and Telangana. The COD is 35%. The equation for winter monsoon rainfall over Rayalaseema is:

$$R_{RS} = 193.93 - 6.06\,T_{vsk(850)} - 2.43\,T_{ndh(850)} \quad (3a)$$

The PR values of rainfall along with the AR values are presented in Table 2.

The SE is 1.5 cm. The model performs best in 1989 and 1992. In the other years, the differences between the PR and AR values are greater than 10 cm. The above algorithm could be improved by including other parameters such as wind components and SOI.

The equation using data for 1965 to 1994 is:

$$R_{RS} = 196.91 - 3.80\ T_{vsk(850)} - 4.62\ T_{ndh(850)} \quad (3b)$$

The MCC and the COD are 0.56 and 31% respectively. When compared with equation 3(a), this equation has a slightly lower MCC. The SE is 1.6 cm. The PR values in 1959 and 1961 agree with AR values (Table 2). In other years the errors are large. Cooling in the lower troposphere (850 hPa) at Visakhapatnam and New Delhi favours a good monsoon for Rayalaseema.

3.4. Tamilnadu (30)

Tamilnadu subdivision (TN) (Figure 1) receives about 60% of its annual rainfall during the winter monsoon season. Hence the assessment here of the relationship between rainfall and mean September temperature is of paramount importance. There are eleven significant parameters for rainfall (Table 1). Among these parameters, $T_{ngp(500-300)}$, $T_{jdp(500)}$ and $T_{jdp(200-150)}$ have correlations with the Tamilnadu rainfall of 0.43, –0.37 and 0.35 respectively. This means that there is a positive relationship between rainfall and the first and last parameters, while the second shows a negative relationship with rainfall. The principal parameter ($Tngp_{(500-300)}$) indicates a positive relationship with rainfall (Figure 3b); through the entire 30-year period (1959–88), the relationship holds well in 20 of those years (i.e. a positive $Tngp_{(500-300)}$ anomaly leads to a positive rainfall anomaly, or a negative $Tngp_{(500-300)}$ anomaly leads to a negative rainfall anomaly). An algorithm containing these three variables has a MCC of 0.60, which is significant at the 0.1% level. The COD and the SE are 36% and 2.3 cm respectively. The equation is as follows:

$$R_{TN} = -182.54 + 6.53\ T_{ngp(500-300)} - 2.33\ T_{jdp(500)} + 4.08\ T_{jdp(200-150)} \quad (4a)$$

This equation is tested over six years and the PR and AR values are shown in Table 2. In every year, the error is larger than the SE of the observed totals, the largest errors occurring in 1989 and 1993. The model, however, was not able to predict the exceptionally wet winter monsoon of 1993. Other unknown factors might be important in explaining this extreme event. More investigation is needed in this regard.

The MCC of the equation with the above parameters for the period 1965 to 1994 is 0.56, which is slightly less than that of equation 4a and the COD is 31%. The algorithm is

$$R_{TN} = -198.81 + 7.12\ T_{ngp(500-300)} - 1.99\ T_{jdp(500)} + 4.28\ T_{jdp(200-150)} \quad (4b)$$

The SE is 2.4 cm. The AR and PR values in the years 1959 to 1964 are shown in Table 2. The PR values in 1959 and 1962 agree with the AR values (less than one standard error). The errors are relatively large in 1960, 1961 and 1963.

In comparing our results to those obtained by Raj (1998), it is apparent that he used six local parameters drawn from the months of April to September; whereas in this present study we used three parameters from September only. There are no comparable studies for the prediction of rainfall over other meteorological subdivisions, but Jayanthi & Govindachari (1999) explained the importance of SST anomalies over Niño 3–4 region by linking SST anomaly data for the period 1978 to 1997 and Tamilnadu winter monsoon rainfall. They obtained a significant positive correlation. Ten-year running correlations showed that the relationship is stable.

It is pertinent to note that an increase in the temperature difference between 500 and 300 hPa at Nagpur (warming at 500 hPa and cooling at 300 hPa); cooling at 500 hPa over Jodhpur; and an increase in the temperature difference between 200 and 150 hPa at Jodhpur (warming at 200 hPa and cooling at 150 hPa) lead to an active monsoon over Tamilnadu.

3.5. North Interior Karnataka (NIK) (32)

Although there are eight significant temperature parameters with the winter monsoon rainfall (Table 1), only three of these parameters – $T_{mds(850-700)}$, $T_{mds(850)}$ and $T_{ndh(850)}$ – were incorporated into the prediction algorithm. Their respective correlations with the winter monsoon rainfall of North Interior Karnataka are −0.42, −0.36 and −0.33 respectively. All three parameters thus show an inverse relationship with winter monsoon rainfall. The algorithm is:

$$R_{NIK} = 128.23 - 3.58\ T_{mds(850-700)} - 1.22\ T_{mds(850)} - 2.52\ T_{ndh(850)}. \quad (5a)$$

The MCC of the above equation is 0.60, which is significant at the 0.1% level and the COD is 36%. The PR and AR values are presented in Table 2. The equation predicted near to the actual values only in 1990.

The equation with the same parameters for the period 1965–94 is:

$$R_{NIK} = 161.7 - 4.18\ T_{mds(850-700)} - 0.94\ T_{mds(850)} - 4.07\ T_{ndh(850)}. \quad (5b)$$

The MCC and the COD are 0.57 (slightly less than that of equation 5(a)) and 32% respectively. The SE is 1.3 cm.

The PR values are nearer to the AR values only in 1960, 1963 and 1964 (Table 2).

From the above, one can see that a decrease in the temperature difference between 850 and 700 hPa at Chennai (cooling at 850 hPa and warming at 700 hPa) and cooling in the lower troposphere at New Delhi enhances the winter monsoon rainfall over North Interior Karnataka.

3.6. South Interior Karnataka (SIK) (33)

There are only two parameters ($T_{bmb(700-500)}$, $T_{bmb(850-500)}$) that are significantly related to the division's winter monsoon rainfall (Table 1). Their correlations with rainfall are –0.34 and –0.30 respectively. However, these two parameters are intercorrelated (correlation coefficient = 0.44), so using both parameters will not result in a regression model with a significantly higher MCC value. It was decided to combine $T_{bmb(700-500)}$ with the parameter that not only showed the highest non-significant correlation with monsoon rainfall, but was also insignificantly related to $T_{bmb(700-500)}$. Further, the parameter ($T_{bmb(700-500)}$) is insignificantly correlated with $T_{trv(150-100)}$ which has a correlation of 0.29 with rainfall. A regression equation is attempted with these two parameters.

The equation using the data for the period 1959–88 is:

$$R_{SIK} = 64.61 - 3.76\ T_{bmb(700-500)} + 0.76\ T_{trv(150-100)}. \tag{6a}$$

The MCC and the COD are 0.41 (significant at 5% level) and 17% respectively. The SE is 1.37 cm. The equation made good rainfall predictions in 1990 and 1994 (Table 2).

The MCC of the equation for the period 1965 to 1994 is 0.40 with a COD of 16%. These figures are comparable to the 1959–88 equation. The equation is:

$$R_{SIK} = 67.57 - 3.82\ T_{bmb(700-500)} + 0.47\ T_{trv(150-100)}. \tag{6b}$$

The SE is 1.37 cm and the errors in the PR values (except in 1963) are more than 4 cm (Table 2).

3.7. Coastal Karnataka (CK) (31)

In subdivision 31 (Figure 1), there are twelve significant parameters (Table 1). Three parameters – $T_{vsk(850)}$, $T_{trv(700)}$ and $T_{bmb(700-500)}$ – are used in the winter monsoon rainfall prediction model. The correlation coefficients are –0.40, 0.39 and –0.38 respectively. The two parameters $T_{vsk(850)}$ and $T_{bmb(700-500)}$ are inversely correlated, while the second one showed a positive relationship with rainfall. The equation's MCC is 0.68, which is highly significant (0.1% level), and the COD is 46%. The equation is as follows:

$$R_{CK} = 222.03 - 8.35\ T_{vsk(850)} + 5.49\ T_{trv(700)} - 6.20\ T_{bmb(700-500)} \tag{7a}$$

The PR values using the above equation for the winter monsoon rainfall over Coastal Karnataka are given (Table 2). The SE is 2.14 cm. The PR values are good (less than one SE) except for the years 1989 (drought event), 1993 (wet event) and 1992.

The algorithm with the above combination of parameters for the period 1965 to 1994 is:

$$R_{CK} = 201.0 - 9.55\ T_{vsk(850)} + 6.1\ T_{trv(700)} - 3.37\ T_{bmb(700-500)} \tag{7b}$$

The MCC and the COD are 0.67 and 45% respectively. These values are similar to those of the 1959–88 equation. The SE is 2.28 cm. The PR value in 1960 agrees well with the AR value. However, predictions for the other years are much poorer, particularly in 1961, 1962 and 1959.

3.8. Kerala(KL) (34)

There are five significant parameters for Kerala (Table 1), out of which $T_{bmb(850)}$, $T_{Tvsk(850)}$ and $T_{jdp(500)}$ are related to the winter monsoon rainfall with correlation coefficient values of 0.35, –0.33 and –0.32 respectively. The equation with these parameters has a MCC of 0.64, which is significant at the 0.1% level. The COD is 41% and the corresponding algorithm is as follows:

$$R_{KL} = -14.50 + 12.4\ T_{bmb(850)} - 8.67\ T_{vsk(850)} - 1.75\ T_{jdp(500)} \tag{8a}$$

Here SE is 3.02 cm. The AR and PR values with the above equation are shown in Table 2. The PR value for 1989 is good, but for the remaining years the differences are more than 10 cm. This equation should be modified further.

The algorithm with the above three parameters for the period 1965 to 1994 is:

$$R_{KL} = -20.00 + 11.86\ T_{bmb(850)} - 7.74\ T_{vsk(850)} - 1.41\ T_{jdp(500)} \tag{8b}$$

The MCC is 0.55 and the COD is 30%. In the preiod 1965–94, this set of parameters provides a less powerful measure of monsoon rainfall when compared to the period 1959–88. The SE is 3.1 cm. The PR value in 1960 is good (Table 2). The errors in the years 1959, 1962 and 1963 are more than 10 cm.

4. Summary and conclusions

Mean upper-air temperatures in September at different stations over the Indian subcontinent show significant correlations with winter monsoon rainfall over the subdivisions south of 20° N. These correlations suggest that seasonal forecasts of winter monsoon rainfall may be feasible. Two sets of forecasting equations were developed containing two or three parameters, one for the period 1959–88 and another for the period 1965–94. The first set of algorithms was tested for the succeeding six years (1989–94); similarly, the second set was tested for the preceding years 1959–64 and the results were discussed. Most of the algorithms throw light on the importance of the predictors in the lower troposphere (850 hPa). On most occasions, the parameters showed stationarity and yielded more or less the same MCCs for both periods.

The mean upper-air temperatures in April/May over India are crucial factors in the ensuing Indian summer monsoon rainfall (Bhaskara Rao et al. 2001). This study has also found that cooling in the lower troposphere, generally prevalent from New Delhi to Chennai in September, leads to enhanced winter monsoon precipitation over southern India. Secondly, temperature at Nagpur in the upper troposphere plays a crucial role in the algorithm and it is noteworthy that Nagpur is under the influence of an intensified subtropical ridge, which affects winter monsoon performance.

Finally, the winter monsoon rainfall is a result of a series of feedback mechanisms, such as the mean upper-air temperature in September over the Indian subcontinent. Although the forecasts are not always accurate (or correct), this paper has demonstrated that long-range prediction of winter monsoon rainfall is feasible using September upper-air temperatures only. Further research could be directed at improving the algorithms developed in this paper, by using parameters such as SOI, El Niño, Indian Ocean Dipole and North Atlantic Oscillation.

Acknowledgments

The authors wish to thank the Department of Science and Technology, Government of India for their financial support for research, project DST No. ESS/63/B2-139/95 – ‘Studies of winter monsoon over India’.

References

Banerjee, A. K., Sen, P. N. & Raman, C. R. V. (1978) On foreshadowing southwest monsoon rainfall over India with mid tropospheric circulation anomaly of April. *Indian J. Meteorol. Hydrol. Geophys.* **29**: 425–431.

Bhalme, H. N., Sikader, A. B. & Jadhav, S. K. (1990) Relationships between the planetary scale waves, Indian monsoon rainfall and ENSO. *Mausam* **41**: 279–284.

Bhanu Kumar, O. S. R. U. (1988) Eurasian snow cover and long-range forecast of Indian monsoon rainfall. *Hydrol. Sci. J.* **5**: 515–525.

Bhanu Kumar, O. S. R. U., Naidu, C. V., Rao, S. R. L. & Naga Ratna, K. (2003a) An empirical relation for prediction of winter monsoon rainfall over Tamilnadu. *Proc. A.P. Akademi of Sciences* **7**: 151–154.

Bhanu Kumar, O. S. R. U., Naidu, C. V. & Rao, S. R. L. (2003b) Influence of ENSO and IOD on Indian winter monsoon rainfall. Paper presented at 14th Global Warming International Conference, 27–31 May 2003, Boston, USA.

Bhaskara Rao, K., Naidu, C. V. & Bhanukumar, O. S. R. U. (2001) Forecasting of summer monsoon rainfall over India. *Meteorol. Appl.* **8**: 245–252.

De, U. S., Joshi, K. S. & Lele, R. R. (1992) Intra-seasonal variation in circulation and rainfall during northeast monsoon. *Vayu Mandal* **22**: 103–108.

De, U. S. & Mukhopadhyay, R. K. (1999) The effect of ENSO/Anti ENSO on northeast monsoon rainfall. *Mausam* **50**: 343–354.

Dhar, O. N., Rakhecha, P. R. & Kulkarni, A. K. (1982a) Fluctuations in northeast monsoon rainfall of Tamil Nadu. *J. Climatol.* **2**: 339–345.

Dhar, O. N., Rakhecha, P. R. & Kulkarni, A. K. (1982b) Trends and fluctuations of seasonal and annual rainfall of Tamil Nadu. *Proc. Indian Acad. Sci (Earth Planet Sci)* **91**:97–104.

Doraiswamy Iyer, V. (1941) Forecasting of northeast monsoon rainfall of south Chennai, India Met. Dept., Sci. Notes, vol.VIII, no. 98.

Gowariker, V., Thapliyal, V., Sarker, R. P., Mandal, G. S. & Sikka, D. R. (1989) Parametric and power regression models: new approach to long-range forecasting of monsoon rainfall in India. *Mausam* **40**: 115–122.

Gowariker, V., Thapliyal, V., Kulshrestha, S. M., Mandal, G. S., Sen Roy, N. & Sikka, D. R. (1991) A power regression model for long-range forecast of southwest monsoon rainfall over India. *Mausam* **42**: 125–130.

Hastenrath, S. (1987) On the prediction of Indian monsoon rainfall anomalies. *J. Climate Appl. Meteorol.* **26**: 847–857.

India Meteorological Department (1973) Northeast monsoon. *FMU Report,* No.4 – 18.4.

India Meteorological Department (1979) *Tracks of Storms and Depressions in the Bay of Bengal and Arabian Sea, 1877–1970* . India Meteorological Department, New Delhi.

India Meteorological Department (1987) *Report on the Tenth Conference of Forecasting Officers.* India Meteorological Department, pp. 43–46.

India Meteorological Department (1996) *Tracks of Storms and Depressions in the Bay of Bengal and Arabian Sea, 1971–1990.* India Meteorological Department, New Delhi.

Jayanthi, N. & Govindachari, S. (1999) El Niño and northeast monsoon rainfall over Tamilnadu. *Mausam* **50**: 217–218.

Joseph, P. V. (1978) Sub tropical westerlies in relation to large scale failure of Indian monsoon. *Indian J. Meteorol. Hydrol. Geophys.* **29**: 412–418.

Medha Khole & De, U. S. (2003) A study on north-east monsoon rainfall over India. *Mausam* **54**: 419–426.

Mooley, D. A. & Shukla, J. (1987) Variability and forecasting of the summer monsoon rainfall over India. *Monsoon Meteorology, Monogr. Geology Geophysics.* Oxford University Press, 26–58.

Mooley, D. A., Parthasarathy, B. & Panth, G. B. (1986) Relationship between Indian summer monsoon rainfall and location of ridge at 500 mb level along 75°E. *J. Climate Appl. Meteorol.* **25**: 633–640.

Murakami, T. (1977) Regional energetics over the north Pacific, South China Sea and the Indonesian Seas during winter. *PAGEOPH* **115**: 1283–1301.

Naga Ratna, K, Bhanu Kumar, O. S. R. U., Reddy, K. K., Naidu, C. V., Rao, S. R. L. & Somanadam, S. V. S. (2003) A study of mean features of winter monsoon circulation over India and neighbourhood using NCAR/NCEP reanalysis data. *Proc. A. P. Akademi of Sciences,* **7**: 87–94.

Nageswara Rao, G. (1999) Variations of the SO relationship with summer and winter monsoon rainfall over India: 1872–1993. *J. Climate* **12**: 3486–3495.

Parthasarathy, B. & Pant, G. B. (1985) Seasonal relationships between Indian summer monsoon rainfall and the southern oscillation. *J. Climatol.* **5**: 369–378.

Parthasarathy, B., Rupa Kumar, K. & Deshpande, V. R. (1990) Indian summer monsoon rainfall and 200 mb meridional wind index: application for long range prediction. *Int. J. Climatol.* **11**: 165–176.

Parthasarathy, B., Munot, A. A. & Kothawale, D. R. (1995) Monthly and seasonal rainfall series for all-India, homogeneous regions and meteorological subdivisions. IITM, Research Report, Pune.

Raj, Y. E. A. (1989) Statistical relations between winter monsoon rainfall and the preceding summer monsoon. *Mausam* **40**: 51–56.

Raj, Y. E. A. (1998) A scheme for advance prediction of Northeast monsoon rainfall of Tamilnadu. *Mausam* **49**: 247–254.

Raj, Y. E. A., Sen, P. N. & Jamadar, S. M. (1993) Outlook on northeast monsoon rainfall of Tamilnadu. *Mausam* **44**:19–22.

Rao, P. R. K. (1953) Rainfall of Madras state with special reference to Tamil Nadu and Rayalaseema, Memoirs, India Meteorological Department, 30, Part I, 1–60.

Rao, P. R. K. & Jagannathan, P. (1953) A study of the northeast monsoon rainfall of Tamilnadu. *Indian J. Meteorol. Geophys.* **4**: 22–44.

Rao, K. V. (1963) Indian NE monsoon season. *Ind. J. Meteorol. Geophys.* **14**: 145–155.

Ropelewski, C. F. & Halpert, M. S. (1987) Global and regional scale precipitation patterns associated with the El Niño/Southern Oscillation. *Mon. Wea. Rev.* **115**: 1606–1626.

Sen Guptha, P. K. (1960) Sunspot influence on movement of storms over the Bay of Bengal and associated atmospheric variations. *Weather* **15**: 52–58.

Singh, G. P. & Chattopadhyay, J. (1998) Influence of some circulation anomalies on Indian northeast monsoon rainfall. *Mausam* **49**: 443–448.

Singh, N. and Sontakke, N. A. (1999) On the variability and prediction of rainfall in the post monsoon season over India. *Int. J. Climatol.* **19**: 309–339.

Sontakke, N. A. (1993) Fluctuations in NE monsoon rainfall over India since 1871. In R. N. Keshavamurthy and P. C. Joshi, (eds), *Advances in Tropical Meteorology,* Tata McGraw Hill, New Delhi, 149–158.

Sridharan, S. and Muthuswamy, A. (1990) NE monsoon rainfall in relation to El-Niño, QBO, and Atlantic hurricane frequency. *Vayu Mandal* **20**: 105–111.

Srinivasan, V. and Ramamurthy, K. (1973a) Comprehensive articles on selected topics, Northeast Monsoon. *FMU Report, No. IV,* 18.4, India Meteorological Department.

Srinivasan, V. and Ramamurthy, K. (1973b) Weather over the Indian seas during the post monsoon season, *FMU Rep. No. IV,* 18.4, India Met. Dept.

Subbaramayya, I. (1976) The northeast monsoon and the causes of the winter rains of southeast India. *Meteorol. Mag.* **105**, 153–159.

Thapliyal, V. & Kulshrestha, S. M. (1992) Recent models for long range forecasting of southwest monsoon rainfall in India. *Mausam* **43**: 239–248.

Thapliyal, V. & Rajeevan, M. (2003) Updated operational models for long range forecasts of Indian summer monsoon rainfall. *Mausam* **54**: 495–504

Thiruvengadathan, A. (1965) Mean upper air flow pattern associated with spells of strong and weak northeast monsoon conditions over the Madras state in the month of November. *Ind. J. Meteorol. Geophys.,* **16**: 61–68.