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Seasonal variation of 200 hPa upper tropospheric features over India in relation to performance of Indian southwest and northeast monsoons

Y. E. A. RAJ, R. SURESH*, P. V. SANKARAN and B. AMUDHA

Regional Meteorological Centre, Chennai, India

**Cyclone Detection Radar, Chennai, India*

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सार – इस शोध–पत्र में 1963 से 1998 तक की 36 वर्षों की अवधि की 14 सुवितरित भारतीय रेडियो सौंदे स्टेशन से प्राप्त हुए मासिक और मौसमी उपरितन वायु के आँकड़ों के आधार पर भारतीय दक्षिणी पश्चिमी मानसून और उत्तरी पूर्वी मानसून ऋतुओं के साथ भारत के तापमान, क्षेत्रीय और याम्योत्तरी पवनों जैसे 200 है.पा. पर ऊपरी क्षोभ मंडलीय प्राचलों के मध्य पाए जाने वाले संबंध का अध्ययन किया है। इससे यह पता चला है कि कुल मिलाकर पूर्ववर्ती महीनों/ऋतुओं के दौरान के अनुकूल तापमान/अत्याधिक विसंगतियाँ, प्रतिकूल क्षेत्रीय पवन विसंगतियाँ और उपउष्णकटिबंधीय रिज की उत्तरी स्थिति, सही दक्षिणी पश्चिमी मानसून/खराब उत्तरी पूर्वी मानसून ऋतुओं के साथ संबद्ध होते हैं और यह ऊपर बताई गई खराब दक्षिणी पश्चिमी/सही उत्तरी पूर्वी मानसून के अनुपूरक हैं। मई और सितंबर/अक्तूबर के महीने में ऊपर बताए गए संबंध की विशेषताएँ दोहरे चरम पर परिलक्षित होती है। अक्तूबर माह के आँकड़ों के आधार पर उत्तरी पूर्वी मानूसन वर्षा के मौसमी पूर्वानुमान के लिए एक बहुसमाश्रयण पूर्वानुमान योजना तैयार की गई और जब इसकी 5 वर्षों के स्वतंत्र नमूनों की जाँच की गई तो लगभग 50 प्रतिशत पूर्वानुमान सही पाया गया। भारत की दक्षिणी पश्चिमी मानसून वर्षा नकारात्मक संबंध दिखाती है। भारत के दक्षिण पश्चिम मानसून वर्षा और तमिलनाडु/भारत के दक्षिणी भागों के उत्तर पूर्वी मानसून वर्षा से नकारात्मक संबंधों का पता चलता है हालाँकि ये संबंध निश्चित होने की अपेक्षा बेमेल पाए गए हैं जिसे, दक्षिण पश्चिम मानूसन के कम वर्षा वाले वर्षों को निकाल देने पर, बेहतर परिभाषित किया जा सकता है। अधिक शीत वाले उपरितन क्षोभमंडलीय तापमानों के प्रारम्भ होने वाले भारतीय उत्तर–पूर्वी सही मानसून के लक्षण, जैसा कि इस अध्ययन में बताया गया है, साईबेरिया की उँचाई से आने वाली शीत लहरों के कारण एशिया की तीव्र होने वाली शीत मानसून की स्वीकृति प्रक्रिया से सही मेल खाते हैं।

ABSTRACT. The relation between 200 hPa upper tropospheric parameters such as temperature, zonal and meridional winds over India with the Indian southwest and northeast monsoons has been studied, based on monthly and seasonal upper air data of 14 well-distributed Indian radiosonde stations for the 36 year period 1963-98. It has been found that by and large, positive temperature/height anomalies, negative zonal wind anomalies and northerly position of the sub-tropical ridge during the preceding months/seasons are associated with good southwest/poor northeast monsoons and that complement of the above with poor southwest/good northeast monsoons. The profiles of the above relationship display a double peak in May and September/October. A multiple regression forecast scheme for seasonal forecasting of northeast monsoon rainfall, based on October data has been derived which when tested in an independent sample of 5 years yielded nearly 50% correct forecasts. The southwest monsoon rainfall of India and the northeast monsoon rainfall of Tamil Nadu/Southern parts of India have been shown to share a negative relationship, though the relationship is discordant rather than decisive, which gets defined better when years of deficient southwest monsoon rainfall get excluded. The feature of good Indian northeast monsoon getting preceded by colder upper tropospheric temperatures as shown in the study tie in well with the accepted mechanism of Asian winter monsoon getting intensified due to cold surges from the Siberian High.

Key words – Southwest monsoon, Northeast monsoon, India, Tamil Nadu, Southern Region, 200 hPa level, Sub-tropical ridge, Thermal wind, Cold surges.

1. Introduction

The southwest monsoon, which is the major rain-giving phenomenon for India, provides it with nearly 75% of its annual rainfall during the four-month monsoon season of June-September. Over parts of southern peninsula the northeast monsoon season of October-December also contributes significantly, to the extent of

35% of annual rainfall. The state of Tamil Nadu located in the southeastern part of India receives nearly 48% of the annual rainfall of 100 cm during northeast monsoon season against 34% during southwest monsoon season. Expectedly the features of northeast monsoon are better defined over Tamil Nadu when compared to other subdivisions. The switchover from southwest to northeast monsoon is marked in the southern peninsula by a 180° reversal of surface and lower tropospheric winds from southwesterlies to northeasterlies. Does the large scale southwest monsoon exert any influence on the succeeding smaller scale Indian northeast monsoon and if so to what extent is a question that inevitably crops up.

The extensive studies conducted on the interannual variation of southwest monsoon rainfall have identified several meteorological features, large scale flow patterns and global events that predispose, concurrently occur or succeed extreme behaviour of monsoon leading to instances of drought/flood. Identification and analysis of such features go a long way towards comprehending the vagaries of monsoon as well as the complex but fascinating nature of its variation. For the Indian northeast monsoon also certain synoptic features associated with its yearly variation have been identified though these are not as well defined or well organised as those associated with the southwest monsoon.

2. Objective and scope of the study

Considerable amount of work has been carried out on the influence, mid/upper tropospheric features over India during winter and pre-monsoon exert over the ensuing southwest monsoon. Rao (1976), Thapliyal (1981), Das (1986), Mooley *et al*. (1986) and Asnani (1993) provide descriptive summaries of several important relations. Some of the significant relations identified are listed below :

(*i*) 200 hPa westerlies extending to lower latitudes as well as prevalence of westerlies stronger than normal during winter/pre-monsoon are not favourable for a normal/good southwest monsoon (Joseph, 1978 and Parthasarathy *et al*. 1990).

(*ii*) Positive temperature/contour height anomalies at 200 hPa favour good southwest monsoon, negative anomalies favour poor monsoon. (Jagannathan and Kandekar, 1962, Kothawale and Rupa Kumar, 2002).

(*iii*) Meridional wind over India in May at 200 hPa is negatively related to ensuing monsoon rainfall. Northerly component associated with good monsoon and southerly winds associated with poor monsoon (Joseph *et al*., 1981).

TABLE 1

Statistics of seasonal 200 hPa mean upper air parameters averaged over India

	Season	*TT* (ºC)	DD (degrees)	FF (m/s)	U (m/s)	V (m/s)
Normal	JF	-53.7	263	26.7	26.5	3.4
	MAM	-52.2	262	17.2	17.0	2.5
	JJAS	-50.0	87	10.9	-10.9	-0.6
	OND	-53.6	252	15.6	14.9	4.9
SD	JF	1.4			2.7	2.6
	MAM	1.3			2.0	1.7
	JJAS	1.4			1.2	0.6
	OND	1.4			2.8	1.7

TT - temperature, DD - wind direction, FF - wind speed, U and V - zonal and meridional wind components, JF : Jan to Feb, MAM – Mar to May, JJAS - Jun to Sep, OND - Oct to Dec, SD - standard Deviation

Some of the upper tropospheric parameters identified as related with the northeast monsoon are :

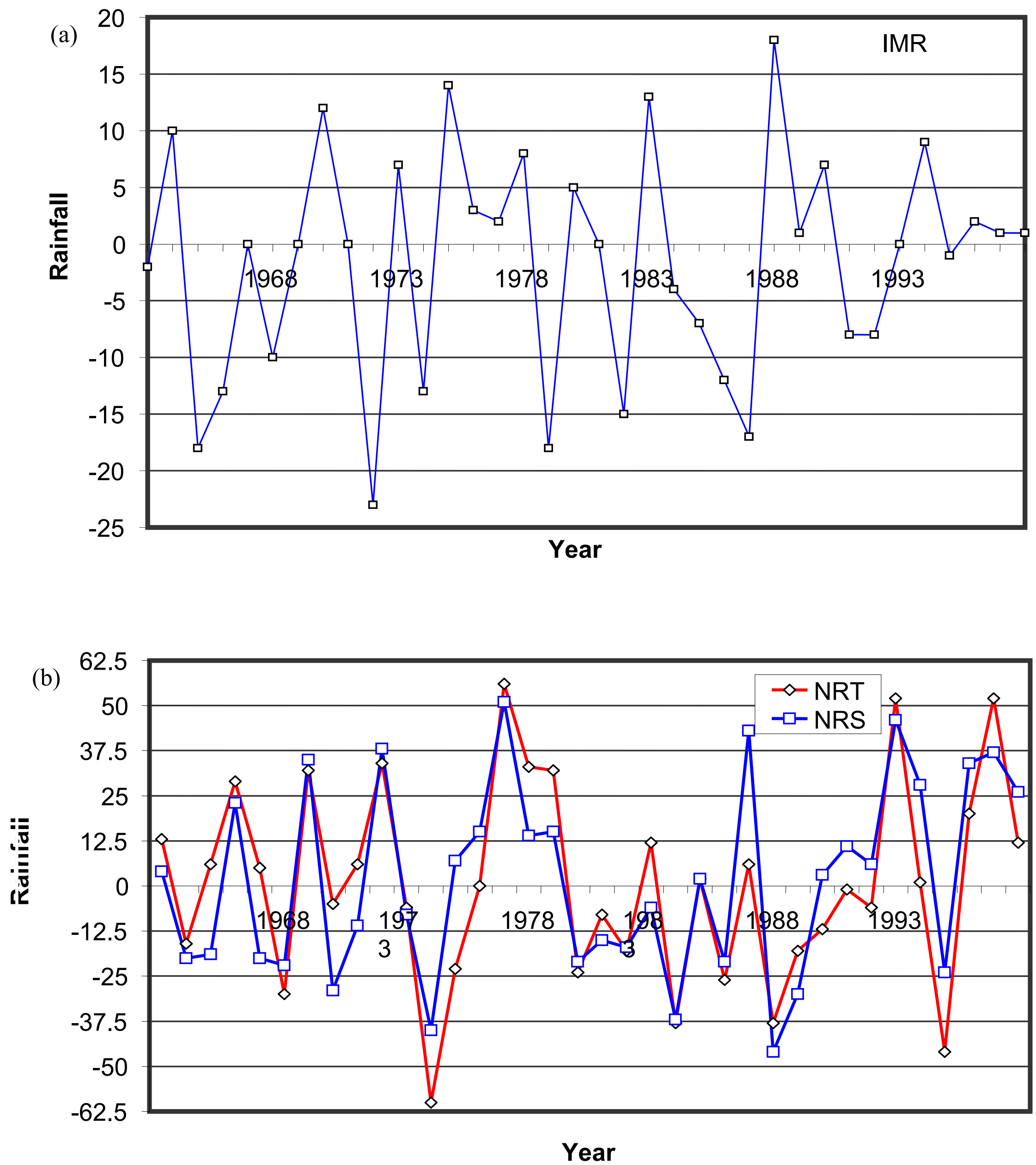
(*i*) Strong zonal westerly winds over India in April at 200 hPa favour a good northeast monsoon, weak winds favour poor northeast monsoon (Raj, 1998).

(*ii*) Colder temperatures over some parts of India at 150 hPa during June-September favour good northeast monsoon, warmer temperatures favour poor northeast monsoon (Raj, 1998; Singh and Dash, 2001).

(*iii*) Weak Tropical Easterly Jet (TEJ) over Thiruvananthapuram at 150 hPa during August-September favour good northeast monsoon, strong TEJ favours poor northeast monsoon (Raj, 1989 & 1998).

There is considerable variation in the degree of relationship present in the relations listed above. Not every antecedent relation may qualify as a candidate for a seasonal forecasting scheme. The relations have been derived based on different periods of time and there could have been decrease/increase in their intensity during the recent period. For Indian northeast monsoon, most of the relationships have emerged from the upper troposphere only and so the upper tropospheric region over India appears to hold some importance in unraveling the complex and not yet well understood interannual variation of this monsoon.

The objective of the present study is to analyse how the upper tropospheric features that evolve over India are related to the southwest and northeast monsoon rainfall of India in antecedent, concurrent and succeeding time lags; and that how such relations, to the extent possible could



Figs. 1(a&b). Rainfall (as percentage departure from normal) during 1963-98 (a) India, June-September (IMR) and (b) Tamil Nadu & Southern region, October-December (NRT & NRS)

possibly lead to a better understanding of the variation of both the monsoons especially the latter and thereupon the features associated with good and poor monsoons.

3. Data

3.1. *Upper air data*

The upper air mean monthly data at 200 hPa level of 14 Indian radiosonde stations for all the 12 months of the year for the 36 year period 1963-98 formed the major database for the study. The stations are : Delhi (DLH), Jodhpur (JDP), Ahmedabad (AHD), Bombay (now Mumbai) (BMB), Nagpur (NGP), Lucknow (LKN), Gauhati (GHT), Bhuvaneswar (BWN), Hyderabad (HYD), Visakhapatnam (VSK), Madras (now Chennai) (MDS), Thiruvananthapuram (TRV), Minicoy (MNC) and Port Blair (PBL). The source of data for the period 1963-88 is National Centre for Atmospheric Research, USA. The data for 1989-98 was obtained from National Data

TABLE 2

Statistics of southwest monsoon rainfall of India and northeast monsoon rainfall of Tamil Nadu and Southern Region

Rainfall	Period: 1901-2000		1963-98	
	Mean (mm)	CV (%)	Mean (mm)	CV (%)
IMR	868.9	9.9	861.1	10.2
NRT	488.3	27.1	497.4	27.2
NRS	391.6	25.1	401.9	26.1

IMR - Indian Monsoon Rainfall, June - September
NRT / NRS - North East Monsoon rainfall of Tamil Nadu / Southern Region, October - December, CV – Coefficient of Variation

TABLE 3

Sub-intervals for IMR & NRT / NRS

Rainfall	Category	Rainfall (PDN) range
IMR	A_{-2}	$\leq$ -10
	A_{-1}	(-10, -5)
	A_0	(-5, 5)
	A_1	(5, 10)
	A_2	$\geq$ 10
NRT/NRS	B_{-2}	$\leq$ - 25
	B_{-1}	(-25, -12.5)
	B_0	(-12.5, 12.5)
	B_1	(12.5, 25)
	B_2	$\geq$ 25

IMR, NRT, NRS – as in Table 2, PDN - Percentage Departure from Normal

Centre, India Meteorological Department (IMD), Pune. The data series used in the study are the average of both 0000 and 1200 UTC series. Normally monthly mean is computed and archived only if data for atleast 20 days are available.

The parameters temperature (TT), zonal and meridional winds (U&V) have been considered in the study. The basic data was thoroughly scrutinised to identify and score off inconsistent values. Nearly 10% of the records had some missing data, which were estimated by following a methodology, which is described below. The time series of the parameter with a missing data point was correlated with the time series of the same parameter for the same month of several neighbouring stations. The station corresponding to the highest positive correlation coefficient (CC) with data being available for the concerned year was identified and the missing data estimated through regression equation. All the missing data could be patched up through the above procedure. In addition to monthly time series, those for the four seasons of India *viz*., January-February (JF, Winter), March-May (MAM, Pre-Monsoon), June-September (JJAS, Monsoon) and October-December (OND, Post monsoon/Northeast monsoon) were also generated by computing the averages from the monthly data series.

A single representative time series for India for each of the upper air parameters considered was also derived by averaging the respective parameters over the 14 stations, for each month/season and year. Table 1 presents the normals and standard deviations (SD) of the above parameters and also the normal wind vectors for the four seasons *viz*., JF, MAM, JJAS and OND.

3.2. *Rainfall data*

The rainfall data for all the 35 meteorological sub-divisions of India were obtained from National Data Centre, IMD, Pune. The following rainfall series were derived :

(*i*) June-September southwest monsoon rainfall of India, based on data of all 35 meteorological subdivisions (IMR).

(*ii*) October-December northeast monsoon rainfall of Tamil Nadu (NRT).

(*iii*) October-December northeast monsoon rainfall of the region comprising Tamil Nadu, Kerala, coastal Andhra Pradesh and Rayalaseema. This region will be referred as Southern Region (SR) and the rainfall series as NRS.

The above series were derived for the 100 year period 1901-2000. Fig. 1 presents the time series of IMR, NRT and NRS for 1963-98 in the form of percentage departure from normal (PDN). Table 2 presents the statistical details for this long period as well as for the period of study *viz*., 1963-98. The IMR has a mean of nearly 87 cm with a coefficient of variation (CV) of 10%. The NRT & NRS have means of nearly 49 and 40 cm respectively with CV close to 25%.

In Table 3 are defined sub-intervals for IMR and NRT/NRS that divide the range of each rainfall series into five intervals. These sub-intervals have been defined taking into consideration the magnitude of CV of the rainfall series. The intervals A_{-2} and A_2 can be taken to define deficient (D) and excess (E) IMR respectively. For NRT/NRS B_{-2} and B_2 define D and E. In accordance with this definition the period 1963-98 had 9 deficient and 5 excess IMR years. For NRT the number of E/D years are 8 & 6 and for NRS they are 9 & 5 respectively. The CC between NRS and NRT is 0.87 showing that both the rainfall series are closely related.

TABLE 4

Significant Correlation coefficients between 200 hPa mean upper air parameters over various regions of India and monsoon rainfall series for different periods

Rainfall	Stations representing the region	Month	Parameters		
			TT	U	V
IMR	India	May	0.42 **		-0.44 **
	India	JJAS		-0.47 **	-0.57**
	India	OND		-0.37 *	
	DLH, JDP, LKN, GHT, NGP, BMB	Sep		-0.70 **	-0.33 *
	NGP, BWN, BMB, HYD, VSK, MDS, PBL, MNC, TRV	Oct		-0.43 **	
NRT	India	MAM		0.40 *	
	AHM, NGP, BWN, HYD, VSK, MDS	Apr		0.48 **	
	NGP, HYD, VSK	May		0.33 *	
	BWN, HYD, VSK	Jun	-0.37 *	0.45 **	
	NGP, BWN, BMB, HYD, VSK, MDS, PBL	Oct	-0.40 *	0.48 **	
NRS	India	MAM	-0.34*	0.38 *	
	NGP, BWN, HYD, VSK, MDS	Apr	-0.37 *	0.45 **	
	NGP, HYD, VSK	May	-0.38 *	0.43 **	
	BWN, HYD, VSK	Jun	-0.49 **	0.37 *	
	AHM, BWN, HYD, VSK, MDS, PBL, MNC, TRV	Aug	-0.51 **		
	BWN, HYD, VSK, MDS, PBL	Oct	-0.50 **	0.36 *	

Abbreviations as in Tables 1 & 2. *, **: CCs significant at 5, 1 % levels

4. Computations and analysis

The relation between 200 hPa parameters and the monsoon rainfall has been studied in three different ways, *viz*., by employing correlation analysis, by computing the conditional means of either rainfall or 200 hPa parameters given the other (Panofsky and Brier, 1968). In addition to the directly measured 200 hPa parameters, the latitudinal position of the east-west sub-tropical ridge (STR) over India which is a derived parameter has also been used as an input parameter. The methods and the results obtained are discussed below.

4.1. *Correlation analysis*

The CCs between the time series of monthly/seasonal 200 hPa parameters of India with IMR, NRS and NRT were computed. The months/seasons of the time series, which were paired to derive the CCs, belonged to the same calendar year. Thus in case of IMR, the CCs computed were antecedent (corresponding to Jan, Feb, Mar, Apr, May, JF, MAM), concurrent (Jun, Jul, Aug, Sep, and JJAS) and succeeding (Oct, Nov, Dec and OND). In case of NRS and NRT the CCs were antecedent/concurrent only. The significance of the CCs computed was tested by means of Students' *t*-test. Table 4 presents the statistically significant CCs at 5% or 1% level of significance (LS) between the parameters *TT*, U and V for the four seasons and the rainfall series IMR, NRT and NRS. In some cases it was found that the relations were better defined for individual months rather than for the whole season and also for specific regions compared to the whole country. The significant CCs corresponding to such cases are also shown in Table 4.

4.1.1. *Relation with IMR*

The *TT* of India for May is significantly positively related to IMR, indicating that warmer upper troposphere over India in May is favourable for a good monsoon and colder to a poor monsoon. The meridional wind of May shows a CC of –0.44 significant at 1% level. The winds over India during JJAS exhibit a strong concurrent relation with IMR with CC values of –0.47 and –0.57 respectively for U and V during JJAS. From this relation and from the climatic values of U and V of JJAS (Table 1), it follows that strong zonal easterlies and meridional northerlies are concurrently associated with

TABLE 5

Conditional mean anomalies of 200 hPa mean upper air parameters over India given rainfall for selected months / seasons

Rainfall	Season / Month	Parameter	Rainfall intervals				
			A_{-2}	A_{-1}	A_0	A_1	A_2
IMR	Jan	*TT* (ºC)	-0.3	-0.3	0.1	0.3	0.2
	May		-0.4	-1.5	0.0	0.7	1.2
	MAM		-0.1	-1.1	-0.1	0.7	0.8
	Jun		-0.2	-0.6	-0.3	0.6	1.0
	Aug		-0.2	-0.6	-0.2	0.1	1.3
	Sep		0.4	-1.2	-0.2	-0.2	1.1
	JJAS		0.0	-0.8	-0.3	0.2	1.1
	Oct		0.2	-0.9	-0.1	-0.4	1.2
	Nov		0.6	-1.5	-0.1	-0.3	0.6
IMR	May	U (m/s)	0.5	3.4	-0.3	-2.0	-0.7
	JJAS		1.2	-0.2	-0.2	-1.1	-0.2
	May	V (m/s)	2.2	-0.4	-0.6	-0.5	-1.0
	JJAS		0.5	0.2	0.0	-0.3	-0.7
			Rainfall intervals				
			B_{-2}	B_{-1}	B_0	B_1	B_2
NRT	MAM	*TT*	0.2	0.4	0.2	0.2	-0.7
	JJAS		0.3	0.4	0.0	0.7	-0.9
	OND		0.3	0.5	0.0	0.4	-0.8
	JF	U	-0.8	-0.4	-0.2	1.4	0.5
	MAM		-1.3	-0.6	-0.3	1.8	0.9
NRS	MAM	*TT*	1.0	0.0	0.2	-0.1	-0.6
	JJAS		1.1	0.2	0.0	-1.2	-0.3
	OND		1.3	0.1	-0.3	-0.5	-0.4
	Apr	U	-2.0	-0.4	0.2	0.2	1.1
	JJAS		-0.4	-0.1	-0.4	0.4	0.5

Abbreviations – As in Tables 1 & 2,
A_{-2}, A_{-1}, A_0, A_1, A_2 & B_{-2}, B_{-1}, B_0, B_1, B_2 as in Table 3

good monsoon and complement thereof to a poor monsoon. The relation between IMR and 200 hPa zonal wind averaged over India is clearly defined in September in respect of 6 stations located north of 20º N, with a CC of –0.70 (1% LS), which shows that a good (poor) monsoon produces zonal easterly (westerly) anomalies over the country at 200 hPa. Same type of relation is continued in October also, but the stations where the relation is manifested stretch southwards. The zonal mean wind of 9 stations all located over the peninsula shows a CC of –0.43 (1% LS,) with IMR. However the relation between zonal wind and IMR fades out in November and December. It is thus evident that the 200 hPa parameters of May offer the best predictive value for IMR, but best concurrent relation is obtained with the parameters of September.

4.1.2. *Relation with NRT/NRS*

In regard to the relationship with northeast monsoon rainfall the following relations are noteworthy :

(*i*) Mean monthly/seasonal 200 hPa temperatures over India are negatively related with NRT and NRS. The interpretation is that colder (warmer) upper troposphere over India favours a good (poor) northeast monsoon.

(*ii*) Zonal winds are, generally, positively related with NRT/NRS. The relation is well defined for NRT in April and again in October with CCs of 0.48 (1% LS) obtained for both the months. The relation is by and large non-existent during the southwest monsoon months of July and August, for both the series. The interpretation is that zonal westerly anomalies in pre-monsoon, favour a good northeast monsoon and easterly anomalies a poor northeast monsoon. From the relationship October zonal winds exhibit with IMR and NRT/NRS it is evident that a good southwest monsoon is associated with and perhaps causes zonal easterly anomalies in October, which in turn is associated with a weak northeast monsoon and *vice-versa*.

(*iii*) No systematic and significant relationship between meridional winds and NRT / NRS could be detected.

TABLE 6

Conditional means of IMR, NRT & NRS (in PDN) for various intervals of 200 hPa parameters over India, for selected months / seasons

Rainfall	Season	Parameter	Intervals (ºC)		
			≤ -1	±1	≥ 1
IMR	May	*TT*	-9	0	2
NRT	MAM		11	-2	-2
	Oct		16	-6	-4
	OND		7	0	-6
NRS	MAM		13	1	-12
	JJAS		9	3	-10
	Oct		15	-2	-6
			Intervals (m/s)		
			≤ -2	± 2	≥ 2
IMR	May	U	6	-4	-5
	Sep		7	-1	-14
	OND		7	-3	-7
NRT	Jan		-12	-1	16
	MAM		-20	2	15
	Jul		-12	0	12
	Oct		-14	12	7
	OND		-10	3	7
NRS	Jan		-13	3	10
	MAM		-17	2	18
	OND		-9	6	4
IMR	May	V	3	0	-8

Abbreviations as in Tables 1 & 2, PDN – Percentage Departure from Normal

4.2. *Analysis based on conditional means*

In this section we analyse the relation between the Indian upper tropospheric parameters with southwest and

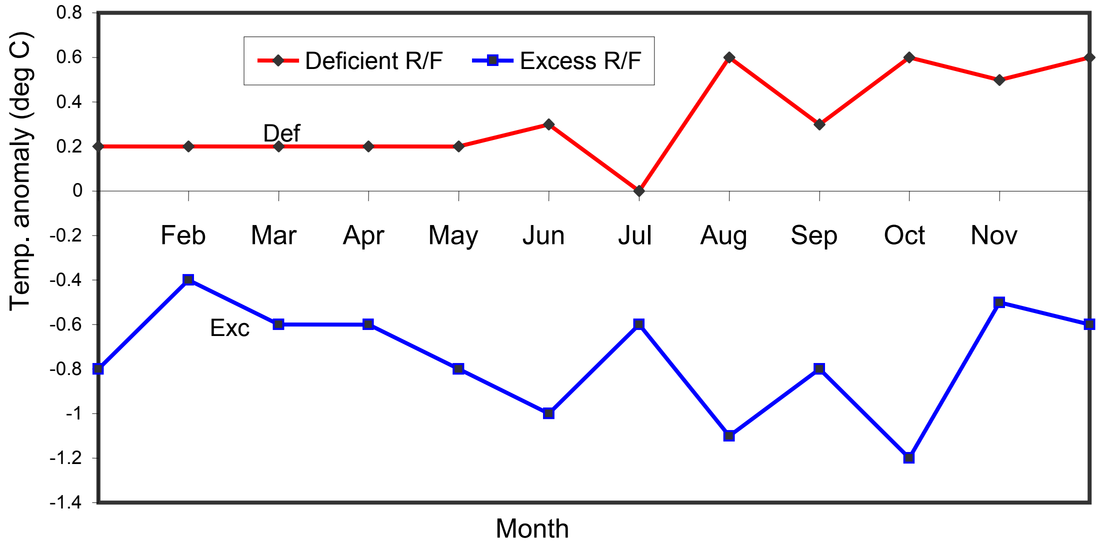


Fig. 2. 200 hPa mean monthly temperature anomalies (averaged over India) in years of 25% deficient/excess northeast monsoon rainfall over Tamil Nadu

northeast monsoon rainfall through the concept of conditional means. If *x* and *y* are two parameters to be studied for interrelationship, we can compute the conditional means of *y* for various sub-intervals of *x* and also means of *x*, for sub-intervals of *y*. Though a given conditional mean may not be based on all the available data, this line of approach to a certain extent eliminates the bias of assumption of linearity inherent in the correlation analysis. For IMR/NRT/NRS Table 3 defines the sub-intervals. For the upper air parameters, the intervals have been defined taking into consideration the range of the given parameter. In Table 5 the conditional mean anomalies of the 200 hPa parameters over India given rainfall of selected months/seasons are presented.

The 200 hPa temperatures of India are colder by 0.1 to 0.4º C during the months/season preceding deficient IMR years and 0.8 to 1.3º C warmer in pre monsoon and monsoon months in years of excess IMR. However, a deficient monsoon appears to slightly warm the upper troposphere in September and subsequent months, as seen from the temperature anomalies of 0.4° C and 0.6° C respectively for September and November of deficient IMR years, which brings out the non linear nature of the relation. The zonal and meridional winds are negatively related with IMR. The temperatures are warmer by 0.2 to 0.4º C in years of deficient NRT, but colder by 0.3 to 0.9º C in years of excess NRT during all the seasons, but again the relation manifests lack of linearity. The zonal winds are of easterly anomaly during JF and MAM in subnormal NRT years and are of westerly anomaly in above normal NRT years. Similar pattern is observed in respect of NRS also.

TABLE 7

Normal seasonal latitudinal position of 200 hPa Sub-tropical ridge at 77.5° E over India

Season	Normal (°N)	SD (°Lat.)
JF	8.9	1.7
MAM	9.0	2.1
JJAS	28.5	1.5
OND	12.7	1.3

Abbreviations – As in Table 1, SD – Standard deviation

In Table 6, the conditional means of IMR, NRT and NRS given the various intervals of anomalies of the parameters are presented. The sub-intervals are $\leq$ -1, (-1, 1) and $\geq$ 1 in ºC for *TT* and $\leq$ -2, (-2, 2) and $\geq$ 2 in m/s for U & V. When *TT* is colder in May, PDN of IMR has conditional mean of –9 but when *TT* is normal or warmer the relation is not that well defined. When zonal westerly anomalies and meridional southerly anomalies (both positive) prevail in May, the IMR has negative anomalies whereas easterly and northerly wind anomalies (both negative) are associated with positive IMR anomalies. The zonal wind anomalies persist through the monsoon months and extend into OND also as seen from the conditional means for September and OND.

When *TT* is colder in MAM and JJAS, NRT/NRS are in excess by 9 to 16 % of normal. When *TT* is warmer in MAM and JJAS, NRS is in deficit by 10 to 12 % of normal . When *TT* is colder in October, NRT and NRS are in excess by 15 to 16 % of normal suggesting a strong link. When *TT* is warmer, NRT and NRS are deficient

TABLE 8

Relation between Sub-Tropical Ridge position over India at 77.5º E and monsoon rainfall for selected months/seasons

Season / Month		IMR	NRT	NRS	
(a) Significant CCs					
May		0.36 *		-0.38 *	
JJAS		0.44 **			
Oct		0.40 *	-0.45 **	-0.37 *	

(b) Conditional means of rainfall (in PDN) given STR location

		Rainfall Intervals				
		A_{-2}	A_{-1}	A_0	A_1	A_2
IMR	May	-0.7	-1.8	0.0	1.4	0.9
	JJAS	-1.2	-0.3	0.2	1.6	0.2
	OND	-0.3	-0.4	0.0	0.1	0.9
		Rainfall Intervals				
		B_{-2}	B_{-1}	B_0	B_1	B_2
NRT	JF	0.8	0.8	-0.2	-0.8	-0.5
	MAM	0.8	1.7	0.2	-1.4	-1.1
NRS	MAM	1.9	0.3	0.5	0.8	-2.0

(c) Conditional mean anomalies of STR (in º latitude) given rainfall

		STR anomaly in degree Latitude		
	Season/Month	≤ -1	± 1	≥ 1
IMR	MAM	-4	-4	2
	JJAS	-9	-2	4
	OND	-4	-3	3
NRT	MAM	14	9	-15
	JJAS	19	-3	-5
	OCT	12	2	-12
NRS	MAM	19	5	-12
	JJAS	14	1	-6
	OCT	13	0	-9

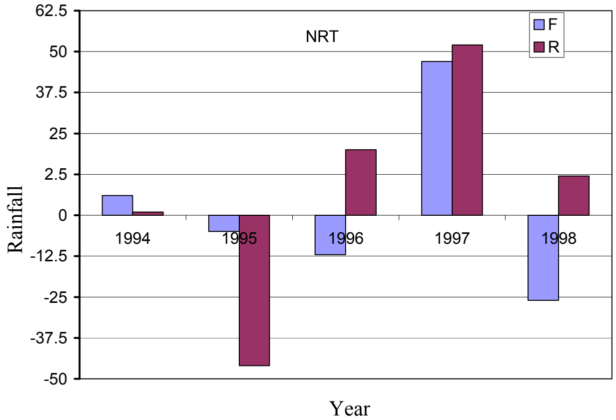
Abbreviations - as in Tables 1,2 & 3

from normal by 4 to 6%. Fig. 2 clearly illustrates the systematic variation of monthly temperature anomalies over India during above/below normal NRT years *i.e.*, colder (warmer) temperatures associated with excess (deficient) northeast monsoon rainfall. The prevalence of easterly (westerly) zonal wind anomalies during a few months in winter, pre-monsoon and monsoon is associated with negative (positive) NRT/NRS anomalies. The relation persists through OND also for both the rainfall series.

From Tables 4, 5 & 6, it is evident that the seasonal profiles of relation between the 200 hPa parameters over India and NRT/NRS display a double peak. The profile in respect of NRT/NRS peak in April and October which clearly brings out the important role played by the monsoon rainfall in modifying the heating and hence the divergence pattern at the upper troposphere. It has been found that month to month persistence of temperature is very high with CC values of more than 0.8 between two consecutive months.

4.3. *Analysis based on 200 hPa ridge position*

The east-west sub-tropical ridge at 200 hPa over India, which separates the extra tropical westerlies in the north and the tropical easterlies in the south, and overlaps the area of warmest temperature of the region, is an important feature of the upper tropospheric flow pattern. We have derived the approximate mean latitudinal position of the STR at 77.5º E for the twelve months and four seasons for each year of the entire period 1963-98 from the monthly seasonal mean zonal wind data for all the 14 stations considered in the study. The derivation was accomplished by adopting the following methodology. If u_i is the mean zonal wind for a month /



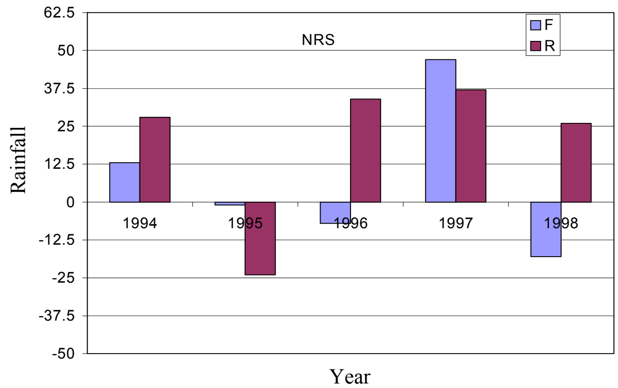


Fig. 3 Performance of regression scheme, 1994-98 for NRT/NRS based on October data. [Forecast (F) and Realised (R) rainfall as percentage departures from normal]

season for the station say S_i, we set up the equation $u_i = A\,\lambda_i + B\,\varphi_i + C$, $i = 1,2,\ldots, 14$ where (λ_i, φ_i) is the longitudinal and latitudinal position of S_i. The values of A, B and C were estimated from the method of least squares and the concept of multiple regression. In all the cases, the fit was very good with the variance explained being generally higher than 95%. The mean latitudinal STR position was then computed by setting $u_i = 0$ and $\lambda_i = 77.5$ in the above equation which was done for all months and years. From this data, normal position of the STR and its standard deviation were derived for each month and season presented in Table 7.

The STR that is located at nearly 9º N during winter and pre-monsoon shifts to 28-29º N during June-September and thence shifts southwards to nearly 13 ºN during post-monsoon. As is well known the considerable northward movement of STR is in association with the establishment of Indian monsoon, the heating over Tibetan plateau and several other dynamical features of monsoon. The relation between the STR position and the monsoon rainfall was studied as done in Sec.4, using correlation analysis and by computing conditional means. Table 8 presents the results.

The STR position is positively correlated with IMR in May, JJAS and October, *i.e.*, northerly (southerly) position associated with good (poor) monsoon. In May, during years of sub/below normal monsoon, the STR is located south of its normal position by 0.7 to 1.8 º, and in years of slightly above normal / above normal monsoon, it is located north by 0.9 to 1.4º, though the relation is not linear. This pattern of relation persists in JJAS and OND also in varying degrees. From Table 8(c) we observe that when STR is south of its normal position by 1º in MAM, JJAS and OND, IMR is deficient by 4 - 9% of normal and when STR is north of its normal position, IMR is excess by 2 - 4%. These deviations are not that large and when viewed in conjunction with the magnitude of CCs presented in 8(a), indicate the modest yet consistent nature of relation between IMR and STR location.

With northeast monsoon rainfall, the STR position manifests relation in the opposite sense, the CCs are negative and are significant (with NRS) in May and (with both NRT and NRS) in October. Thus a southward location of the ridge in October favours a good northeast monsoon. The relation is still better defined through conditional means. During years of deficient NRT, the STR is located north of its normal position by 0.8 to 1.7º even during JF and MAM. During years of excess NRT, it is located south by 0.5 to 1.4º N. When STR is south of its normal position by 1º in MAM, NRT is excess by 14% and if it is north by 1º, NRT is deficient by 15%. Similar is the case in JJAS and October also, the NRT excess by 19% and 12% for southerly location and deficient by 5-12% for northerly location.

5. Outlook on northeast monsoon rainfall based on October data

In a few studies referred in Sec. 2, statistical equations for forecasting northeast monsoon rainfall over the Indian peninsula have been developed, and the results presented. Such studies have been based predominantly on upper air data of the preceding months, *i.e.*, period upto September. The comparatively high degree of relation between U, *TT* and STR positions and NRT/NRS during October when compared to the preceding months suggest October data also as a strong candidate in a forecasting scheme of northeast monsoon rainfall despite the fact that by the time forecast based on October data gets prepared, the season is partly over.

We have derived multiple regression equations for predicting NRT/NRS based on October data of the 31 year

TABLE 9

Multiple regression forecast scheme for NRT/NRS based on October 200 hPa parameters, 1963-93

Predictand *y*	Predictor *x*	Mean (*x*)	SD (*x*)	CC (*x*, *y*)	Multiple CC
NRT	U (m/s)	-0.5	3.8	0.44**	
	TT (°C)	-52.5	1.5	-0.44**	0.58**
	R (°lat.)	16.4	1.8	-0.40*	
NRS	U	-2.9	3.7	-0.52**	
	TT	-52.3	1.6	0.40*	0.61**
	R	16.4	1.8	-0.36 *	

U/*TT* : Mean zonal wind/ Temperature of October 200 hPa of : NGP, BWN, BMB, HYD, VSK, MDS, PBL for NRT; BWN, HYD, VSK, MDS, PBL for NRS; R: Mean position of 200 hPa subtropical ridge at 75 °E over India in October. Abbreviations as in Tables 2&4.

period 1963-93 and tested the equations in the 5 year independent sample of 1994-98. The three predictors are: temperature and zonal wind averaged over a few stations and latitudinal position of STR at 77.5° E. Table 9 contains details of the predictors, their means and standard deviations, the CCs between the predictors and the predictand based on the test period, and the multiple CC obtained. Fig. 3 presents the performance of the regression equation during 1994-98. The scheme has given correct forecasts in 1994 & 1997 for NRT and in 1994, 1995 & 1997 for NRS. For both the series, the forecasts are wrong for 1996 and 1998. The performance of the scheme in the test period is evidently mixed and perhaps in line with the modest value of the multiple CC which explains only upto 36% of total variation of the predictand.

6. Relation between IMR, NRT and NRS

Having studied how the relation between 200 hPa upper air temperature/flow pattern over India and the southwest/northeast monsoons has evolved in monthly and seasonal time scales, it is perhaps appropriate to examine the direct relation between IMR and NRT/NRS. Based on the 100-year data of 1901-2000 the CCs between IMR and NRT&NRS are obtained as -0.16 and -0.10 respectively, both not significant. However the analysis based on conditional means brings out the relation between the two pairs of series in a much better perspective. In Fig. 4. we present the conditional means of PDN of NRT and NRS corresponding to different class intervals of the IMR range. The profiles of conditional means clearly reveal that negative relation between IMR and NRT/NRS is clearly defined when PDN of IMR is > -10, *i.e.*, when IMR is normal or excess. The conditional

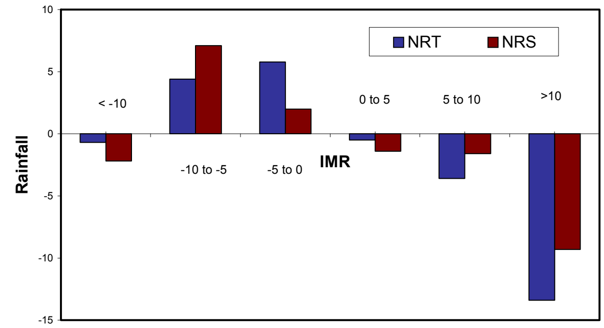


Fig. 4 Conditional means of northeast monsoon rainfall of Tamil Nadu/Southern region (NRT/NRS) given Indian southwest monsoon rainfall (IMR) based on 1901-2000 data (Rainfall as % departure from normal)

means for the intervals < -10, (-10, -5) (-5, 0) (0,5) (5,10), >10 are respectively -0.7, 7.3, 5.8, -0.5, -3.6 and -13.4 for NRT and -2.2, 7.1, 2.0, -1.4, -1.6 and -9.3 for NRS. However when IMR is deficient the conditional means (based on 21 deficient years of IMR) are close to zero in both the cases showing that the negative relation obtained when IMR is normal/excess does not get extended when IMR is deficient. When the 21 deficient IMR years are excluded, the CC between IMR and NRT is -0.24 (1% LS) and -0.18 for NRS (5% LS). A noteworthy feature of the contingent relation between IMR and NRT is that when IMR was excess (> 10%) NRT has not been above normal (> 25%) during 1901-2000 and that during 82% of the occasions had negative rainfall departures. Out of the 21 deficient IMR years NRT was deficient and excess (PDN < -25 & >25) in 5 years for each category and was normal in the remaining 11 years. The two series are thus negatively related save for years of deficient IMR.

7. Discussions

The following broad based features emerge from the analysis performed in the previous sections on the relation the 200 hPa upper tropospheric parameters over India have, with the Indian monsoon and subsequent northeast monsoon.

Warmer temperatures, higher northerly component in the meridional wind and northern position of STR in May, JJAS and October are by and large associated with good IMR and complement with poor IMR. Now, a good (poor) southwest monsoon causes warming (cooling) of the atmosphere and generates higher (lower) amount of upper tropospheric divergence. The monsoon therefore could be seen as a major causative mechanism behind the variation of upper tropospheric parameters over India during JJAS and October. This could be due to the excess/poor release of latent heat during excess/poor monsoon season. Pre-indication of this, as evidenced by the relation in May serves as a predictor which may be related to influence of mid-latitude circulation in May. For the smaller scale northeast monsoon during OND, surprisingly signals albeit weak are available from the beginning of the year itself with the zonal winds positively related and temperatures/contour height negatively related with NRT/NRS. The STR position during JF and MAM is negatively correlated with southern position favouring good northeast monsoon. By and large we find that features that favour good southwest monsoon, do not favour good northeast monsoon and *vice versa* which ties up with the discordant, if not decisive negative relationship between IMR and NRT. The equatorial trough and subtropical high are transpositioned in a substantially northern location during southwest monsoon season when compared to northeast monsoon season resulting in reversal of thermal wind from westerly (during the former) to easterly (during the latter) over most parts of India. This feature appears to play an important role in the existence of the discordant relation between the two monsoons (Raj, 1998).

The physical significance of the antecedent parameters related with southwest monsoon has been widely discussed in the literature, Asnani (1993) providing a detailed summary. The differential heating of land and sea and the response of the atmosphere to the high land surface temperatures prevailing over the Asian region during the northern hemispheric summer is considered as the primary cause of the summer monsoon. Most of the antecedent relations identified for southwest monsoon from the northern hemisphere are perhaps different manifestations of the above feature only.

As for northeast monsoon, Krishnamurthy (1979) and Das (loc.cit) have mentioned that the Siberian anticyclone and sub-tropical jet stream of winter are important components of Asian winter monsoon and replicate more or less the role played by the Mascarene high and tropical easterly jet stream of winter during summer monsoon and that the intense outflow from the Siberian High generates the so-called `*cold surges*' that intensify the Asian winter monsoon. The results of this study are in good agreement with the above broad based postulates. As the Siberian high is a cold high, cold surges would correspond to colder temperatures at all levels, strong westerly jet over large parts of northern hemisphere and also a southward position of STR. The Siberian cold high reaches its peak intensity during December-February only, but being such a dominant feature, its build-up in the preceding months could be expected to influence the wind and temperature anomalies over Asian region.

Finally the relations that we have been able to bring out of the upper troposphere explain only a modest percentage of northeast monsoon rainfall variation perhaps suggesting that it is just one of the several components exciting this monsoon. For IMR numerous studies have been already published and are still appearing, bringing into focus several new global antecedent/concurrent relations. For Indian northeast monsoon also, some global relations have been identified, *e.g.*, with ENSO the relation expectedly in contrast with that with IMR *viz*. El-Nino and negative Southern Oscillation Index (SOI) favouring good northeast monsoon and La-Nina and positive SOI favouring good southwest monsoon. (Jayanthi and Govindachari 1999). Despite the identification and consolidation of a few antecedent relations for northeast monsoon we feel that the degree of relationship as obtained herein may not be high enough to provide very accurate quantitative seasonal forecasting of NRT / NRS as is the case with IMR. However an outlook using preferably qualitative terminology could be prepared ahead of the northeast monsoon season, or by the end of October as shown in the study.

8. Summary

Herein below we provide a brief summary of the results deduced in the paper wherein relation between monthly and seasonal means of wind and temperature at 200 hPa level 14 Indian stations for the 36 year period 1963-98 with the southwest and northeast monsoon rainfall has been studied.

(*i*) Easterly zonal wind anomalies, positive temperature anomalies, northerly meridional wind anomaly, northern position of the sub tropical ridge at 77.5° E during the period May-October are features by and large associated with good southwest monsoon and complement of the above with poor southwest monsoon.

(*ii*) Westerly zonal wind anomalies, negative temperature anomalies, and southern position of sub tropical ridge at 77.5° E during the preceding pre-monsoon and monsoon seasons, by and large, favour good northeast monsoon while complement of the above are associated with poor northeast monsoon.

(*iii*) The monthly profiles of the above relationships have generally displayed a double peak one in May and the other in September/October. The comparatively strong relation in October results from the influence of southwest monsoon in modifying the atmosphere.

(*iv*) The above relations however have been generally modest barring a few. Generally weather parameters that favour good southwest monsoon do not favour a good northeast monsoon and *vice versa*.

(*v*) A multiple regression forecast scheme for October-December rainfall of Tamil Nadu/Southern Region, based on three 200 hPa parameters of October, provided nearly 50% correct forecasts.

(*vi*) The southwest monsoon rainfall and the succeeding northeast monsoon rainfall share a negative relationship, which is discordant rather than decisive. The relation however is significant and clearly defined for years when IMR is normal/excess and not deficient.

(*vii*) The northeast monsoon though may not appear to be directly influenced by the differential heating of land and ocean, nevertheless gets influenced by large scale circulation features that eventually result from summer land-sea thermal contrast, considered as the major mechanism driving the southwest monsoon.

(*viii*) That colder upper tropospheric temperatures over India in the preceding months favour good Indian northeast monsoon tie in well with the accepted mechanism of cold surges from the Siberian cold High intensifying the Asian winter monsoon.

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