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551.511 : 551.513 : 551.553.21 (548.1)

Inter and intra-seasonal variation of thermodynamic parameters of the atmosphere over coastal Tamilnadu during northeast monsoon

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सार — वर्ष 1976-77 से 1985-86 की दस वर्ष की अवधि के, मद्रास के अक्तूबर से जनवरी के 1000 और 500 एम. बी. स्तरों के बीच के दैनिक 0000 यू. टी. सी. उपरितन वायु आंकड़ों के आधार पर तटीय तमिलनाडु में उत्तरपूर्वी मानसून के दौरान वायुमंडल की तापगतिकीय संरचना का विस्तृत रूप से अध्ययन इसमें किया गया है। उत्तर-पूर्वी मानसून के शुष्क और आर्द्र दौर की तथा उत्तरपूर्वी मानसून के आरम्भ से पहले की दक्षिण-पश्चिमी मानसून की लघु अवधि की सामान्य उपरितन वायु दशाओं का आकलन किया गया है। मानसून की विविध गतिविधियों के लिए मद्रास के ऊपर जलीय अंश और मद्रास के पार आर्द्रता अभिवाह का आकलन किया गया है। इस बात का पता चला है कि मद्रास में सभी स्तरों पर 500 एम. बी. तक वायुमंडल में 1 डिग्री सेल्सियस तक तापमान गिर जाने पर पूर्वी हवाएं चलनी आरम्भ होती हैं। उत्तर-पूर्वी मानसून के विशिष्ट आर्द्र दौर में मद्रास में एक डिग्री सीमा के पार प्रतिदिन 21.1 × 10⁸ मीट्रिक टन के पूर्व से पश्चिम आर्द्रता अभिवाह ने तट पार किया। अध्ययन की अवधि की अच्छी उत्तर-पूर्वी मानसून के लिए तट पार करते आर्द्रता अभिवाह और आकलित सामान्य अभिवाह,विभिन्न अन्य अध्ययनों से प्राप्त दक्षिण-पश्चिमी मानसून के दौरान पश्चिम तट पार करते हुए आर्द्रता अभिवाह के अनुरूप पाए गए हैं। उत्तर-पूर्वी मानसून के आरम्भ होने के बाद तटीय तमिलनाडु में वायु झोंकों की शक्ति क्षीण होती पाई गई। द्रव-जल अंश की परिवर्तिता के विश्लेषण से पता चलता है कि कम वर्षा वाले दिनों में भी वायुमंडल में निम्न स्तरीय आर्द्रता पर्याप्त मात्रा में पाई गई। न तो उत्तर-पूर्वी मानसून के शुष्क दौर के दौरान तथा न ही इसकी वापसी के बाद बड़े पैमाने पर हवाएं चलने के तटीय तमिलनाडु में स्पष्ट संकेत थे।

ABSTRACT. The thermodynamic structure of the atmosphere over coastal Tamilnadu during the northeast monsoon season has been studied in detail based on the daily 0000 UTC upper air data between 1000 and 500 hPa levels of Madras for October-January for the 10-year period 1976-77 to 1985-86. Normal upper air soundings have been computed for dry and wet spells of northeast monsoon and for the brief period of southwest monsoon prior to northeast monsoon onset. The moisture flux crossing Madras and the liquid water content over Madras have been computed for various categories of monsoon activity. It has been shown that the onset of easterlies over Madras is accompanied by a cooling of 1°C of the atmosphere over Madras at all levels upto 500 hPa. An east to west moisture flux of 21.1×10^8 metric tons per day across one degree wall over Madras has been found to cross coast during typical wet spell of northeast monsoon. The moisture flux crossing coast for good northeast monsoon and also the normal flux computed for the period of study compared fairly well with the moisture flux crossing west coast during southwest monsoon obtained in various other studies. The energy of an air column over coastal Tamilnadu was found to decrease subsequent to the onset of northeast monsoon. Analysis of variation of liquid water content revealed that even during deficit rainfall years there was considerable amount of low level moisture in the atmosphere. Neither during dryspells of northeast monsoon nor after its retreat was there any clear sign of spreading of continental air mass over coastal Tamilnadu.

Key words — Northeast monsoon, Southwest monsoon, Onset, Withdrawal, Coastal Tamilnadu, Thermodynamic structure, Moisture flux, Liquid water content (LWC), Lapse rate, Energy, Airmass.

1. Introduction

The northeast monsoon is a monsoon of smaller scale and dimension benefiting the southern parts of India during the post-southwest monsoon months of October-December. Tamilnadu, located in the southeastern parts of India, is a major beneficiary of northeast monsoon rains. In Tamilnadu itself it is in the coastal strip where the onset, activity and the withdrawal of northeast monsoon are well pronounced. IMD (1973) provides a detailed description of Indian northeast monsoon. Though the literature abounds in several studies on the various aspects of this monsoon, its thermodynamic structure does not appear to have been researched in detail like that of southwest monsoon (Srinivasan and Sadasivan 1975). In the present study an attempt has been made to study in some detail the variation of upper air parameters over coastal Tamilnadu during northeast monsoon.

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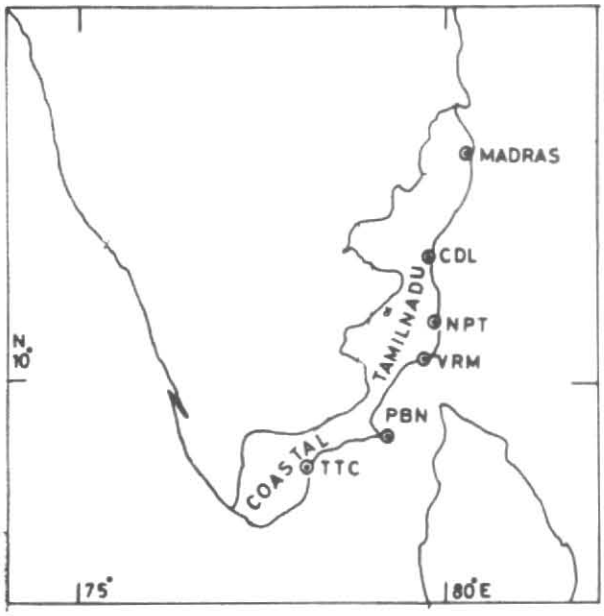


Fig. 1. Location of coastal Tamilnadu stations under study

2. Data

Upper air data, *viz.*, height, dry bulb and dew point temperatures and winds between 1000 and 500 hPa levels at each 50 hPa level for 0000 UTC at Madras was obtained from National Data Centre, India Meteorological Department, Pune, for the four month period of 1 October-31 January for each year of the 10-year period 1976-77 to 1985-86. In the decade 1976-85, the state and meteorological sub-division of Tamilnadu, received excess rainfall in 1977, 1978 and 1979, deficient rainfall in 1980 and 1984 and normal rainfall during the rest. As such this decade could be by and large considered as a representative period of northeast monsoon activity over Tamilnadu. The dates of onset of easterlies over Madras, the dates of onset and withdrawal of northeast monsoon over coastal Tamilnadu (CTN) and the rainfall during October-December over Tamilnadu alongwith the long term normals of these parameters are given in Table 1. These dates have been taken from Raj (1992). As seen from Table 1, in some years the northeast monsoon spilled over to January of next calendar year and hence the inclusion of January in the period of study. Daily rainfall data for six stations of CTN, *viz.*, Madras, Cuddalore, Nagapattinam, Vedaranyam, Pamban and Tuticorin were also obtained and utilised in the study. Fig. 1 depicts the geographical location of these stations including Madras and also of coastal Tamilnadu.

3. Methodology and analysis

The normal dates of onset of low level (surface — 850 hPa) easterlies and northeast monsoon over CTN are 14 and 20 October respectively (Table 1). From May onwards lower level winds over Madras are predominantly westerlies which reverse to north-easterlies in October as a prelude to the onset of northeast monsoon. An active rainspell over CTN in October during the westerly regime prior to the onset of northeast monsoon is not at all uncommon. The onset is always associated with a wet spell with the succeeding season interspersed with wet and dry spells upto the time of withdrawal whose normal date is 27 December. We propose to study whether the thermodynamic structure over CTN as represented by the upper air observations of Madras responds to the sequence of these various events.

TABLE 1

Northeast monsoon parameters during 1976-77 to 1985-86

Year	Dates A	Dates B	Dates C	D (mm)
1976-77	1 Oct	15 Oct	26 Dec	0
1977-78	5	10	6	56
1978-79	20	21	1 Jan	33
1979-80	6	22	15 Dec	32
1980-81	3	10	6	−24
1981-82	6	23	24	−8
1982-83	2	18	19	−18
1983-84	17	24	18 Jan	12
1984-85	24	3 Nov	7	−38
1985-86	19	24 Oct	17	2
Normal (1901-90)	14 Oct	20 Oct	27 Dec	477

A — Onset dates of low level easterlies over Madras

B — Onset dates of northeast monsoon over coastal Tamil Nadu

C — Withdrawal dates of northeast monsoon from coastal Tamil Nadu

D — Rainfall of Tamilnadu during October-December as percentage departure from normal

The daily rainfall data of stations of CTN was scrutinised and based on the dates of Table 1, periods pertaining to the following six spells were identified, which are :

(*i*) Wet spell during southwest monsoon regime prior to onset of easterlies.

(*ii*) Dry spell during southwest monsoon regime prior to onset of easterlies.

TABLE 2

Normal intra-seasonal variation of 0000 UTC upper air temperatures (°C) over Madras

Month	Pressure levels (hPa)					
	1000	900	800	700	600	500
October	25	22	16	9	3	−5
November	24	20	15	9	3	−5
December	22	18	14	9	3	−5
January	19	18	14	9	3	−6

(Normal based on 1976-77 to 1985-86 data)

(*iii*) Wet spell during northeast monsoon.

(*iv*) Dry spell during northeast monsoon.

(*v*) Spells during northeast monsoon that are neither fully wet nor fully dry.

(*vi*) Dry spell after the withdrawal of northeast monsoon.

The mean dry bulb and dew point temperatures, zonal and meridional components of the wind at each 50 hPa level were computed by averaging data of individual days for the period of study for each of the six types of spells listed above. The mean relative humidity was obtained from the mean dry bulb and dew point temperatures. The liquid water content (LWC) between 1000 and 500 hPa levels was computed from the formula

$$\text{LWC} = -1/g \int q \, \mathrm{d}p \qquad (1)$$

where, q is specific humidity. Climatologically the atmosphere over Madras cools in the lower levels with the advancement of the season as can be seen from Table 2 which presents the short term normal monthly temperatures, based on the period of study, at some levels. As the mean calendar dates of the various spells (*i*) — (*vi*) are not expected to be the same, it is appropriate to adjust the mean temperature for the march of the season before making any comparison. Therefore, the daily short period normal temperatues at each 50 hPa level for each day of 1 October-31 January were computed based on the 10-year data and smoothed with a moving average filter. Using this normal daily data, mean temperature anomalies were also computed for the six spells.

3.1. *Flux computations*

The transport of water vapour from Arabian sea, across the west coast and over the Indian region during southwest monsoon has been studied extensively by Sikka and Mathur (1965), Pisharoty (1965), Desai (1966 and 1968), Ramamurthy *et al.* (1976). Saha and Bavadekar (1977), Ghosh *et al.* (1978 and 1981), Dewan *et al.* (1984) and Appa Rao (1985) etc. The vertically integrated zonal (Fz) and meridional (Fm) moisture fluxes over a longitude/latitudinal distance s and a period of time t is given by

$$Fz = 1/g \int\int\int qu \, \mathrm{d}p \, \mathrm{d}s \, \mathrm{d}t \qquad (2)$$

$$Fm = 1/g \int\int\int qv \, \mathrm{d}p \, \mathrm{d}s \, \mathrm{d}t \qquad (3)$$

where, u and v are the zonal and meridional components of winds at pressure level p. In this study we have computed the flux over one degree wall (ODW) centred at Madras extending from 1000-500 hPa for a period of 24-hr using the daily 0000 UTC upper air data as the input. During October-January the surface pressure at Madras is only slightly above 1000 hPa and so this level can be taken as the surface level for all practical purposes.

Table 3 presents the mean profiles of temperature, temperature anomaly, relative humidity, zonal and meridional winds at every 50 hPa level for the various cases listed in the preceding paragraph. Table 4 gives the moisture flux, LWC and also the mean date of the spell. The salient features deduced from a critical evaluation of Tables 3 and 4 are discussed below.

The wet spells over CTN before the establishment of low level easterlies have a mean date of 5 October. Values of relative humidity are upward of 60% even at 500 hPa. The atmosphere is warmer than normal at almost all levels. Zonal winds change from westerlies in the lower levels to week easterlies in the mid-tropospheric levels. The LWC is 54 mm with the WE zonal moisture flux at 9.9×10^8 metric tons per day (mtpd) crossing an ODW.

The dry spells during the westerly regime have a mean date of 12 October. Nearly 60% relative humidity prevails upto 700 hPa level. Sharp decrease of moisture is observed only aloft. The atmosphere is warmer than normal at all levels. Both westerlies and northerlies are stronger than those of wet spells and the westerly depth goes

TABLE 3

Mean structure of the upper air atmosphere over Madras during various spells

Type of spell		Pressure levels (hPa)										
		1000	950	900	850	800	750	700	650	600	550	500
(*i*)	T	25.5	25.5	22.8	20.0	17.0	13.9	10.9	7.5	4.1	0.5	−3.7
	TA	−0.3	0.5	0.4	0.4	0.5	0.7	0.8	0.7	0.8	0.8	0.8
	RH	89.8	81.0	80.7	81.1	80.3	78.3	72.5	69.8	68.8	65.5	60.4
	U	2.2	4.0	3.4	2.3	1.6	1.0	0.4	−0.2	−1.0	−1.3	−1.5
	V	0.5	0.5	0.2	−0.4	−0.3	−0.1	0.7	0.9	1.1	1.3	2.1
(*ii*)	T	25.8	25.3	22.8	19.8	16.3	12.8	9.6	6.6	4.0	0.3	−3.7
	TA	0.4	0.7	0.8	0.7	0.3	0.2	0.1	0.2	0.8	0.9	0.8
	RH	82.9	69.5	63.6	62.0	62.5	60.0	58.0	49.0	41.4	39.7	37.0
	U	2.6	4.3	4.1	3.3	2.7	2.5	2.9	2.9	2.8	1.8	1.1
	V	0.9	1.8	−0.2	−2.1	−3.3	−3.4	−2.6	−1.1	0.1	0.4	−0.3
(*iii*)	T	23.8	22.7	20.0	17.3	14.7	12.0	9.1	5.9	2.5	−1.1	−5.3
	TA	0.3	−0.1	0.1	0.1	0.0	−0.1	−0.2	−0.3	−0.4	−0.3	−0.2
	RH	92.2	86.3	82.9	80.6	75.5	72.1	67.4	61.7	56.7	55.7	50.7
	U	−2.1	−4.7	−5.9	−6.0	−5.7	−5.3	−4.8	−4.2	−4.1	−4.0	−4.4
	V	−3.1	−2.9	−1.8	−1.6	−1.4	−0.5	0.0	0.4	0.6	0.9	1.1
(*iv*)	T	22.6	22.3	19.5	16.6	14.4	12.3	10.0	6.9	3.6	−0.3	−4.7
	TA	−0.4	−0.1	−0.1	−0.3	0.0	0.3	0.6	0.7	0.7	0.5	0.3
	RH	86.9	74.0	64.0	54.3	43.9	42.6	33.9	34.5	29.2	29.5	32.7
	U	−0.8	−2.8	−3.8	−3.8	−3.1	−3.1	−2.9	−2.7	−2.9	−3.6	−4.3
	V	−3.2	−3.7	−3.3	−3.1	−2.8	−2.2	−1.7	−1.1	−1.1	−0.6	−0.7
(*v*)	T	23.3	22.5	19.5	16.8	14.6	12.2	9.6	6.4	2.9	−0.9	−5.0
	TA	0.2	0.2	0.1	0.0	0.3	0.3	0.3	0.1	0.0	0.0	0.1
	RH	87.7	80.3	75.6	66.2	54.0	49.8	45.8	43.3	40.9	39.9	41.8
	U	−1.6	−4.0	−5.0	−5.0	−4.7	−4.2	−3.8	−3.6	−3.4	−3.7	−3.6
	V	−4.0	−4.8	−4.1	−3.3	−2.0	−1.5	−0.9	−0.5	−0.1	0.1	0.0
(*vi*)	T	21.5	21.0	17.9	15.6	13.5	11.5	9.0	6.3	2.7	−1.3	−5.7
	TA	−0.2	−0.1	−0.1	−0.1	−0.1	−0.1	−0.2	−0.1	−0.1	−0.1	−0.2
	RH	86.7	76.0	67.1	49.8	37.6	31.1	29.0	29.5	28.9	29.9	27.1
	U	−2.4	−4.1	−4.9	−4.7	−3.9	−2.7	−1.3	−0.3	0.2	1.0	2.0
	V	−3.0	−2.2	−1.7	−2.0	−2.0	−1.3	−0.7	−0.5	−0.4	−0.9	−1.1

(*i*) Wet spell during southwest monsoon regime (*ii*) Dry spell during southwest monsoon regime (*iii*) Wet spell during northeast monsoon (*iv*) Dry spell during northeast monsoon (*v*) Spells during northeast monsoon neither wet nor dry (*vi*) Dry spell after the withdrawal of northeast monsoon

T — Temperature (°C), TA — Temperature anomaly (°C), RH — Relative humidity (%), U — Zonal wind (m/s), V — Meridional wind (m/s)

beyond 500 hPa. The LWC at 41 mm is only 24% lower than the LWC for the wet spell. A higher zonal flux of 12.9×10^8 mtpd over ODW crosses from west to east.

During active northeast monsoon spells (mean date 21 November) the temperature anomalies are near zero upto 800 hPa and are negative aloft. The meridional wind, which is northerly in the lower levels, veers to southerly in the higher levels. The LWC is 46 mm and the EW and NS daily moisture flux values over an ODW are 21.2×10^8 and 5.8×10^8 mtpd respectively.

During dry spells of northeast monsoon the temperature anomalies are negative upto 800 hPa and positive aloft, a feature that is in contraposition to that corresponding to wet spells. The relative humidity decreases rapidly with height and is below 60% aloft at 850 hPa level. The northerly component of the wind is considerably higher than that of wet spell and also persists upto higher levels. The LWC

TABLE 4

Moisture flux and LWC during various spells

Type of spell	LWC	Zonal flux	Meridional flux	Mean date of spell	No. of days of spell
(*i*)	54.4	9.9	1.5	Oct 5	30
(*ii*)	41.1	12.9	−3.0	Oct 12	59
(*iii*)	46.0	−21.2	−5.8	Nov 20	271
(*iv*)	28.1	−7.0	−7.0	Nov 28	172
(*v*)	36.0	−13.7	−9.8	Nov 29	216
(*vi*)	22.1	−8.0	−4.2	Jan 11	340

(*i*) to (*vi*) — As in Table 3 LWC — Liquid Water Content (mm) Flux — Crossing 1° wall during 24 hr (10^8 metric tons) W, S Flux — Positive E, N Flux — Negative

is 28 mm which is only 61% of that of wet spell. At 7.0×10^8 mtpd the NS and EW fluxes over an ODW are near identical.

During spells of intermediate type of activity, *viz.,* neither fully wet nor completely dry, the temperature anomalies are near zero at all levels. There is good saturation upto 850 hPa where the relative humidity is 66%. Aloft this level the moisture decreases sharply. The LWC is 36.0 mm and the EW & NS fluxes are 13.7×10^8 & 9.8×10^8 mtpd respectively over an ODW.

After the retreat of northeast monsoon the temperatures are closer to normal. The LWC is lightly lower at 22 mm compared to that for the dry spell. The atmosphere is considerably drier as seen from the lower values of humidity. The EW and NS fluxes are respectively 8.0×10^8 & 4.2×10^8 mtpd for ODW.

It is evident from the above description and from Tables 3 and 4 that, over CTN the atmosphere is generally more moist during the westerly than the easterly regime. The LWC during a westerly dry spell is only 12% lower than LWC of a northeast monsoon wet spell. During dry spells of northeast monsoon the atmosphere becomes substantially dry in the higher levels in contrast to those of westerly regime when considerable moisture is available in the atmosphere.

Rao (1963) has advanced a theoretical reasoning, based on the tilting term of the vorticity equation (Holton, 1979), in support of the hypothesis that the meridional component of the wind over Madras during northeast monsoon has to be northerly in the lower levels and should veer to southerly in the middle levels for wet spells (active monsoon) but has to remain northerly in all the levels for dry spells (weak monsoon). Though the postulate does stand reinforced from the normal wind pattern for wet and dry spells derived in this study, the theoretical explanation does not appear to hold good as dv/dz, *viz.,* the variation of v with height is found to be more or less the same in both the cases. It appears that transport of higher amount of moisture due to the predominantly southerly component, into the shore, in view of the convergence associated with such a feature, could be a possible mechanism for active northeast monsoon rather than higher amount of vorticity generated from the contribution of tilting term.

Table 5 presents the difference between temperature anomalies of wet and dry spells of northeast monsoon. That the atmosphere during a wet spell is slightly warmer upto 800 hPa and colder aloft is clearly brought out. This feature is associated with a slightly higher lapse rate which evidently causes more instability and so favours good monsoon activity. As seen from Table 3, the temperature anomalies are positive during westerly regime for both dry and wet spells. To examine this feature further, the mean temperature profiles for 10 days before and 10 days after the time of easterly onset were computed. The temperature anomalies in each period and the difference in anomalies are given in Table 5. It is evident that nearly 1°C cooling takes place at every level of atmosphere upto midtroposphere. A similar exercise carried out for periods prior to and after the date of onset of northeast monsoon did not manifest any such abrupt discontinuity of temperature. Thus the onset of easterlies over CTN, which roughly takes place one week prior to the onset of northeast monsoon,

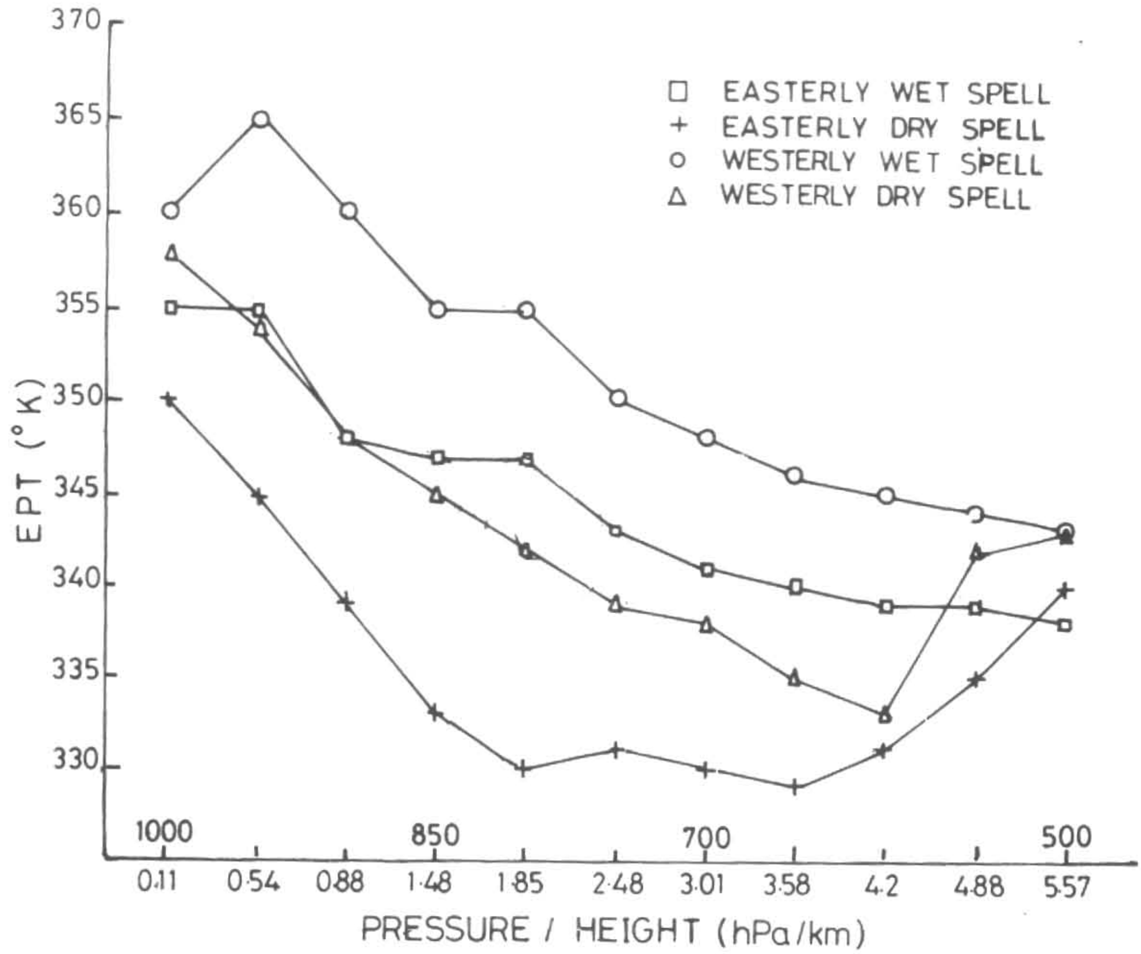


Fig. 2. Profiles of equivalent potential temperature (EPT) over Madras during various spells (October-December)

TABLE 5

Temperature anomaly profile over Madras

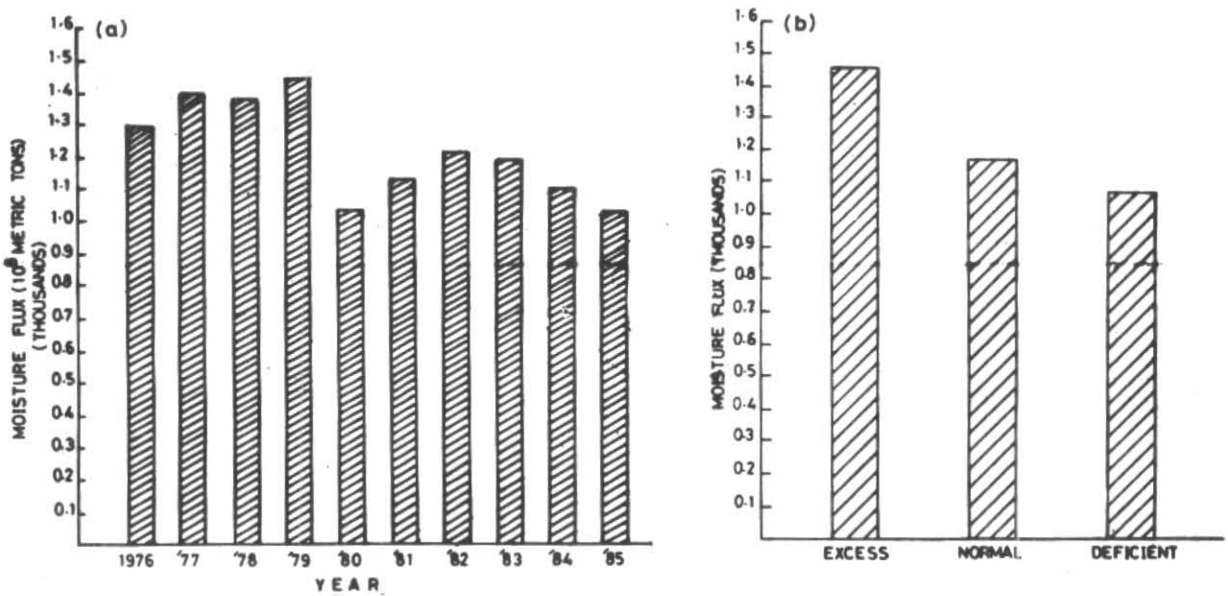
Type of spell	Pressure levels (hPa) 1000	950	900	850	800	750	700	650	600	550	500
(*i*)	0.8	0.3	0.2	0.4	0.0	−0.4	−0.8	−1.0	−1.0	−0.7	−0.5
(*ii*)	0.2	0.5	0.6	0.6	0.4	0.3	0.2	0.3	0.6	0.7	0.7
(*iii*)	−0.2	−0.3	−0.4	−0.4	−0.4	−0.3	−0.2	−0.3	−0.3	−0.2	−0.2
(*iv*)	0.4	0.8	1.0	1.0	0.8	0.6	0.4	0.6	0.9	0.9	0.9

(*i*) Difference between mean temperature anomalies of active and weak northeast monsoon spells
(*ii*) Mean temperature anomalies prior to onset of easterlies
(*iii*) Mean temperature anomalies for 10 days after the onset of easterlies
(*iv*) Difference between (*ii*) and (*iii*)

is associated with a noticeable cooling of atmosphere.

3.2. *Lapse rate and equivalent potential temperature*

The temperature lapse rates in the 1000-500 hPa layer for the six spells, (*i*)-(*vi*), were computed based on the mean heights of the isobaric levels. The lapse rates thus obtained are 5.0, 5.2, 5.1, 4.7, 4.9 & 4.7°C per km. The notable feature here is the slightly higher lapse rate during dry spell of westerly regime when compared to wet spell. Whereas, for northeast monsoon the lapse rate during wet spell is noticeably higher. This is a direct outcome of (*i*) of Table 5.



Figs. 3 (a & b). East-west moisture flux crossing Madras over 1° wall (October-December) during (a) 1978-85 and (b) excess, normal and deficient monsoons (average flux)

The equivalent potential temperature (EPT) was computed for the various cases for the various levels. Fig. 2 presents the EPT profiles. Generally the EPT values are higher for the wet spell than for the dry spell. Given the type of spell wet or dry, the values are higher during westerly regime than during easterly regime. During wet spells convective instability is present at all the levels above 950 hPa upto 500 hPa as $d\theta e/dz < 0$. During dry spells convective instability persists only upto 600 hPa. The total energy of an air column is represented adequately by $\int \theta e dp$ (Srinivasan and Sadasivam 1975 and Ramage 1971). It is evident from Fig. 2 that there is a decrease of energy after northeast monsoon has set in and also more energy is available during wet spells than dry spells both before and after the onset of northeast monsoon. These changes are primarily due to changes in the moisture content of the lower and middle troposphere.

3.3. *Interannual variation of moisture flux, LWC and winds*

An examination of total flux crossing Madras from all the four directions revealed that the fluxes from east to west and north to south are the largest and significant. The EW flux crossing Madras could be reasonably representative of the flux crossing CTN, whereas, making such an assumption for the N/S flux could be unrealistic in view of the known decrease of moisture from coast to inland. Fig. 3 (a) presents the total E/W flux for October-December crossing a N/S ODW centred at Madras and Fig. 3 (b) depicts the average such flux for excess, normal and deficit year. At 1171×10^8 and 1069×10^8 mtpd, the total flux for normal and deficient years does not differ substantially but at 1454×10^8 mtpd the flux for excess years is much larger. This is a direct result of more moisture and stronger winds in a wet season. The average moisture flux, in 10^8 metric tons, crossing an ODW centred at Madras during October-December from all the four directions is given below:

EW	—	1221
WE	—	226
NS	—	810
SN	—	203

The NS flux is quite substantial though EW flux is the largest.

The state and sub division of Tamilnadu covers an area of 1, 26, 575 square km over the plains and receives a normal rainfall of 477 mm during October-December which is equivalent to 604×10^8 mt of water. The total average flux from east alone crossing CTN is approximately 4945×10^8 mt for the same period. The total flux entering Tamilnadu would be the sum of the EW flux with the other three fluxes which can not be

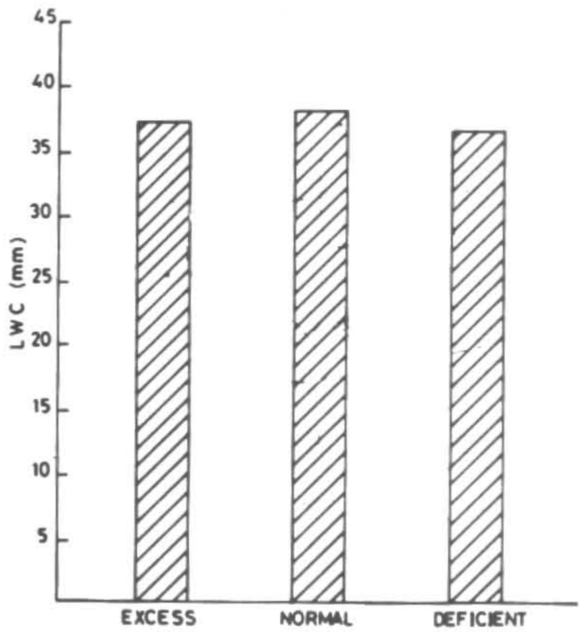


Fig. 4. Average liquid water content (LWC) over Madras during excess, normal and deficient monsoons

accurately determined from the data utilised in the present study. However, even from the data on EW flux crossing CTN it can be deduced that less than 12% of the moisture flux entering Tamilnadu precipitates into rain and the rest is advected out of the area. Thus much larger moisture flux is available than what is precipitated over the area obviously moisture convergence in the key variable.

3.4. *Comparison with other studies*

Both the daily and seasonal moisture flux during northeast monsoon obtained in this study compare well with the amount of moisture transported during southwest monsoon across west coast, as derived in other studies. Appa Rao (1985) reported 2.92×10^{10} mtpd over the Ahmedabad-Thiruvananthapuram sector for the good monsoon of 1967. For an ODW the figure works out to approximately 16.5×10^8 mtpd. For good northeast monsoon the flux is 1454×10^8 for season or 15.8×10^8 mtpd for ODW. Saha and Bavadikar (1977) reported 2.75×10^{10} mtpd over west coast or 17.9×10^8 mtpd for ODW computed from nine SW monsoon seasons. The normal EW flux crossing CTN over an ODW is 1221×10^8 mt for the season October-December or 13.3×10^8 mtpd. It is thus seen that the daily moisture flux crossing CTN from EW during northeast monsoon season is only slightly lower than the flux crossing west coast during southwest monsoon season for similar category of monsoon activity.

The variation of mean LWC upto 500 hPa for excess, normal and deficient years is presented in Fig. 4. The mean LWC was computed by averaging the LWCs of the individual days. It is observed that the mean LWC does not show much variation from excess to deficient years. As for the inter-annual variation of winds, easterly and southerly anomalies prevailed during excess years and westerly and northerly anomalies during deficient years.

During both the westerly and easterly regimes the respective winds over Madras reach maximum strength at 950-900 hPa and so the northern parts of Madras are warmer than southern parts during the former with the reversal of this thermal gradient observed during the latter. The abrupt cooling at the time of onset of easterlies is an obvious manifestation of the passage of equatorial trough over Madras.

As discussed earlier, for spells which are neither dry nor wet the LWC is 36.0 mm and the EW flux over ODW is 13.7×10^8 mtpd. From the vertical distribution of relative humidity (Table 3) it is evident that even on such days there is plenty of low level moisture available in the atmosphere. From the smaller scale of inter-annual variation of LWC [Figs. 3 (a & b)] and from the above inference it can be concluded that it is the absence of mechanism to lift the moisture to higher levels which eventually leads to a season of deficit rainfall and not lack of low level moisture.

As seen from Table 3, during prolonged dry spells of northeast monsoon the relative humidity in the lower troposphere reaches very low values and so is the LWC. However, the vertically averaged dry-bulb temperatures remain almost the same which perhaps shows that the air mass over CTN does not completely change into continental type airmass even during prolonged dry spells. Despite the low values of relative humidity and LWC during the post withdrawal period of northeast monsoon, the zonal easterlies are stronger in the lower levels. As a result, an EW flux of 8×10^8 mtpd for ODW still gets pumped up as against only 7.0×10^8 mtpd during dry spells of northeast monsoon. This renders it difficult to provide a firm answer as to the spread or otherwise of continental air mass over CTN even after the retreat of northeast monsoon. Herein it is worthwhile to comment that the northeast monsoon withdrawal is not associated with any abrupt change in the wind pattern over CTN except that some change is observed in the vertical moisture distribution.

4. Conclusions

The results of the study are summarised as under :

(*i*) The atmosphere over coastal Tamilnadu undergoes a cooling of nearly 1°C at all levels upto mid-troposphere at the time of onset of easterlies which normally takes place in mid-October.

(*ii*) During the westerly regime, which normally persists during the first half of October, not much difference is observed in the amount of moisture in the atmosphere over CTN between wet and dry spells.

(*iii*) During active northeast monsoon conditions over CTN the meridional wind which is northerly in the lower levels veers to southerlies. During dry spells the meridional winds are northerly at all the levels upto mid-troposphere.

(*iv*) The atmosphere over CTN during a wet spell of northeast monsoon is slightly warmer upto 800 hPa and colder aloft when compared to a dry spell.

(*v*) During active northeast monsoon conditions an average east to west moisture flux of 21.1×10^8 metric tons per day over one degree wall is transported across coastal Tamilnadu. During an excess northeast monsoon year the similar figure is 16.5×10^8 and the normal flux is 13.3×10^8. These amounts are only slightly lower than the amounts of moisture flux crossing west coast during southwest monsoon season on similar occasions.

(*vi*) An average total moisture flux of 1454×10^8 mtpd over ODW crosses CTN during excess northeast monsoon (October-December), whereas, the figures for normal and deficient seasons are 1171×10^8 and 1069×10^8 respectively.

(*vii*) Strong easterlies prevail over CTN even after the retreat of northeast monsoon. A moisture flux of 8.0×10^8 mtpd over ODW is transported across the coast which is higher than the flux during dry spell of northeast monsoon.

(*viii*) The total energy of an air column as obtained by the vertical integration of equivalent potential temperature revealed that the energy over CTN during wet/dry spell is more during the southwest monsoon than during northeast monsoon. For both the monsoons the energy during wet spell is more than that of dry spell.

(*ix*) The mean liquid water content over CTN for the whole season does not show much inter-annual variability. It has been inferred that it is not the lack of low level moisture that eventually leads to a season of deficit northeast monsoon rainfall.

(*x*) There is no sign of spreading of continental air mass over CTN even during prolonged dry spells as seen from the absence of any cooling in the atmosphere during such spells. There is also no conclusive evidence of such a phenomenon even after the withdrawal of northeast monsoon from CTN.

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