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Interaction between lower and upper tropical tropospheres during the southwest monsoon season over India

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ABSTRACT. Raman and Ramanathan's suggestion that latent heat released by "excessive cloudiness and copious precipitation" speeds up upper tropospheric winds over the west coast of India during the southwest monsoon is not borne out by observational evidence. Their proposition is shown to support rather than contradict Koteswaram's hypothesis regarding upper tropospheric easterlies and the southwest monsoon activity along the west coast of India. The influence of these easterlies on the onset of monsoon over Kerala is illustrated for the year 1961-68.

1. Introduction

Raman and Ramanathan (1964) have stated that theire is a "significant contribution to the upper level (flow) patterns by precipitation in the lower troposphere" during the southwest monsoon season over India. According to them, this contribution "probably results from the release of large amounts of *latent heat* from excessive cloudiness and copious precipitations". This idea has also attracted other workers at the International Meteorological Centre during the International Indian Ocean Expedition (1963—65), *e.g.*, Ramage (1963), Miller and Keshavamurthy (1967). Their attempt appears to be meant to disprove an earlier hypothesis suggested by Koteswaram (1958) that the upper tropospheric easterly jet, may activate the burst of the southwest monsoon over India, rather than be activated by it. In this study, the facts and figures given by Raman and Ramanathan are shown to support, instead of contradict, Koteswaram's hypothesis. Observational evidence during the years 1961-68 is also presented in support of this hypothesis.

2. Latent heat and its disposal

Raman and Ramanathan (1964) attribute the strengthening of the upper level easterly winds observed by them, after heavy rains have occurred at a given location or region, to the release of latent heat by cloudiness and 'precipitation'. It is indisputable that latent heat of condensation released by water clouds and that of fusion released by ice clouds may warm the middle and upper troposphere by convective and advective processes, although the same processes warming the lower troposphere also (*say*, above 700 mb) cannot be ruled out. The area where such warming becomes effective will not always be where the release has occurred. This largely depends upon the prevailing winds which would advect the released heat downstream. The authors, however, suggest that this extra input of heat energy is converted, during the course of the *next 24 hours* on a synoptic scale and *half to one month* on a climatological scale, into the kinetic energy as evidenced by the strengthening of upper level winds noticed by them over a station or region, where heavy precipitaton has already occurred. The following points, however, do not support their contention.

(*a*) Raman and Ramanathan appear to envisage lifting up of the pressure surface leading to the development of a transient high pressure in the upper levels over the region of release of latent heat. But, how transient such development could be is better understood from its converse in the lower troposphere. For example, surface highs built up by cold downdrafts in the area of widespread thunderstorms are wiped out in a matter of hours without influencing the low level wind circulation to any recognisable extent. If this was not the case in the higher levels also, heavy rainfall regions during the monsoon season with copious release of latent heat would have drastically modified the monsoon circulations over India for short or long periods.

(*b*) An assessment of net available latent heat released by clouds is rather complicated. One has to reckon with warm clouds, cold clouds and those having the same temperature as the environment having moist adiabatic lapse rate. Loss of latent heat by evaporation of falling precipitation, dissipation of clouds and entrainment of relatively cooler environmental air has also to be taken into account. Assuming that there is net amount of latent heat available for warming the atmosphere

TABLE 1

Mean monthly frequency (1931—60) of thunder along west coast of India during March—October

Stations	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	No. of years
Alleppey	6·0	12·0	10·0	5·0	1·3	0·5	3·0	7·0	15
Bombay (Colaba)	0·1	0·4	2·0	5·0	1·2	0·8	3·0	3·0	22
Cochin	6·0	13·0	12·0	5·0	1·8	1·2	3·0	8·0	29
Honavar	0·5	1·6	4·0	6·0	0·5	0·0	0·7	2·0	16
Mahabaleshwar	1·2	4·0	4·0	2·0	0·2	0.4	2·0	4·0	22
Mangalore	1·2	5·0	8·0	5·0	1·9	0·8	1·3	7·0	21
Marmagao	0·4	3·0	4·0	4·0	0·3	0·7	2·0	9·0	23
Ratnagiri	0·0	0·4	0·9	1·4	0·0	0·0	1·2	2·0	17
Surat	0·1	0·1	0·1	1·7	0·3	0·3	1·5	0·5	22
Trivandrum	8·0	16·0	12·0	3·0	1·2	1·4	3·0	9·0	21

during active monsoon along the west coast of India, the strong zonal motion prevailing over this area is likely to ensure quick transport of the excess of heat downwind without enabling it to influence the energetics of the upper level winds over the place of release of latent heat, as pointed out by Swinbank (1965).

(*c*) Table 1 gives the mean monthly frequency of thunderstorms at representative stations along and near west coast of India. It will be seen that during July and August, which are the months of active monsoon, the frequency dwindles to almost nil along this region. Even at a hill station like Mahabaleshwar getting very large amount of rain in the season, the frequency of thunderstorms in July and August is 0·2 and 0·4 respectively. It is well-known that the frequency of thunderstorms over the monsoon trough is high during this season. Accordingly, in the absence of thunderstorms or 'hot-towers' transporting latent heat into the upper levels over the west coast, very little warming may be expected there in the upper troposphere above 500 mb during the active monsoon months. Mean temperatures at 200 mb over the south Peninsula are about 10°C colder than those over north India.

(*d*) It is common knowledge that during the dry seasons, strong wind maxima occur in the subtropical westerly jet streams over India under blue skies. Obviously, these speed maxima in the upper troposphere are not due to latent heat released below. Large scale atmospheric circulation should, by and large, be controlled by inputs of *sensible heat* rather than by *latent heat*. The latter is, no doubt effective in smaller scale circulations like tropical cyclones. The upper flow patterns over the southwest monsoon area are so large that the release of latent heat along the west coast of India, even if transported to the upper levels, may not be able to modify the circulation and increase the kinetic energy. These patterns generally repeat themselves without much change irrespective of antecedent rainfall activity from year to year. On occassions when heavy rains occur along the west coasts of India and Burma for many days, the seasonal upper tropospheric east-west ridge does not shift southwards nor does it become oriented along these coasts where heavy rain occurs.

(*e*) The upper tropospheric easterly jet over the Peninsula is associated with north-south thermal gradient in the levels below the jet maximum. Since the heaviest monsoon rainfall occurs all along the west coast of India, the release of copious latent heat over the region, warming the upper troposphere as supposed by Raman and Ramanathan, should, in the first instance, reduce this north-south thermal gradient and weaken the high level easterlies, instead of increase their speed as postulated by them.

(*f*) Latent heat, however, may contribute to the upper air monsoon circulations over India on occasions and at places where it may add to the effect of sensible heat. This is presumably what happens when (1) good monsoon rains follow a good pre-monsoon thunderstorm activity over northeast India, where thunderstorm frequency continues to be large, or (2) the easterly jet increases in speed during 'break-monsoon' conditions, when heavy downpours occur along the Himalayan foot-hills. Both cases lead to the intensification of the seasonal 'high' in the upper levels and consequent changes in the high level winds. Contrary to what would happen under strong zonal flow, the upper anticyclone helps to entrap the latent heat advected from below and in turn is intensified by it.

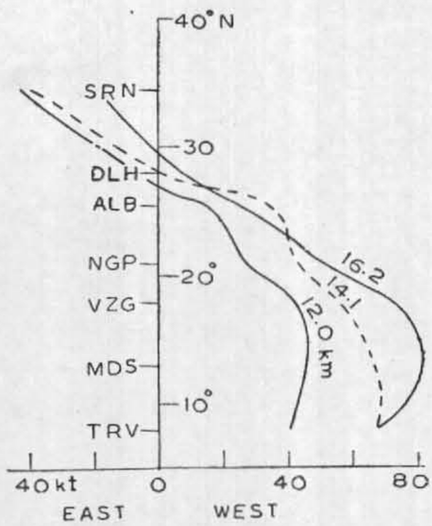


Fig. 1. Profile along Long. 77°E of mean upper tropospheric east winds (in knots) for 47-day of "break" monsoon conditions during July and August 1962-67

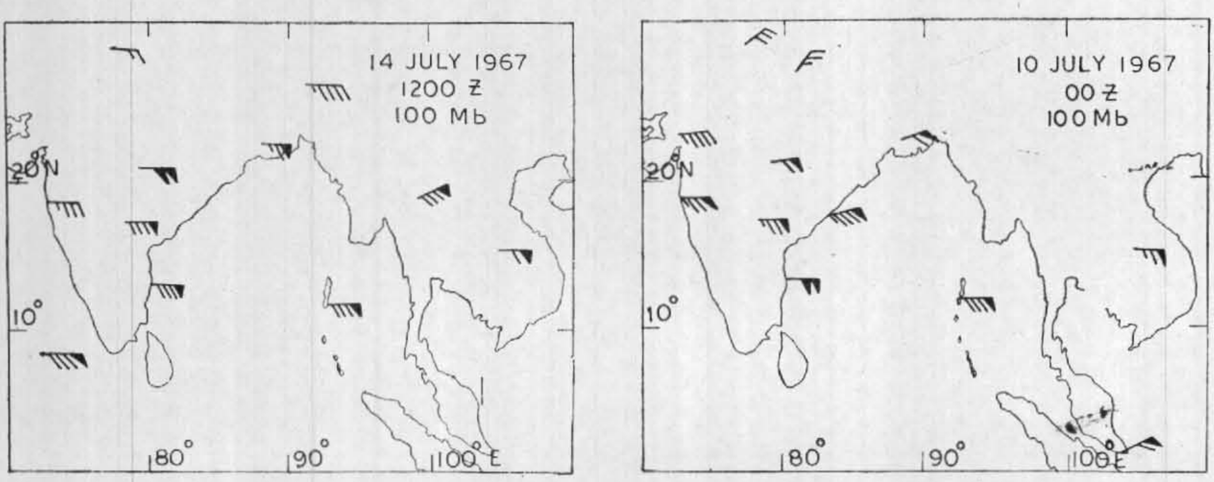


Fig. 2(a) **Fig. 2(b)**

Figs. 2 (a & b). Winds at 100 mb for (a) normal and (b) 'break' monsoon day

Half barb=5 kt, full barbs=10 kt and pennant=50 kt

Parthasarathy's (1958) opinion that high level easterlies over peninsular India weaken during 'break-monsoon' periods, as quoted by Raman and Ramanathan in support of their finding of strengthening of upper level winds south of the region of heavy rains is *not* correct, as seen from more recent high level wind data during 'break' periods. Fig. 1 shows the meridional profile of mean zonal winds in the upper levels along Long. 77°E from Srinagar to Trivandrum averaged over 47 days during break monsoon periods in July and August for the years 1962—67. The mean east wind at Madras at 16·2 km is stronger (81 kt) during the above 'breaks' than the seasonal mean maximum (79·1 kt) in July. Strong easterlies, however, extend further northwards upto Lat. 20°N on individual days during 'break' periods as pointed out by Koteswaram (1958). Figs. 2(a) and 2(b) depict 100-mb wind charts for a typically normal and 'break' monsoon day respectively. The increase of wind over Madras on break monsoon day compared to the normal monsoon day is noteworthy. The general absence of precipitation over the Peninsula during such 'breaks' and the large increase of east wind maximum over Madras are not consistent with Raman and Ramanathan's proposition.

3. Climatological and synoptic evidence

Raman and Ramanathan have tried to substantiate their hypothesis both climatologically and synoptically. Climatologically, they consider

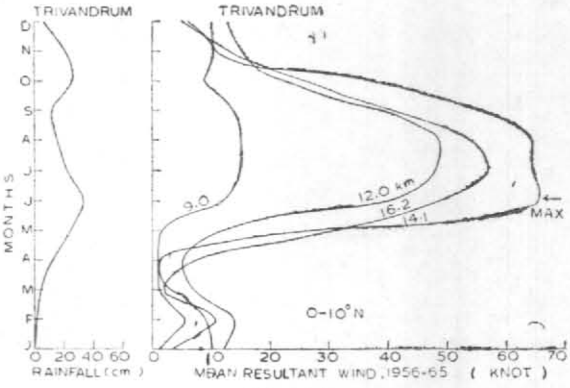


Fig. 3(a)

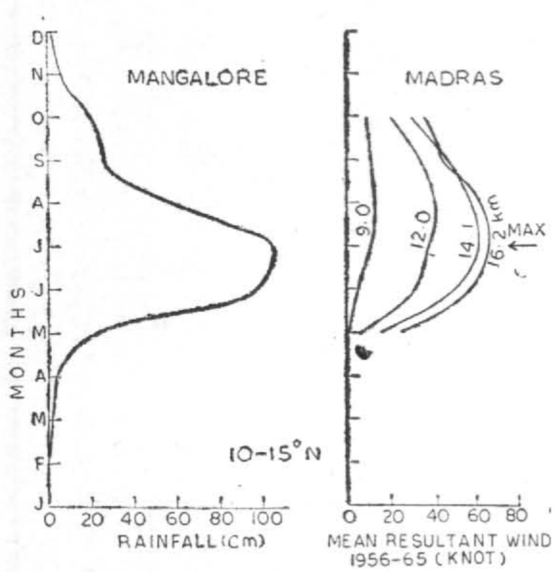


Fig. 3 (b)

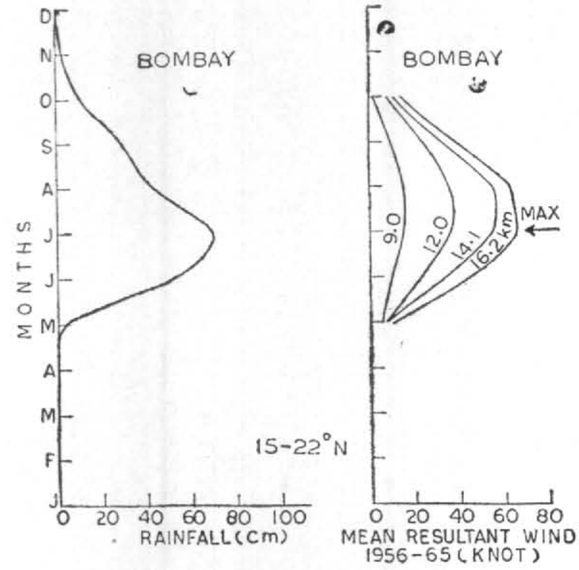


Fig. 3 (c)

Fig. 3 (a-c). Profiles of mean rainfall (in cm for 1930-60) and upper tropospheric wind (in kts for 1956-65) normals over altitude zones (a) 0°– 10°N (b) 10°—15°N and (c) 15°—22°N along west coast of India

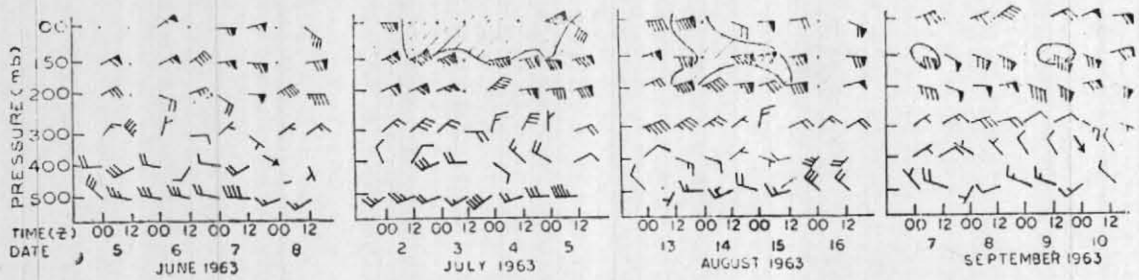
three zones along the west coast of India, *viz.*, Lat. 0-10°N, 10-15°N and 15-22°N. Rawin stations representing these three zones are presumably Trivandrum/Colombo, Madras (on the east coast) and Bombay respectively. Similar profiles of rainfall and wind maxima over the sections Lat. 10-15°N along Arakan-Chittagong coasts have also been given. It is seen from their diagrams that, except for the zone 15-22°N, high level wind peaks occur about *half to one month* after the occurrence of rainfall peak.

The above profiles of rainfall and upper winds over the west coast of India, based on India Meteorological Department's rainfall (1930-60) and wind (1956-65) normals are given in Fig. 3. The latter are more representative than the wind normals (1956—60) which Raman and Ramanathan have presumably used. It will be seen from Fig. 3, that there is no time lag between rainfall and wind peaks, which coincide in June at Trivandrum and in July at Bombay and at Mangalore (for rain)/Madras (for wind). Thus the climatological 'evidence' given by Raman and Ramanathan has no basis. It is also too far-fetched for the authors to imagine that the increase in the rainfall over a station in July would cause an increase in the wind strength in August.

The coincidence of the wind and rainfall peaks as seen from Fig. 3 is not to be mistaken for a suggestion of their inter-dependence. Wright and Ebdon (1968) have recently shown that at Victoria (Seychelles) the mean monthly rainfall in July and August based on 1902—55 normals are 81 and 64 mm respectively, whereas the east component of winds at 150 mb reach a maximum of 60 kt in August, when the mean rainfall is a

24 hrs rainfall (mm) ending 0300 GMT

Mangalore	82	6	7	8	83	103	13	9	155	106	18	19	4	12	23	11
Kozhikode	52	77	99	—	71	61	53	52	124	20	24	4	38	3	5	4
Cochin	20	24	47	18	23	8	59	30	35	48	6	33	13	6	—	5
Alleppey	19	22	15	2	35	10	42	51	14	29	28	—	8	6	6	9
Trivandrum	8	12	23	29	17	4	12	35	14	8	1	10	1	—	—	1
Date (1963)	Jun 5	6	7	8	Jul 2	3	4	5	Aug 13	14	15	16	Sep 7	8	9	10



24 hrs rainfall (mm) ending 0300 GMT

Surat	—	10	6	5	1	8	9	61	27	—	—	24	45	45	19	2
Ahmedabad	15	—	1	—	—	—	5	45	70	2	27	5	49	54	100	115
Veraval	—	35	8	1	20	95	105	40	7	9	22	3	22	3	1	5
Dahanu	8	58	52	10	6	307	216	168	86	29	53	111	10	21	7	—
Bombay	59	75	4	2	20	108	61	189	102	105	41	17	4	22	65	—
Date (1963)	Jun 27	28	29	30	Jul 4	5	6	7	Aug 5	6	7	8	Sep 7	8	9	10

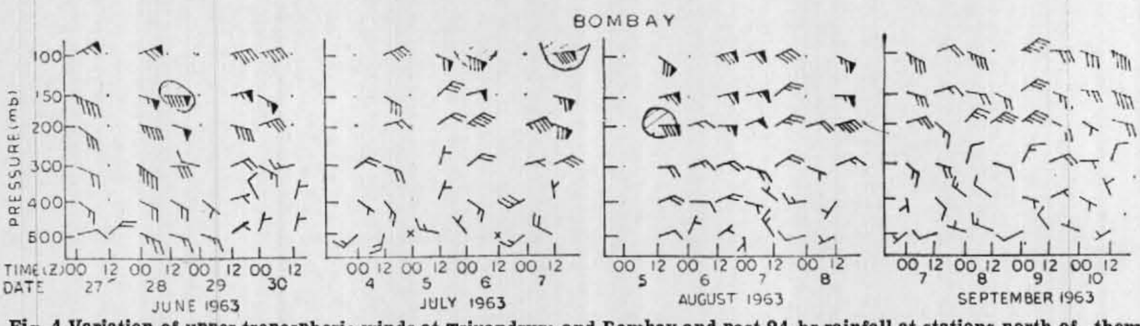


Fig. 4. Variation of upper tropospheric winds at Trivandrum and Bombay and past 24-hr rainfall at stations north of them for selected days during Jun-Sep 1963

minimum. Although the wind observations at Seychelles (Victoria 4° 37′S, 55° 27′E) covered only a period of September 1963—December 1964, the similarity of wind variations at Victoria with those at Gan Island (0° 41′ S, 73° 10′E) and at Canton Island (2°46′S, 171°43′W) and Ascension Island (7°58′S, 14°24′W) was very striking. Upper tropospheric easterly maxima and rainfall peaks are out of phase at Victoria and Gan Island and release of latent heat has a role at these stations opposite to Raman and Ramanathan's findings along the west coasts of India and Burma.

Synoptically, Fig. 4(a) of Raman and Ramanathan's note shows a well defined axis of east wind maximum about one degree of latitude south of the previous day's rainfall peaks. No such systematic relationship between the axis of east wind maximum and the next day's rainfall peaks is noticed by them (*vide* their Fig. 4b). In view of the absence of rawin stations along the west coast between Bombay (about Lat. 19°N) and Trivandrum (about Lat. 8°N), the delineation of the jet axis in relation to the west coast rainfall would be very subjective and questionable. Even if some aircraft reports are available on some occasions, these will be confined to levels of 200 mb or below, where the easterly jet maximum is not as sharply defined as at 125 and 100-mb levels. The authors have not mentioned whether the jet was in an accelerating or decelerating stage—an important feature to associate rainfall with jet stream structure. In both stages, however, one could get an axis of east wind concentration on a daily basis. Raman and Ramantahan have obviously not selected days on which heavy rainfall peaks

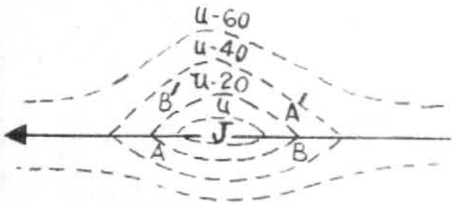


Fig. 5. Isotach delineation and dynamic characteristics of an easterly jet

A—Area of positive advection favourable for low level cyclogenesis

B—Area of negative vorticity unfavourable for low level cyclogenesis

In case of easterly jet, A>A' & B >B'

have occurred to the south of the east wind maximum. Such occasions are, in fact, generally as numerous as the cases chosen by them.

Fig. 4 illustrates the variation of upper tropospheric winds at Trivandrum and Bombay during specific spells of moderate to heavy or very heavy rain at these stations as well as those within five degrees of latitude to the north of them for the months June to September 1963. Similar illustrations for other years as well are too numerous for reproduction (*see* also Figs. 7a to 7h). It will be seen that no definite relation is shown by these diagrams between prior rainfall to the north and subsequent waxing or waning of upper level winds at these stations to the south of the rather extensive rainfall belt along the west coast of India.

In Table 1 of their note, Raman and Ramanathan have shown a very high degree of correlation between the upper tropospheric east wind maximum on a day with the previous day's rainfall peak at the same location. Correlation between precipitation peak on the same as well as the the next dates with the east wind maximum of a given date is not significant. If latent heat alone was the controlling factor, there is no reason why the correlation between east wind and rainfall maxima is not as significant on the same and next dates as on the previous date, allowing the same time lag of 24 hours between the release of latent heat and subsequent strengthening of winds. It is also worth noting that while Raman and Ramanathan find a time lag of only *one day* between these peaks of wind and rainfall on a synoptic scale, a longer time lag of *half to one month* is found by them between these maxima on a climatological scale.

4. Upper tropospheric flow patterns during the southwest monsoon period

The dynamics of the upper tropospheric winds during the monsoon, *viz.*, the easterly jet and the wave trough in the upper easterlies, have been illustrated by Koteswaram and George (1958). Isotach delineation of an easterly jet as given by them is reproduced in Fig. 5 for reference. Strong wind at a particular level at a given station cannot by itself have any influence on the vertical motion resulting in heavy precipitation over that station. What makes this possible is the vertical and lateral shears as well as curvature of flow, if any, associated with the wind structure and their variation downstream. In other words vorticity advection and the associated divergence in the upper levels favour vertical motion below and development of weather. These aspects are built in the different sectors ('exit' and 'entrance') of the jet stream structure.

Synoptic experience has shown that winds at 150/100-mb level strengthen at Port Blair (Lat. 11°40′N, Long. 92°43′E) earlier than at Madras (Lat. 13°0′N Long. 80°11′E) and when Madras winds strengthen those at Port Blair weaken. It is unfortunate that there are no wind data available over the Bay area intervening these two ground stations. Yet, the above sequence of behaviour of the upper easterly winds at these two stations suggests the westward movement of east wind maxima similar to the eastward movement of wind maxima in the sub-tropical westerly jet over the country. Fig. 6 depicts such a sequence : available winds show a maximum over Port Blair at 0000 GMT on 4 July 1968, over Madras at 1200 GMT on on 5th and over Trivandrum at 0000 GMT on 7th. Absence of continuity of data renders *detection* of such sequences rather difficult. It is also found that when the winds over Madras (which is generally in a dry zone in the southwest monsoon season releasing no latent heat) increase or accelerate, heavy rains commence along Mysore and Kerala coasts south of Lat. 15°N.

Occurrence of such rainfall, which is usually associated with a pre-existing lower tropospheric feature, causing low level convergence, coupled with the upper divergence in the left exit portion of the accelerating jet maximum is dynamically logical and feasible. Similarly, heavy rains at stations to the north of the jet axis must be associated with decreasing east winds, as these stations can be under the right entrance portion of the jet maximum. There are also many instances in which heavy rainfall occurs along the west coast of India, in association with the westward progress of an upper easterly wave trough in the 300/150-mb level, with or without the accompaniment of a jet maximum aloft. The role of such features in the burst of monsoon over the west

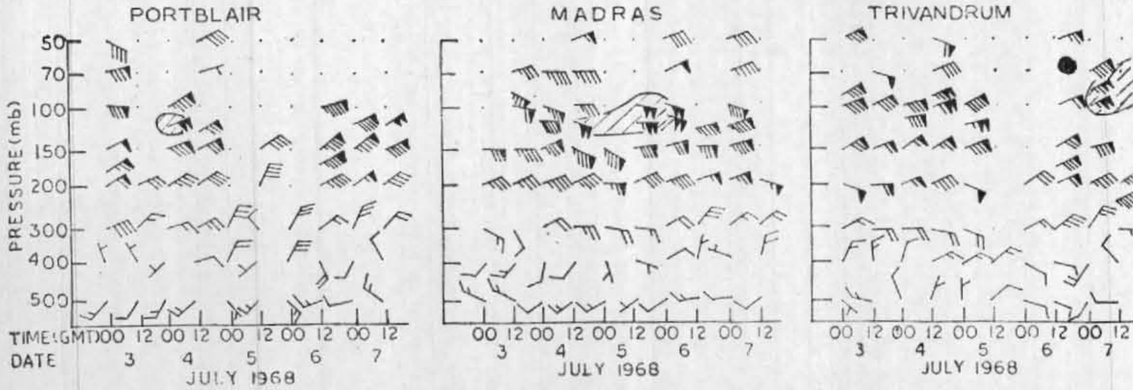


Fig. 6. Vertical time-sections of upper troposphere winds over Port Blair, Madras and Trivandrum showing westward movement of an easterly jet maximum

Relevant 100 kt isotach shown as stipled

coast of India is illustrated in the following paragraph.

Table 1 given by Raman and Ramanathan in their note only corroborates, rather than contradicts the above mentioned dynamical influence of the upper tropospheric easterly jet in causing the rainfall, as first suggested by Koteswaram (1958). The high degree of correlation between the rainfall along the west coast on the day previous to the strengthening of the upper easterly winds only shows that on the day of heavy precipitation at a given location, the east wind maximum must have been further to the east, so that the region of heavy rainfall on the given day was under the left 'exit' portion of the advancing jet maximum, provided the station was to the south of the jet axis. The jet maximum might have advanced to the west coast sometime after the rainfall thereby causing the strengthening of the upper wind a day later. There is no need to take recourse to the latent heat released by earlier cloudiness and 'precipitation', just as the winds over Madras (a dry zone releasing no latent heat) increase as rainfall occurs downwind along the west coast. Over regions north of the jet axis wind speeds should decrease after heavy rainfall, in spite of release of latent heat. This is presumably what Fig. 4 of Raman and Ramanathan's note showing rainfall peaks to the north of the east wind maximum seems to indicate. As already stated, the authors have not mentioned whether the east wind maximum reported by them to the south of the rainfall peak was at a decelerating stage or not. In both cases, one can have an east wind maximum and an axis to delineate the same. The areas to the north of the easterly jet axis might have been under the right entrance portion of the wind maximum looking downwind. This is the only way of attributing heavy rainfall occurring to the north of a given axis of east wind maximum according to vorticity considerations. Here we come to a paradox implied in the thinking of Raman and Ramanathan–latent heat release increases the upper tropospheric easterlies at a given station, if it is to the south of the jet axis, but decreases the winds, if the station is to the north of the jet axis.

5. Upper tropospheric easterlies and the burst of the monsoon over Kerala

Occurrence of fairly widespread and locally heavy to very heavy rain (more than 7 cm) over Kerala coast during the mid-summer period (15 May-15 June) is usually associated with the 'burst' of southwest monsoon. The lower tropospheric feature antecedent to this event is generally a trough or a low pressure area in the southeast Arabian sea off the Kerala coast. As stated earlier, a pre-existing feature like these causing convergence in the lower troposphere is, no doubt, an essential condition for vertical motion resulting in heavy precipitation to occur. This motion is accentuated whenever an upper tropospheric system causing divergence gets superposed over the region of convergence in the lower levels. In what follows, the upper level features, such as easterly jet or wave troughs as envisaged by Koteswaram and co-workers observed prior to or along with such bursts of the monsoon over Kerala coast during the years 1961—68 are presented. These are being given in detail due to statements by Raman and Ramanathan (1964) and Ananthakrishnan *et al.* (1968) that no such association has been observed by them.

Figs. 7 (a-h) show the relevant vertical time sections of winds at Madras and Trivandrum together with 24-hour rainfall recorded upto 0300 GMT at west coast stations. The official dates of onset of the monsoon as mentioned in the *Indian Daily Weather Reports* are **indicated in bold figures**

	24 hours rainfall (mm) ending 0300 GMT								
Trivandrum	—	—	2	40	5	110	9	22	23
Alleppey	1	—	6	2	6	47	65	83	9
Cochin	1	17	12	24	13	13	155	47	41
Minicoy	—	14	13	38	9	36	28	—	28
Kozhikode	2	—	3	4	21	9	137	63	80
Mangalore	—	1	4	14	—	13	80	89	13
Honavar	2	—	5	2	2	134	171	85	83
Vengurla	1	—	—	—	3	72	299	8	47
Ratnagiri	—	—	1	—	—	17	3	3	18
Harnai	—	—	—	—	—	5	9	—	—
Bombay	3	1	—	3	2	—	—	—	—
Date (1961 May)	16	17	18	19	20	21	22	23	24

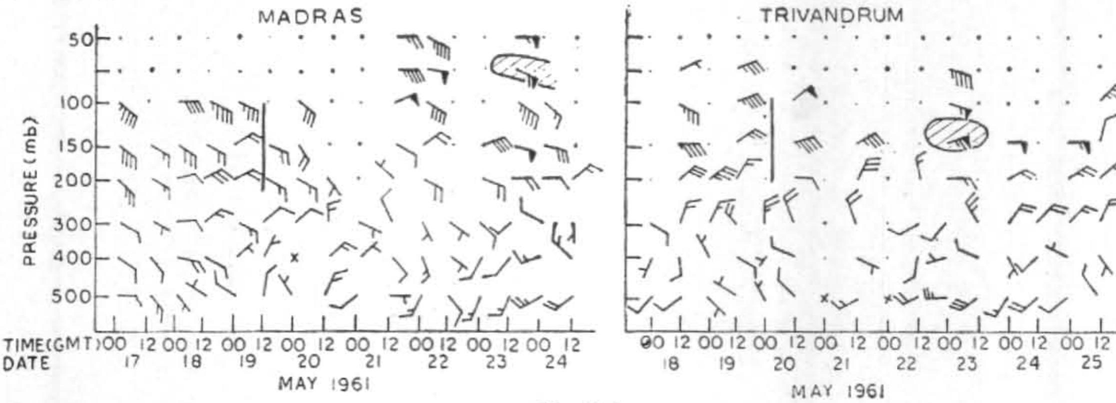


Fig. 7(a)

Fig. 7. (a-h). Vertical time-sections of winds at Madras and Trivandrum together with 24 hours rainfall (in mm) over west coast stations on selected days before & after onset of monsoon over Kerala for the years 1961—68

Wave troughs shown as thick lines and jet maximum isotach as stipled

on the rainfall tables of Fig. 7 (a—h)*. The special features of each year are described below.

1961—During this year, the monsoon set in rather quietly on 18 May without causing heavy rainfall over Kerala coast (Fig. 7a). A wave trough in the easterlies between 200-100 mb passed over Madras on 19th and over Trivandrum on 20 May. The monsoon rains occurred over Kerala coast on the 18th, when this region was still under the diverging western portion of the advancing wave trough. As this trough was cold, it cannot be attributed to the prior precipitation over south Peninsula, as the latent heat so released would warm instead of cool the upper levels; moreover, it could be traced earlier over Madras, where no precipitation occurred.

1962—The southwest monsoon 'burst' over Kerala by 17 May, when Alleppey and Cochin recorded 10·5 and 8·0 cm of rain respectively by 0300 GMT of that date (Fig. 7b). Rainfall figures confirm 17 May as more appropriate date of burst of monsoon over Kerala.

Wind data over Madras is scanty. Nevertheless, a well marked low pressure area extending upto 200 mb moved towards westnorthwestwards across Madras on 15 May from SW Bay. This low pressure area with its deep cyclonic circulation appears to have induced the heavy rainfall over Kerala on 16-17 May. Development of jet maxima over Trivandrum on 14 and 15 May prior to the onset of the monsoon is noteworthy. The increase of rainfall at stations north of Kozhikode on 18 and 19 May and decrease of upper level easterlies over Trivandrum on 19 May are consistent with the right "entrance" portion of the jet maximum that passed over Trivandrum on 17-18 May.

1963—The official date of onset of monsoon was 31 May, when Alleppey recorded 7·6 cm of rain (Fig. 7c). The time-sections show that a wave trough in the upper easterlies between 400-200 mb passed over Madras on 29 May. Over Trivandrum wind data was very scanty. This upper level easterly trough appears to have caused the onset of monsoon over Kerala on 31 May. The relative weakening of upper tropospheric winds over Trivandrum on 31 May and 1 June after the rains, compared to the stronger winds on 29 and 30 May (not reproduced) prior to heavy rains at stations to the north is interesting and is contrary to Raman and Ramanathan's hypothesis.

It may be mentioned that similar upper wave troughs passed over Madras and Trivandrum since

* Ananthakrishnan *et al.* (1968), however, indicate different dates in some cases

24 hours rainfall (mm) ending 0300 GMT

Trivandrum	1	25	63	66	13	35	7
Alleppey	30	76	105	43	24	20	18
Cochin	14	28	80	114	29	1	38
Minicoy	3	2	—	—	4	25	22
Kozhikode	—	5	12	58	112	53	17
Mangalore	—	—	6	97	94	8	10
Honavar	—	—	—	126	56	25	4
Vengurla	—	—	13	23	2	22	—
Ratnagiri	—	—	—	—	—	29	—
Harnai	—	—	—	—	—	3	38
Bombay	—	—	—	2	2	2	4
Date (1962 May)	15	16	17	18	19	20	21

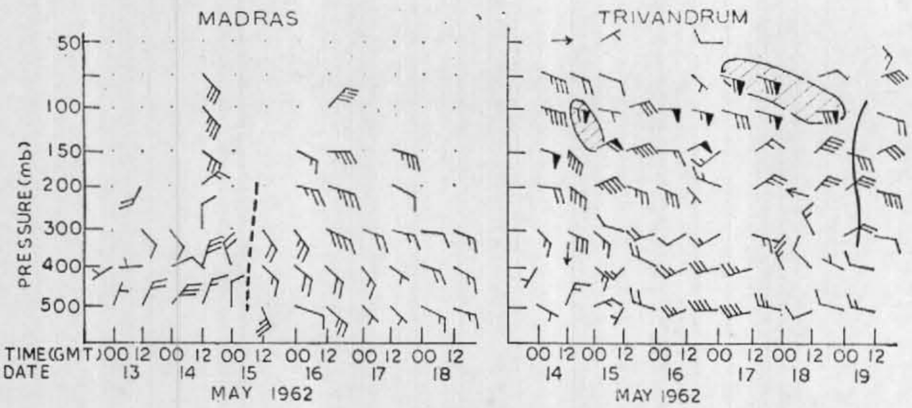


Fig. 7(b)

24 hours rainfall (mm) ending 0300 GMT

Trivandrum	4	—	—	—	—	2	8	12	23
Alleppey	3	76	3	—	42	—	19	22	15
Cochin	—	15	37	—	2	4	20	24	74
Minicoy	—	—	—	1	—	—	2	35	14
Kozhikode	—	—	21	—	4	61	52	77	99
Mangalore	—	—	7	1	20	54	82	72	93
Honavar	—	—	3	24	5	73	33	74	85
Vengurla	—	—	—	—	13	46	46	60	30
Ratnagiri	—	—	—	—	—	8	9	4	45
Harnai	—	—	—	—	2	54	10	10	4
Bombay	—	—	—	—	—	34	7	1	6
Date (1963 May/Jun)	30	31	1	2	3	4	5	6	7

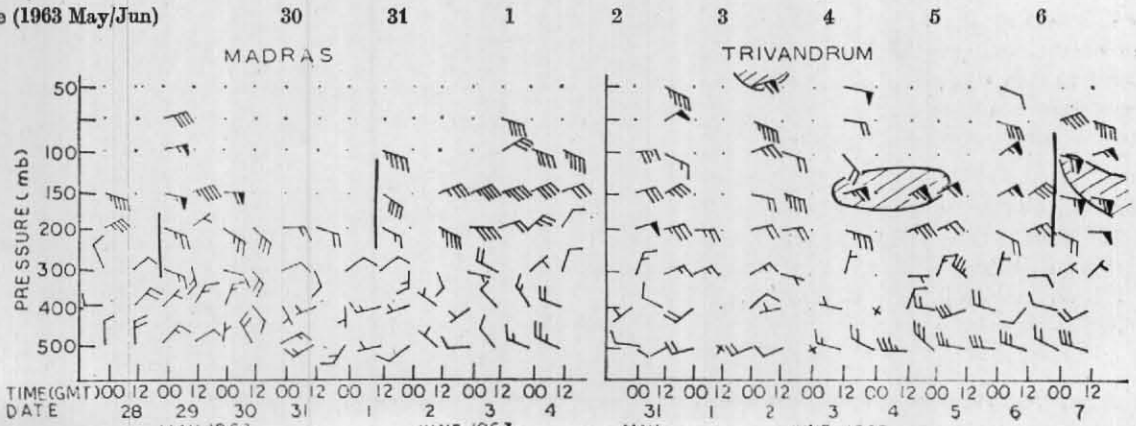


Fig. 7(c)

24 hours rainfall (mm) ending 0300 GMT

Trivandrum	—	—	—	33	1[illegible]	5	—	—	—
Alleppey	5	11	44	34	7	58	2	6	6
Cochin	1	3	3	73	7	41	1	10	1
Minicoy	—	55	—	24	19	11	4	—	8
Kozhikode	—	—	—	50	2	98	—	5	16
Mangalore	—	—	2	2	1	120	24	20	22
Honavar		4	—	—	—	37	54	17	50
Vengurla	—	—	—	—	21	—	41	49	31
Ratnagiri	—	—	—	—	1	—	14	10	59
Harnai	—	—	—	—	—	—	39	16	51
Bombay	—	—	—	—	—	—	1	9	24
Date (1964 Jun)	3	4	5	6	7	8	9	10	11

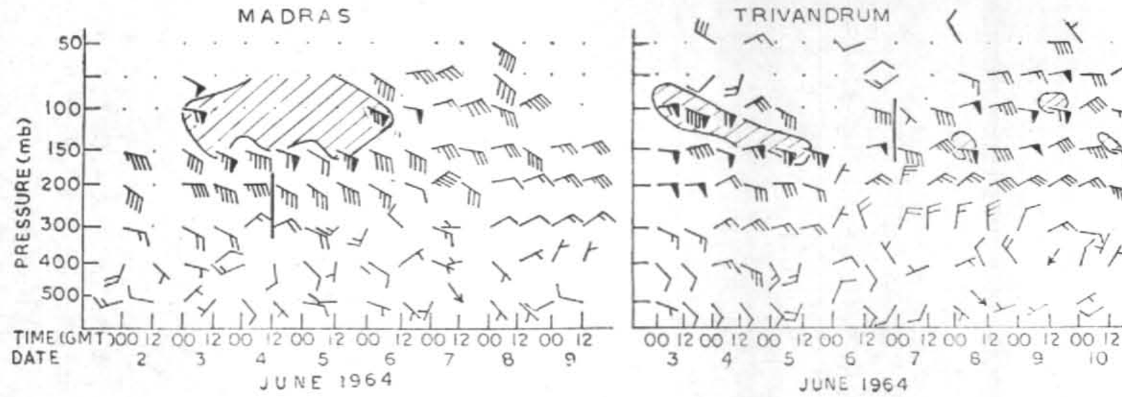


Fig. 7(d)

31 May and the divergence ahead of them seems to have induced further monsoon activity along the west coast upto 5 June and later.

1964 — The monsoon burst over Kerala on 6 June (Fig. 7d). Over Madras, the speed of an easterly jet was increasing between 3 and 6 June and decreasing later. A trough in the easterlies at 300-200 mb passed over Madras between 4-5 June. The role of this advancing upper trough and wind maximum in causing the burst of monsoon over Kerala on 6 June is obvious. Concentration of east winds over Trivandrum prior to this date and their weakening after the rains on 6-7 June are very much contrary to Raman and Ramanathan's hypothesis. Shift of heavy rainfall to stations north of Mangalore from 8 June appears to be consistent with decrease of upper level winds in the rear of the earlier jet maximum over Madras as pointed out in Sec. 4 above.

1965 — This year was characterised by an abnormally poor monsoon. There was also wide disparity between date of onset of monsoon. Rainfall figures, however, indicate 25 May as the appropriate date of burst of the monsoon over Kerala (Fig. 7 e).

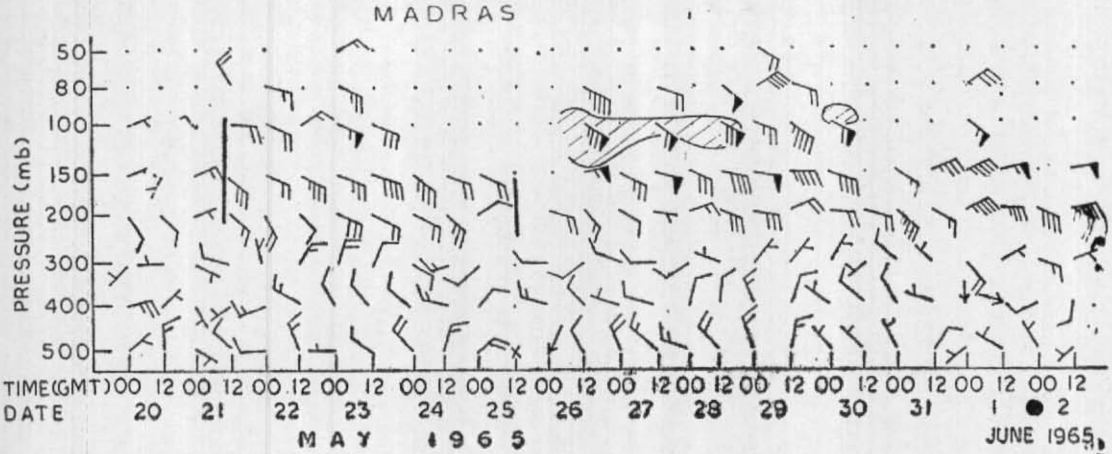
Winds above 150 mb are not available over Madras from 0000 GMT of 24 May till 0000 GMT of 26 May. However, the station reported 75 kt at 1200 GMT of 26th and 60 kt next day evening, suggesting east winds increased till the evening of 26th and decreased later. Wave troughs in the upper easterlies passed over Madras on 21 May and presumably on 25 May and over Trivandrum on 23 and 27 May. The burst of the monsoon over Kerala on 25 May appears mainly to be associated with the accelerating jet stream over Madras on 26 May.

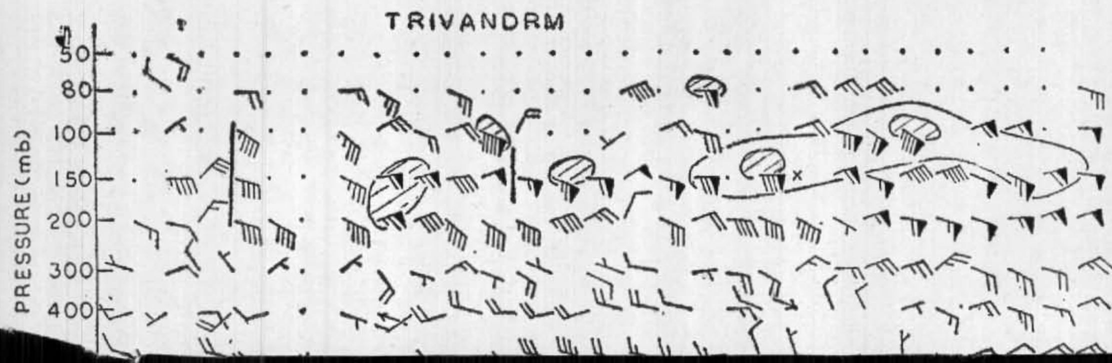
It may be mentioned that Ramaswamy (1969) recently pointed out the appearance of an easterly jet maximum over Bombay prior to the onset of monsoon there and attributed the droughty conditions during this year to the general absence of perturbations in the upper easterlies over the country.

1966 — During this year, the official date of onset of monsoon was 1 June (Fig. 7f). Wind data over Trivandrum between 1-6 June were not available. A wave trough between 200-100 mb passed over Madras between 30-31 May and another between 300-100 mb on 4 June. These

24 hours rainfall (mm) ending 0300 GMT

Trivandrum	1	4	—	63	—	3	2	6	—	—	—	—	—	—	—	7	27	17
Alleppey	—	3	14	86	30	2	—	6	32	14	3	1	2	—	20	16	29	15
Cochin	—	6	11	229	14	4	—	47	22	5	—	11	8	—	94	6	31	—
Minicoy	7	1	1	40	30	14	3	1	1	13	1	—	—	3	—	3	50	1
Kozhikode	9	2	26	95	1	—	—	13	11	1	34	—	—	—	5	47	19	8
Mangalore	–	1	2	–	—	—	—	63	—	—	—	—	1	1	7	104	41	62
Honavar	—	2	—	—	—	—	—	—	—	—	—	—	—	1	—	42	7	38
Vengurla	—	—	—	—	—	—	—	—	—	—	—	—	—	1	2	17	97	1
Ratnagiri	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	15	38	6
Harnai	—	—	—	—	—	—	—	—	—	—	—	—	—	4	—	7	—	1
Bombay	—	—	—	—	—	—	—	—	—	—	—	—	—	—	3	4	—	3
Date (1965 May/ June)	22	23	24	25	26	27	28	29	30	31	1	2	3	4	5	6	7	8





24 hours rainfall (mm) ending 0300 GMT

Trivandrum	—	—	—	1	13	—	27	2	—
Alleppey	—	2	1	113	98	10	9	12	2
Cochin	—	8	—	7	101	25	16	14	—
Minicoy	33	33	55	14	20	55	30	57	—
Kozhikode	—	33	—	4	45	50	1	—	—
Mangalore	—	13	3	—	13	3	3	76	—
Honavar	—	—	—	—	2	8	1	11	1
Vengurla	—	—	—	—	4	—	—	22	9
Ratnagiri	—	—	—	2	—	—	—	—	8
Harnai	—	—	—	—	—	—	—	—	—
Bombay	—	—	—	—	—	—	—	—	—
Date (1966 May/Jun)	30	31	1	2	3	4	5	6	7

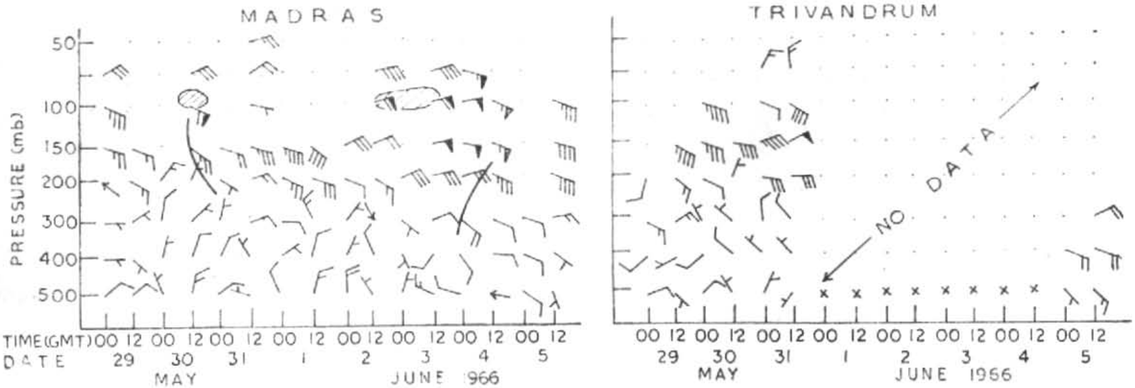


Fig. 7(f)

24 hours rainfall (mm) ending 0300 GMT

Trivandrum	3	—	2	31	30	42	12	1	—
Alleppey	1	1	—	6	87	128	90	50	1
Cochin	—	5	4	1	72	64	73	136	1
Minicoy	9	5	21	7	29	55	26	8	7
Kozhikode	—	—	2	1	3	29	63	34	2
Mangalore	1	—	4	—	7	1	9	30	5
Honavar	6	—	—	—	—	—	—	9	6
Vengurla	—	—	—	—	—	—	1	4	—
Ratnagiri	—	—	—	—	—	—	—	31	—
Harnai	—	—	—	—	—	—	—	—	—
Bombay	—	—	—	—	—	—	—	3	—
Date (1967 June)	5	6	7	8	9	10	11	12	[illegible]

24 hours rainfall (mm) ending 0300 GMT

Trivandrum	—	—	—	25	8	47	54	70	22
Alleppey	2	—	3	14	23	87	77	54	49
Cochin	—	—	20	1	30	12	98	82	41
Minicoy	16	2	8	5	13	6	19	9	30
Kozhikode	—	—	14	19	20	61	153	39	46
Mangalore	—	10	3	5	—	—	43	90	50
Honavar	—	18	51	10	1	7	5	65	142
Vengurla	—	16	—	—	—	50	—	11	38
Ratnagiri	—	—	—	—	—	—	—	7	8
Harnai	—	—	—	—	—	—	—	—	—
Bombay	—	—	—	—	—	—	—	—	—
Date (1968 June)	5	6	7	8	9	10	11	12	13

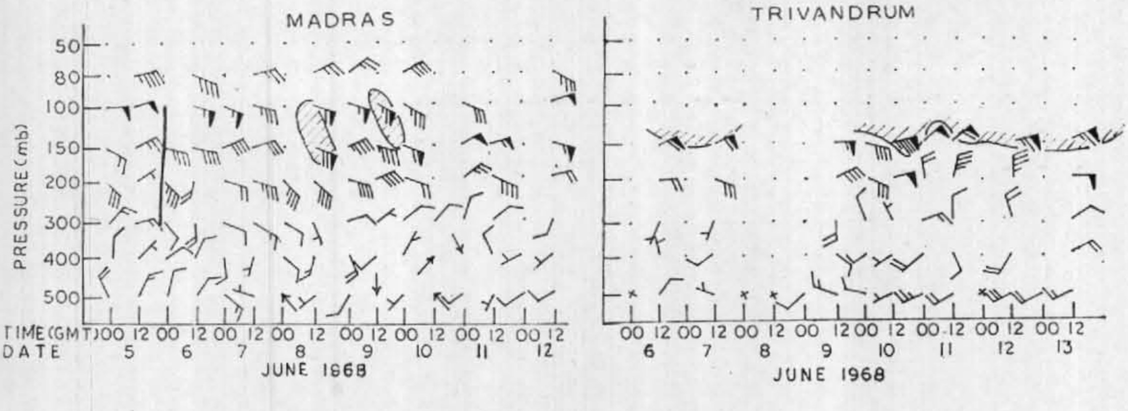


Fig. 7(h)

easterly wave trough between 300-150 mb passed over Madras on 6 June followed by an east wind maximum increasing upto 8 June. The latter is significant in explaining the heavy rainfall over the west coast south of Lat. 15°N on 10 and 11 June.

6. Conclusion

Observational evidence during the years 1961—68 shows that, given a pre-existing lower tropospheric feature causing convergence at sea level along and near Kerala coast, upper divergence in the western portion of an advancing trough in the easterlies or the 'left exit' portion of an accelerating east wind maximum in the upper levels over Madras usually precedes and causes the burst of monsoon over Kerala coast. Development of east wind mxima of jet magnitude is seen to occur in the upper levels even prior to the onset of monsoon. No relationship is aslo seen between release of latent heat by 'cloudines and precipitation' in the lower troposphere and the waxing and waning of upper level east wind maxima. These observed behaviour of the upper tropospheric winds over the Peninsula during the monsoon does not at all support Raman and Ramanathan's finding that "east wind maxima develop in the upper troposphere over India *some time after and not before the occurrence of heavy rain*" as summarised by Ramaswamy (1967).

The high degree of correlation observed by Raman and Ramanathan between a day's east wind maximum and previous day's rainfall peak appears to be largely due to the dynamics of the jet stream structure. Their finding of a rainfall peak to the north of an east wind peak is a result of selective subjectivity in fixing the jet axis, unless, of course, if the wind maximum was in a decelerating stage. In this way, their study largely supports instead of disproving the role of upper level easterly jet in controlling the monsoon activity along the west coast as proposed by Koteswaram.

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