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Rainfall Peaks over West Coast and East Coast of Peninsular India

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ABSTRACT. Latitudinal profiles of monthly normals of rainfall of west coast and east coast stations of Peninsular India were studied. On the west coast, a rainfall peak is seen near lat. 13/14°N in the monsoon season and near latitudes 9/10°N in the other seasons. On the east coast a rainfall peak is seen near latitudes 10/11°N in November, December and January and near latitudes 13/14°N in October. These rainfall peaks are found to occur over belts where, on the mean, there is good supply of moisture as well as low level convergence.

1. Introduction

When monthly, seasonal or annual normals of rainfall of stations extending over very large areas are examined, it is found that there are belts over which greater rainfall occurs. These regions of greater rainfall naturally must have, on the mean, features more favourable for the occurrence of rain. Such favourable low-level features are broadly (*i*) moisture supply, (*ii*) convergence and (*iii*) orography.

An examination of these features which appear to account for the observed rainfall profiles along the west coast and east coast of Peninsular India has been made and the results are presented in the following paragraphs.

2. Data

Monthly normals of rainfall of rain recording stations in India based on data up to the end of 1940 have been published by the India Meteorological Department (1949). These normals are made use of in this study. Seasonal normals are obtained by adding monthly normals for the respective seasons, *viz.*, Winter Season (January and February), Hot Weather Season (March to May), Monsoon Season (June to September) and Post Monsoon Season (October to December).

Stations used in this study are the rain-recording stations located on or very near the east coast and west coast of India, south of latitude 20°N. These stations are shown in Fig. 1. Stations located in each one degree latitudinal belt are grouped together and the average rainfall calculated for each group. This value is taken as the rainfall corresponding to the average latitude of the stations concerned. This procedure is followed to eliminate, as far as possible, effects caused in station rainfall if any by peculiarities of a purely localised nature and defective exposure of raingauge. Latitudinal profiles of rainfall are prepared by

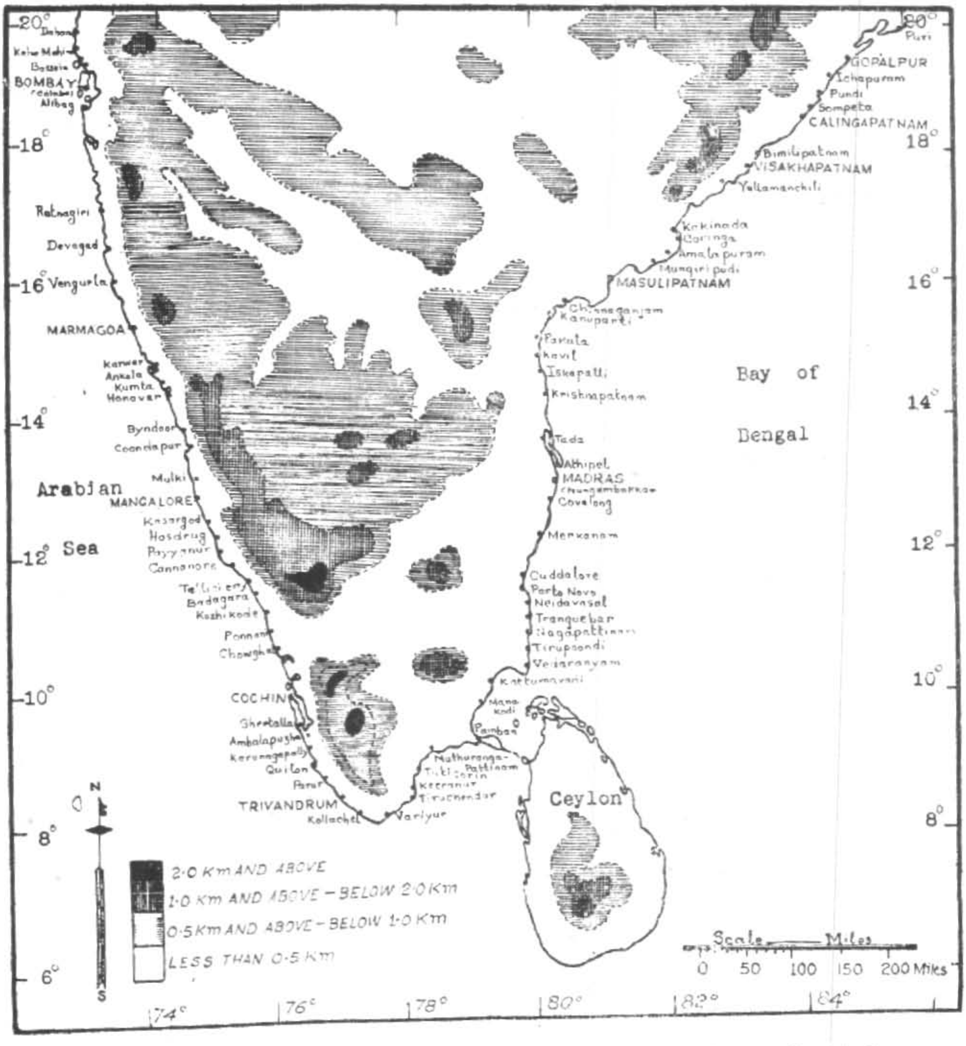

Fig. 1. Map of Peninsular India showing physical features and rain-recording stations

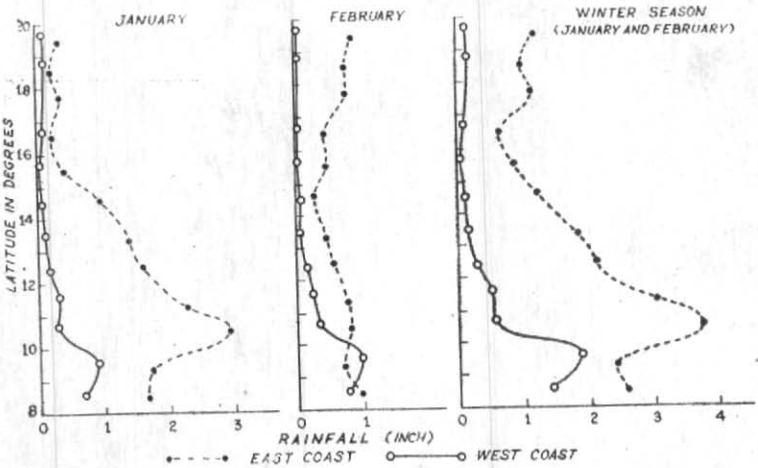

Fig. 2. Rainfall profiles of winter season

plotting rainfall against latitude and drawing smooth curves. Profiles are prepared separately for east coast and west coast for the different months and seasons.

In this study, cyclonic storms and depressions as rain-causing factors have not been considered. The reason for this is that when normal values covering long periods are considered, effects caused by infrequent phenomena like cyclonic storms and depressions get smoothed out and do not stand out prominently.

3. Discussion of rainfall profiles

3·1. *Winter Season (January and February)* —Rainfall profiles of winter season are shown in Fig. 2.

Rainfall activity is confined mainly to the southern portions of the Peninsula. Rainfall is generally more on the east coast than on the west coast. On the east coast, rainfall decreases northwards up to latitude 15°/16°N. On this coast, a rainfall peak of value 2·9 inches is seen between latitudes 10° and 11°N in the month of January; in the month of February the peak is not at all conspicuous.

The west coast profiles of January and February are very much similar, rainfall activity becoming negligible north of latitude 13°N. On this coast both in the months of January and February, a rainfall peak of about 1 inch is seen near latitude 9°/10°N.

Streamlines of upper winds of the Indian monsoon area are given in the India Meteorological Department publication (1945). The streamlines at 1 km a.s.l. for January and February are reproduced in Figs. 3 and 4. Considering these monthly streamlines as mean trajectories, it will be seen that in the month of January, air having progressively increasing travel over sea, flows over the east coast as we go south from latitude 13° N to 10°N. Hence air, having comparatively the longest travel over sea and consequently having the highest moisture content in the month, is over the east coast belt between latitudes 11° and 10°N. Mean value of specific humidity of surface air of Nagapattinam, Guddalore and Madras of this month (shown in Table I) confirms the above. South of latitude 10°N, moisture flow over the east coast will not be representative because of the location of Ceylon to the east.

Over the east coast belt between latitudes 13° and 10°N, streamlines (Fig. 3) are straight and run from east to west in the month of January. An examination of the wind speed at 1 km a.s.l. shows that there is no appreciable horizontal wind shear over this belt. Thus there is neither cyclonic nor

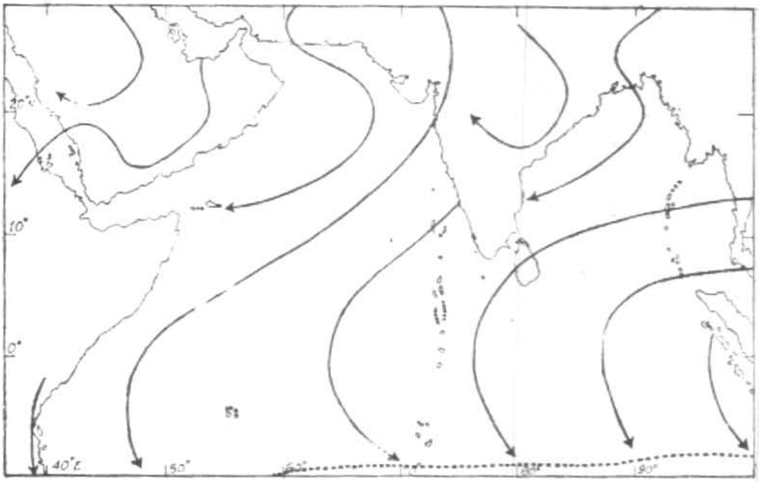

Fig. 3. Streamlines at 1 km a.s.l. for January

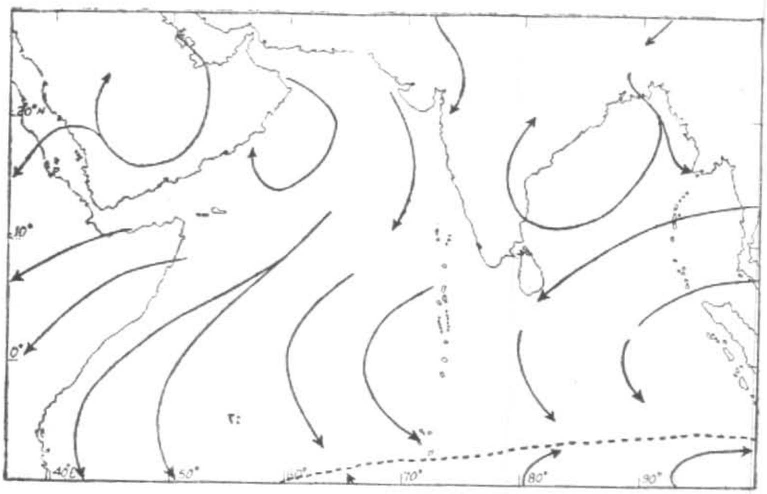

Fig. 4. Streamlines at 1 km a.s.l. for February

TABLE 1

Specific humidity of surface air in January

Station	Height (ft a.s.l.)	Latitude (N)	Specific humidity (gm/kgm)
Nagapattinam	31	10° 46′	15·21
Cuddalore	39	11° 46′	14·88
Madras	51	13° 04′	14·69

anticyclonic vorticity over this belt in the lower levels. The comparatively higher moisture supply and absence of anticyclonic vorticity over this belt of the east coast in the month of January, therefore, account for the rainfall peak observed near latitude 10°/11°N. In this connection it may be mentioned that the Eastern Ghats, because of their comparatively lower heights and location away from the coast, have very little influence on the east coast rainfall.

In the month of February, the specific humidity of surface air at Nagapattinam, Cuddalore and Madras is higher than in January. There is, however, a marked change in the flow patterns as shown in Fig. 4. Streamlines at 1 km a.s.l. for February over the east coast belt between latitudes 13° and 10°N show an anticyclonic curvature. An examination of the wind speed at 1 km a.s.l. over this belt shows no appreciable horizontal wind shear over this belt. It therefore is a region of anticyclonic vorticity and divergence in the lower levels. Thus in the month of February, although the specific humidity of air is higher than in January, yet due to the anticyclonic vorticity and divergence of the flow patterns in the lower levels, rainfall over this east coast belt becomes very much less. The change in the wind flow pattern and the disappearance of the rainfall peak are indeed very striking.

As already mentioned, a rainfall peak is seen on the west coast near latitudes 9°/10°N in the months of January and February. Specific humidity of surface air on the west coast is lowest in the month of January. In February, it is slightly higher. Streamlines of these months (Figs. 3 and 4) are straight or show a slight cyclonic curvature over the southern portions of the west coast. Due to obstruction caused to the wind flow by the Palani, Anamalai and Cardamon Hills (Fig. 1), the easterly wind speed decreases to the south of the Palghat gap, *i.e.*, south of latitude 10°N on the west coast in the lower levels. These considerations show that cyclonic vorticity and convergence exist over this belt of the west coast and these therefore account for the rainfall peak observed on the west coast near latitudes 9°/10°N in these months.

3·2. *Hot Weather Season* (*March to May*)— Rainfall profiles of this season are given in Fig. 5. The east coast profiles of these months are nearly similar with no prominent peak values. In May, rainfall activity becomes more than in previous months, the increase becoming particularly noticeable north of latitude 16°N.

On the west coast, rainfall increases very rapidly as the season advances. A rainfall peak is observed on the west coast near latitudes 9°/10°N in this season. The peak is seen every month and becomes more and more prominent as the season advances. The peak values are about 2 inches in March, 4·8 inches in April and 10·8 inches in May.

In March, both on the east coast and west coast, the wind flow pattern is the same as in February. The higher rainfall observed in this month on both the coasts can be attributed to the slightly higher moisture content of air shown by the value of the specific humidity of surface air.

Streamlines of upper winds at 1 km a.s.l. for April are reproduced in Fig. 6. The flow pattern in this month is very much different from that of the previous months (Figs. 3 and 4). Streamlines over the west coast

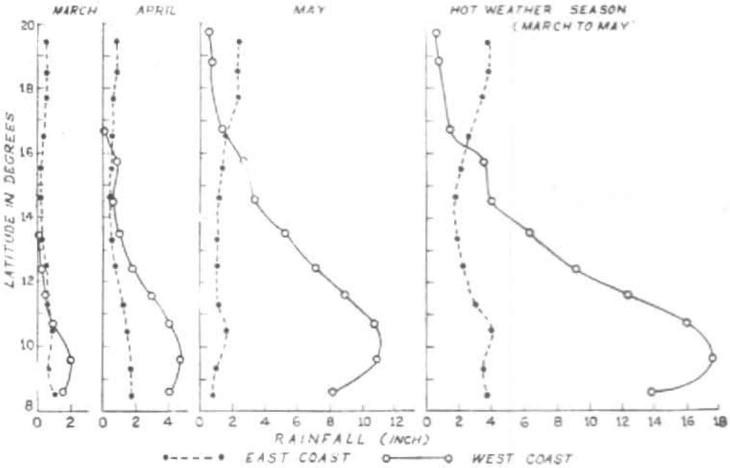

Fig. 5. Rainfall profiles of hot weather season

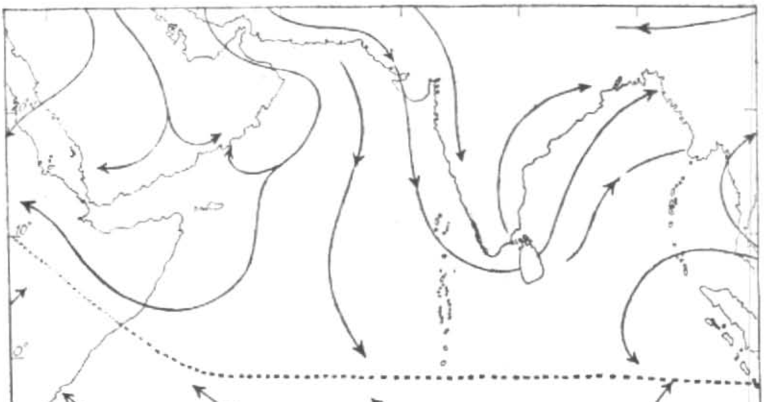

Fig. 6. Streamlines at 1 km a.s.l. for April

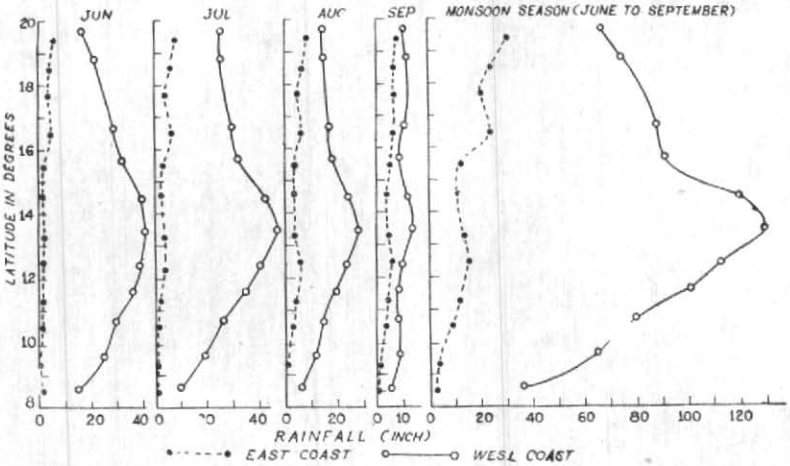

Fig. 7. Rainfall profiles of monsoon season

TABLE 2

Specific humidity of surface air in April

Station	Height (ft a.s.l.)	Latitude (N)	Specific humidity (gm/kgm)
Mangalore	72	12° 52′	17·62
Calicut	27	11° 15′	18·55
Cochin	10	09° 58′	18·72
Trivandrum	200	08° 29′	18·53

are straight and run parallel to the coast upto latitude 10°N. South of latitude 10°N, streamlines have a cyclonic curvature. Since there is no horizontal wind shear over this belt, vorticity here is cyclonic. The cyclonic vorticity existing near latitude 10°N over the west coast and the higher moisture content of air over this belt in this month (shown in Table 2) account for the rainfall peak seen over this west coast belt.

Outside monsoon months, rainfall peak seen over the west coast near lat. 9°/10°N is highest in the month of May. The mean position of the equatorial trough in this month is shown in the India Meteorological Department publication (1945). Its mean position at 1 km a.s.l. in the month of May is near latitude 10°N. Increasing depth of moist air and convergence associated with the equatorial trough produce heavy rain near it. A belt of heavy rainfall, consequently, appears near the mean position of the equatorial trough. Orographic lift provided by the Western Ghats becomes a contributory factor for causing increased rain in this case. These factors, therefore, account for the west coast rainfall peak of this month. Corresponding to the mean position of the equatorial trough in this month, a rainfall peak also appears on the east coast near latitudes 10°/11°N. Due to insufficient moisture supply on the east coast this peak, however, is not very prominent.

3·3. *Monsoon Season* (*June to September*) —Rainfall profiles of this season are shown in Fig. 7.

The east coast profiles of the different months are more or less similar. Rainfall activity remains practically uniform on the east coast up to latitude 15°N. The comparatively lesser rainfall activity over this east coast belt in this season is due to inadequate moisture supply. North of latitude 15°N, rainfall gradually increases on the east coast.

The most interesting feature shown by the rainfall profiles of this season is the prominent rainfall peak observed near latitude 13°/14°N on the west coast. This peak is seen in the monthly profiles as well as in the seasonal profile. The peak is highest in the month of July being 47″, June, August and September peak values are 41, 28·2 and 13·3 inches respectively. Ramakrishnan and Gopinatha Rao (1958) have studied the profiles of normal rainfall of the months June to September along the west coast and have shown the occurrence of a main rain peak at latitude 14°N and a secondary peak at latitude 18°N. The appearance of the secondary peak can be attributed to the value of rainfall recorded at Dapoli. The data of this station has not been taken into account in the present study as the location of this station is not very close to the coast. Fig. 7 does not show any conspicuous secondary peak.

The Western Ghats running parallel and close to the coast play an important part in the causation of rain on the west coast. This is well known and the mechanism of orographic lift by which rainfall is caused is also generally well understood. But the occurrence of a predominant rainfall peak near latitude 13°/14°N against the general background of heavy rainfall on the west coast in this season is an interesting aspect.

To find out whether this part of the western ghats has any features not seen elsewhere, the points to be examined are—(*a*) closeness of the ghats to the coast, (*b*) height of peaks and (*c*) shape of height contours. Height contours of ghats are shown in Fig. 1. The ghats are close to the coast at this place but at other places on the west coast also, they are as close. The highest peak over this portion of ghats is Kudremukh which is 6215 feet. Farther south there are higher peaks such as Doddabetta (8760 ft) and Anaimudi (8841 ft). Height contour lines of the ghats generally run parallel to the west coast but show a bent near latitudes 12°/13°N. This bent, however, does not appear to be of a size which can modify the wind flow pattern to such an extent as to form any stationary or semi-stationary off-shore vortex which can produce concentrated rain in its proximity. Hence the west coast rainfall peak of the monsoon season cannot be considered to be caused by any special feature of the western ghats. Orographic lift provided by the ghats can only be a contributory factor in causing rain when other favourable features appear.

As already referred to, equatorial trough plays an important part in the production of rain and a belt of heavy rain is generally found near its mean position. The mean position of the equatorial trough in the different months of this season is shown in India Meteorological Department publication (1945). In June its position at 1 km a.s.l. is near latitude 22°N, in July near latitude 26°N, in August near latitude 24°N and in September near latitude 20°N. The mean position of the equatorial trough in these months is so far north that the rainfall peak observed on the west coast near latitudes 13°/14°N cannot be attributed to it.

Streamlines at 1 km a.s.l. for July are reproduced in Fig. 8. June, August and September streamlines are similar to those of July. Considering the streamlines as mean trajectories, it will be seen that, on the average, the genuine maritime air on the west coast is confined to portions south of latitude 15°N. Streamlines also show that air reaching west coast between latitudes 13° and 15°N will be having the maximum amount of travel over sea in the summer hemisphere. Besides, its flow near the heated land masses of Africa enables it to pick up more moisture also. Due to these factors, air reaching west coast between latitudes 13° and 15°N will have, on the mean, the highest moisture content during these months.

Between the equator and the west coast, streamlines at 1 km a.s.l. for the months of June to September have an anticyclonic curvature (Fig. 8). If wind speed remains the same along the west coast so that there is

TABLE 3

Mean surface wind speed in miles per hour

Station	June	July	August	September
Mangalore (Height 72 ft, Lat. 12° 52′N)	5·4	5·6	4·5	3·9
Marmagoa (Height 202 ft, Lat. 15° 25′N)	8·1	9·9	8·2	5·4

no horizontal wind shear, then vorticity is given mainly by the curvature term. As the curvature term decreases northwards in such a streamline configuration, the anti-cyclonic vorticity of the flow pattern also decreases northwards. If wind speed decreases northwards along the west coast, besides the decreasing curvature term the shear term is also opposing so that anticyclonic vorticity rapidly decreases northwards. Thus along with the anticyclonic streamlines, if wind speed remains the same or decreases northwards along the west coast then the west coast belt, over which greater rainfall will occur, is the northern edge of the circulation, *viz.*, near latitudes 13°/15° N where there is rapid decrease of anticyclonic vorticity. Isotachs of average wind speed are shown in India Meteorological Department publication (1943). Along the west coast at 1 km a.s.l. in the months of July and August wind speed remains nearly uniform while in the months of June and September wind speed decreases northwards. Horizontal wind speed variation along the west coast, therefore, satisfies the above criterion.

Thus moisture supply and wind flow pattern causing low-level convergence account for the rainfall peak observed on the west coast in this season. In this connection it may be mentioned that although the favourable wind flow pattern extends over the east coast also, yet due to insufficient moisture supply very little rainfall activity is seen on the corresponding portions of the east coast in this season.

In this season rainfall peak over the west coast is highest in the month of July and lowest in the month of September. To account for the large variation observed in the value of the rainfall peak from month to month, total moisture transport or inflow along the surface is a factor to be considered. Since variation of specific humidity at the surface is very small, mean monthly surface wind speed can be taken to represent roughly the total moisture transport or inflow along the surface. Monthly mean surface wind speed of Mangalore and Marmagoa, near which the rainfall peak is observed, is given in Table 3 from the India Meteorological Department publication (1953).

It is of interest to note that mean wind speed is highest in the month of July, when rainfall peak is also highest. Mean wind speed is lowest in the month of September when rainfall peak is also lowest.

Koteswaram (1956) has shown that easterly jets streams regularly exist over southern Asia and Africa during the summer monsoon season near latitude 15°N. Such a mean position of the easterly jet stream can result in large scale ascent of air below the left exit region of the jet stream more or less over the area where the rainfall peak is observed on the west coast. Large scale ascent of air thus induced on the west coast where genuine maritime air is present, will produce heavy falls of rain on the west coast south of latitude 15°N. Koteswaram (1956) has also shown the latitudinal oscillation of the easterly jet stream. The mean position of the jet stream is farther north in the months of July and August compared to that of June and September. If easterly jet stream is the main factor causing the rainfall peak seen on the west coast, then this peak should be more north in July and August than in June and September. Rainfall profiles of these months, however, show no such oscillation, the peak appearing practically at the same position in all the months. The steadiness of the location of the rainfall peak shows that the oscillation of jet stream core is not significant enough as to alter the zone of maximum rainfall which is found to occur over the belt of the west coast near latitude 13°/14°N where the most favourable low-level conditions exist.

Upper air easterly troughs are found to move westwards across India during the monsoon period (Koteswaram and George, 1958). These troughs play a significant part in the causation of rain of the monsoon season. When the divergent forward portion of an upper air easterly trough overlies a region having low level convergence and moisture supply, large scale ascent of air can take place over such region resulting in release of substantial precipitation. The depth and latitudinal extent of these troughs are often variable. Consequently, their effect on the mean rainfall profiles gets blurred. However, it can be stated that as in the case of easterly jet streams, these troughs also produce maximum rainfall on the west coast where low-level conditions are most favourable. Due to insufficiency of moisture, these troughs do not cause much rain along the east coast under normal monsoon conditions as they progress westwards.

3·4. *Post Monsoon Season (October to December)*— Rainfall profiles of this season are given in Fig. 9.

Rainfall activity is generally more on the east coast than on the west coast. In October, on the east coast a rainfall peak is seen near latitudes 13°/14°N. In November and December, the peak has shifted south and is near latitudes 10°/11°N. The peak value is highest in November being 16·3 inches, in October and December the values are lesser being 12·0 and 9·3 inches respectively.

The west coast profiles of the different months are very similar. Rainfall rapidly decreases as the season advances. A rainfall peak is seen in every month of this season on

TABLE 4

Specific humidity of surface air in November

Station	Height (ft a.s.l.)	Latitude (N)	Specific humidity (gm/kgm)
Madras	51	13° 04′	16·62
Cuddalore	39	11° 46′	16·81
Nagapattinam	31	10° 46′	17·06

the west coast near latitudes 9°/10°N. The rainfall peak decreases and becomes less and less conspicuous with the advance of the season being 12·6 inches in October, 7·3 inches in November and 2·0 inches in December.

The mean position of the equatorial trough in the month of October is shown in India Meteorological Department publication (1945). Its mean position at 1 km a.s.l. is near latitude 13°N on the east coast and near latitude 12°N on the west coast. Convergence associated with the equatorial trough has already been referred to. Streamlines of the month show that moisture supply is more to the north of the trough on the east coast and to the south of the trough on the west coast. These, therefore, explain the rainfall peaks in October seen near latitudes 13°/14°N on the east coast, *i.e.*, to the north of mean position of the trough and near latitudes 9°/10°N on the west coast, *i.e.*, to the south of mean position of the trough.

Streamlines at 1 km a.s.l. of the month of November are shown in Fig. 10. Considering the streamlines as mean trajectories, it will be seen that easterly air, having the longest sea travel and maximum moisture, flows over the east coast south of latitude 12°N . This is shown by the specific humidity of surface air of this month given in Table 4.

Besides, streamlines have slight cyclonic curvature over the east coast belt near latitude 11°N. Since wind speed is nearly uniform with no horizontal wind shear over

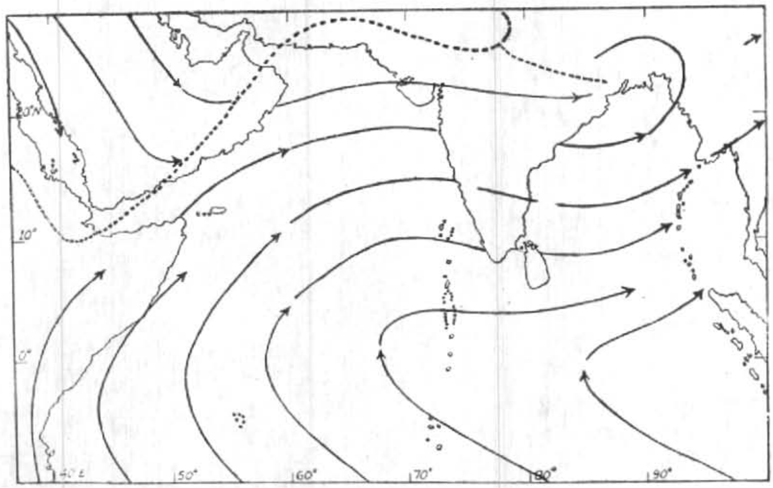

Fig. 8. Streamlines at 1 km a.s.l. for July

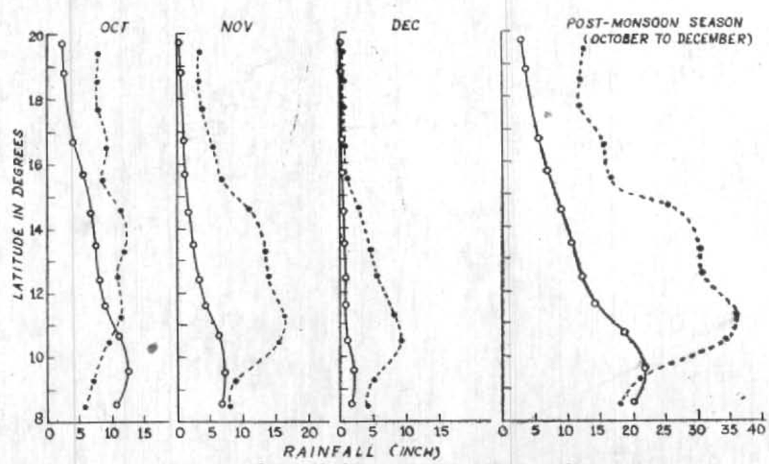

Fig. 9. Rainfall profiles of post monsoon season

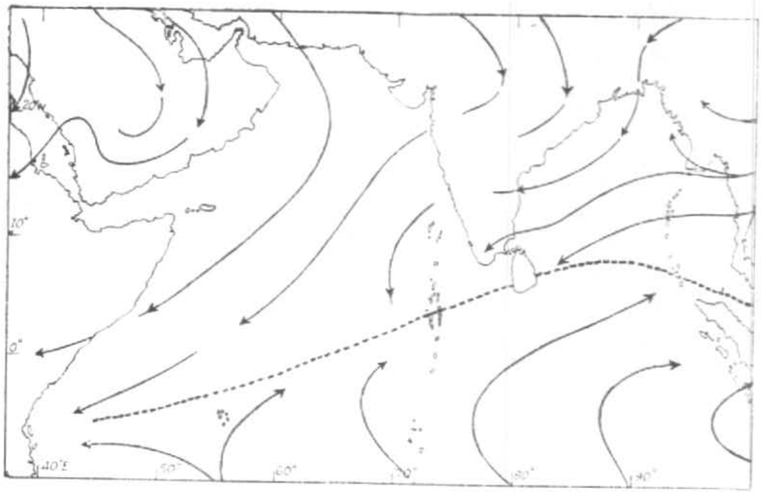

Fig. 10. Streamlines at 1 km a.s.l. for November

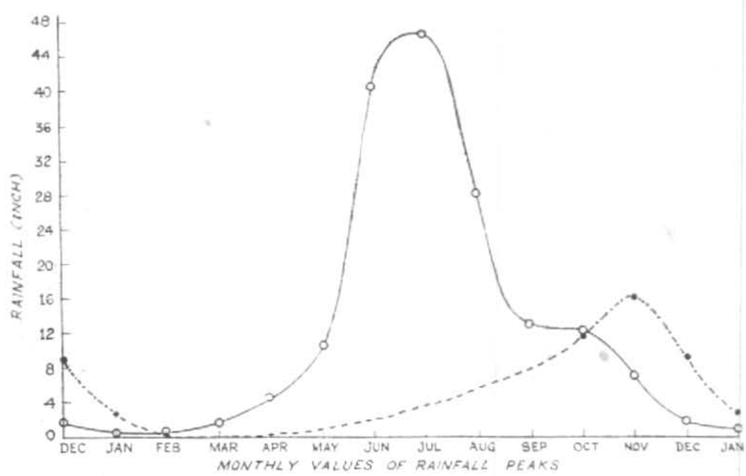

Fig. 11. Monthly values of rainfall peaks

this belt, there is cyclonic vorticity and convergence in the lower levels over this east coast belt. Thus moisture supply and convergence account for the east coast rainfall peak.

In November, rainfall peak on the east coast is the highest of the year. This is attributable to the fact that air having maximum sea travel and moisture, flows over latitudes 10°/12° N of the east coast during this season.

On the west coast, streamlines show a marked cyclonic curvature over the southern portions (Fig. 10). As already explained while discussing the profiles of January, the easterly wind speed over the west coast in the lower levels will be lesser to the south of the Palghat gap. Thus cyclonic vorticity and convergence are the low-level features over this belt of the west coast. The easterly streamlines show that the moisture content of air while flowing over the west coast will be less than while flowing over the east coast. Consequently, the peak value on the west coast is less than that on the east coast.

In December, wind flow pattern is similar to that of January both on the east coast and west coast. Rainfall peaks observed on both the coasts in this month are also similar to that of January. The peak values are higher than in January, presumably due to the higher specific humidity of air in this month compared to that in January.

4. Conclusions

A plot of the rainfall peak values along both the coasts for the different months is shown in Fig. 11.

On the west coast, rainfall peak is near latitudes 13°/14 ° N in the monsoon season and near latitudes 9°/10°N in the other seasons. The peak is lowest in the month of January when specific humidity of surface air has the lowest value of the year. The peak value is highest in the month of July and is near latitudes 13°/14° N where there is good supply of moisture as well as rapid change of anticyclonic vorticity to cyclonic vorticity in the lower levels.

On the east coast, rainfall peak is not seen conspicuously in all the months. It is seen near latitudes 10°/11°N in the months of November, December and January and near latitudes 13°/14°N in the month of October. The peak value of November near latitudes 10°/11°N is the highest of the year. In this month, over this belt of the east coast easterly air, having the longest sea travel, brings in maximum supply of moisture. Besides, over this belt there is cyclonic vorticity and convergence in the low-levels.

Rainfall and peaks are higher on the west coast from April to September when low-level winds are mainly westerlies. In October, rainfall peak on both the coasts is nearly of the same value. In this month in the lower levels, westerlies flow over the west coast belt and easterlies over the east coast belt where the rainfall peak occurs. From November to January, low-level winds are mainly easterlies. Rainfall and peaks over the east coast become higher in these months. In February and March also, easterlies flow but due to the anticyclonic vorticity of the low-level flow over the east coast belt between latitudes 10° and 13°N, no conspicuous rainfall peak is seen over the east coast.

The above study has shown that low-level features such as moisture supply and convergence are chiefly responsible for the observed peaks in the mean rainfall profiles on the coastal belts of Peninsular India.

The role of upper tropospheric flow patterns in influencing the day-to-day variations of low-level circulation features is beyond the scope of this study. This, however, must be given due weightage in deciding areas of heavy rainfall caused by the above mentioned low-level factors in the day-to-day forecasting work.

5. Acknowledgement

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