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Southwest monsoon rainfall in Gangetic West Bengal and its association with upper air flow patterns

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ABSTRACT. The day-to-day occurrence of rainfall over Gangetic West Bengal during three monsoon seasons was studied in the light of the upper air flow patterns and it was noticed that the rainfall occurs mostly due to the upper divergence ahead of upper easterly waves which move across the area. Details of the structure and other characteristics of these easterly wave troughs are given. A study of the occurrence of fast winds and their relationship to the rainfall over Gangetic West Bengal is also included.

1. Introduction

During the southwest monsoon period, the rainfall over any part of India is subject to large day-to-day fluctuations, ranging from dry weather to very heavy rainfall. In the absence of depressions affecting the area, the rainfall distribution, according to earlier Indian Meteorologists, is mainly controlled by the position and the orientation of the axis of the sea level monsoon trough. With the increase in the number of rawin observations over India during the last few years, it is becoming evident that the upper and mid-tropospheric flow patterns have a definite role in the distribution of rainfall. In this paper it is proposed to examine the daily variation of the rainfall pattern in relation to the upper and mid-tropospheric flow patterns during the last few years. This study is confined to rainfall over Gangetic West Bengal only, but the technique discussed and the results arrived at, would possibly be applicable to most of northeast India and also in a general way to the whole of the Indian sub-continent outside northwest India, where similar upper air flow exists in the southwest monsoon season.

2. Upper air flow pattern over India during the southwest monsoon season

When the monsoon is established over India (July-September), the flow pattern above 6 km consists of a large "high" over the Himalayas and the Tibetan plateau with a broad easterly current over the rest of the Indian sub-continent, Arabian Sea, Bay of Bengal, Burma, etc. Koteswaram (1956, 1958) has shown that this easterly current concentrates into a jet stream with the core in mean position along Lat. 15°N at about 150-mb (14 km) level. The easterly stream over the Indian sub-continent is deepest to the north of the axis of the sea level monsoon trough where the easterlies prevail from the surface upwards. To the south of the monsoon trough, there is the westerly "monsoon current" in the lower levels which gradually gives place to the easterlies in the higher levels. The base of the easterlies lifts higher as we go south across the monsoon trough and it reaches a height of about 6 to 7 km over the south Indian Peninsula (Lat. 10°–15°N). Of course, this height over any area is subject to large day-to-day variations. On certain occasions the depth of the monsoon westerlies may go upto 6 km or more even over north India when the axis of the monsoon trough shifts to the Himalayas and a "break" in the monsoon rains sets in. The speed of the easterly current increases with height so that there is a north to south temperature gradient with higher temperatures to the north. Such a current is "dynamically unstable" (Holmboe, Forsythe and Gustin 1948).

This upper easterly current is subject to perturbations like transverse waves or wind maxima travelling from east to west. Although from a very long time, Indian Meteorologists were aware of westward moving isobaric or isallobaric 'lows' during the southwest monsoon season, the existence of the upper perturbations became known only recently when rawin observations were commenced. Koteswaram and George (1958) have discussed the role of these upper perturbations in the development of monsoon depressions. In this paper, the role of these disturbances in the regulation of monsoon rainfall over Gangetic West Bengal will be discussed. Since the wave type perturbations affect Gangetic West Bengal in far larger number than the jet type, the discussion will start with respect to the former one.

3. Dynamics of the wave motion

The vertical structure of the waves and the distribution of weather with respect to the trough line depend on the relative speed of the zonal current with reference to the wave (v-c) and the variation of the strength of the zonal current with height. Riehl (1954a) has discussed the dynamics of the waves in the easterlies. A brief outline of Riehl's discussion and its application to the easterly waves in Indian area are attempted in this section.

If we consider a small parcel of air of thickness $\triangle p$ moving along with an easterly wave travelling in a steady state and denote the initial conditions by the subscript zero, the changes in the parcel of the air after a small displacement will be given by the equation

$$\frac{\triangle p}{\triangle p_0} = \left(f+\frac{v}{r_s}\right) \Big/ \left(f+\frac{v}{r_s}\right)_0$$

where f is the Coriolis parameter,

v the wind speed and

r_s the radius of curvature of the streamline,

so that v/r_s is the relative vorticity. Vorticity due to shear can be neglected as there is not much of strong winds in the field of the easterly waves.

If $\triangle p > \triangle p_0$, the thickness of the parcel increases and there is vertical stretching of air column and consequently covergence. In the reverse case, there is divergence.

Let us consider the case where the air parcel is approaching the trough line with a speed v, greater than the speed of the trough line c, from the ridge to the trough line. During such a motion f increases as well as the curvature changes from anticyclonic to cyclonic. Consequently $\triangle p$ should increase; hence vertical stretching, and convergence should occur to the east of the trough line. For similar reasons there should be vertical shrinking and divergence to the west of the trough line. For this particular level there is divergence ahead of the wave and convergence in the rear. Since the easterlies of the southwest monsoon period increase in speed with height, in the above case there is no change in the sign of divergence with reference to the trough line as we go up. For the same reason in the levels below, v may become less than c (assuming c to be constant at all levels), so that divergence changes sign in the lower layers. Since these waves move west, there should be a net divergence ahead of the trough. In other words, ahead of the trough, the upper divergence predominates over the lower convergence.

In the case of the easterly waves of the southwest monsoon season in India, where the upper easterlies increase with height, the upper divergence ahead of the trough and the upper convergence in the rear are preponderant and cause the weather ahead of the trough line (see Section 5, para c) as well as the westward movement of the trough. Whereas in the Carribean sea model (Riehl 1954b) where the basic current decreases with height, the convergence and divergence in the lower troposphere predominate and cause the weather in the rear of the trough line and the forward movement of the trough. This is a significant difference between the two models.

4. Technique of analysis

By experience, it is noticed that vertical time-section diagram for rawin/radiosonde station is a better method of locating upper perturbations, such as troughs, jet maxima etc than constant pressure charts, particularly over areas where the density of observations is not high. For purposes of this study, the vertical time-sections for Calcutta were prepared for the monsoon periods (July-September) for the three years 1955–1957, and for Gauhati, Visakhapatnam and Madras for 1957. On these time-sections the trough lines and wind maxima were marked on the basis of wind observations, except in the case of Visakhapatnam where the height values had to be used for locating the trough lines, due to the absence of rawin data. It was verified from Calcutta time-sections for 1957, that the troughs shown by wind observations agree fairly well with the location of the troughs marked with height values or 24-hour changes in height values.

In some cases it was found helpful to utilize the thermal property of the progressive waves, *viz.*, that in progressive baroclinic waves the streamlines of thermal winds have a greater amplitude than the streamlines themselves, since the streamlines of thermal winds coincide with isotherms. Therefore, shifts in thermal winds between consecutive standard isobaric surfaces (particularly those between 500 and 200-mb levels) can be utilized for fixing the trough lines.

The constant level streamline charts were also looked into wherever necessary.

Since constant level streamline charts and vertical time-sections were exclusively used instead of constant pressure contour charts, in this study, and as the weakening or deepening of the wave perturbations during the course of their movement across the country, can only be noticed on the upper air contour charts, no attempt was made to study this aspect of the problem, *viz.*, the weakening or the deepening of the wave troughs.

5. Characteristics of easterly wave troughs*

Some of the characteristic features of the easterly troughs observed during this study are given in this section.

(*a*) *Structure*—The wave troughs generally extend from the base of the easterly current to about 10 km (300—200 mb) and they appear to be most marked between 400-mb and 200-mb levels. Above this level they are generally damped. However, deep troughs sometimes extend even above 200-mb level (Koteswaram and George 1958). On some occasions the troughs were found to exist only in the uppermost portions of the easterly current.

The method followed by López (1948) of plotting the 24-hour changes in the thickness values between successive isobaric surfaces, was employed to study the thermal structure of the wave. A study of Calcutta time-sections showed that with the approach of the trough, there was cooling, the coldest air being near the trough line, with relatively warmer air ahead as well as in the rear. The largest changes in the thickness values generally occur between 500-mb and 200-mb levels, suggesting that the troughs are most marked between these levels. Sometimes when the magnitude of the changes are large, the intensity of the associated weather is also great.

The trough lines are almost vertical or slope slightly towards the east. The wave length of these waves (at 300-mb level) is of the order of 20 degrees longitude (2000 km) and their speed of the order of 10 to 15 knots.

(*b*) *Frequency*—The number of westward trough passages over Calcutta during the monsoon season is about 10 per month. The frequency is highest over Calcutta which is located near the thermal equator for the season and decreases as we go both north and south as indicated by the corresponding figures for Gauhati, Visakhapatnam and Madras.

* In the subsequent paragraphs, the terms "easterly waves", "easterly troughs" etc refer to these perturbations in the upper air, unless stated otherwise.

TABLE 1

No. of rainy days over Gangetic West Bengal with reference to the easterly trough position

Year	Number of rainy days with					Total No. of rainy days
	Trough to east of Calcutta	Trough over Calcutta	Trough to west of Calcutta	No trough	No data	
1955	19	16	1	9	5	50
1956	16	19	0	7	13	55
1957	18	22	2	7	2	51
Total	53	57	3	23	20	156
Percentage	39	42	2	17	..	..

(c) *Weather*—(*i*) *Rainfall*—For purposes of this study rainy day at a place in Gangetic West Bengal was defined as the one when at least half of the normal daily rainfall was recorded at that place; and the rainy days were sorted out with respect to the position of the axis of the easterly wave trough near the 300-mb (9-10·5 km) level relative to Calcutta. In the monsoon season, on days of even half the normal rainfall, the amount of rainfall will be of the order of 5 mm per station. The position of the trough during the 24-hour interval in which the rainfall occurred was reckoned. The trough was classified to be "over Calcutta" if the trough line was located on the vertical time-section of Calcutta at any time during the 24-hour interval to which the rainfall refers. The trough line was classified to be "to the east (or west) of Calcutta" if it was located in the vertical time-section within 24 hours before (or after) the day on which the rainfall occurred. The classification is given in Table 1. 'No data' days have been excluded in working out the percentages.

It will be seen from Table 1 that, on 81 per cent of the rainy days Gangetic West Bengal was ahead of or just below the trough line; and since there is divergence ahead of and near the trough line, in the easterly waves, we can associate the rainfall on these occasions with the upper divergence resulting from the passage of the wave. Convergence in the lower levels which is necessary for the maintenance of the upward flow (Koteswaram and Srinivasan 1958) is provided by the sea level trough which is situated near the area under study.

The number of occasions when the rainfall was to the rear of the trough was meagre and the number of occasions when no trough was found to exist at all was small. This clearly indicates the role played by the easterly waves in the causation of rainfall over Gangetic West Bengal during the monsoon season.

Out of the total number of 26 days when there was rainfall to the rear of the trough or without any trough, the rainfall on nearly 65 per cent of the occasions did not exceed the normal for the day. Besides, on some of these days, the weather could be associated with the passage of westerly waves in the middle troposphere or easterly jet maxima.

(*ii*) *Downstream weather*—Having thus established that the rainfall over Gangetic West Bengal during the southwest monsoon season is mainly due to the movement of easterly waves, it would have been quite relevant in this connection to examine the day-to-day rainfall over East Pakistan and Upper Burma and compare them with the rainfall over Gangetic West Bengal on the subsequent day to show the downstream propagation of weather due to the westward moving easterly waves. Due to lack of data, this has not been found possible. However, with the same idea in view a comparison of the daily rainfall over Gangetic West Bengal with the rainfall on the next day over Chota Nagpur and Orissa was made; the results thereof are given in Table 2.

While the figures under columns 2 and 3 prove the downstream correlation of weather, the figures under column 3 also indicate the possibility of the easterly waves weakening during their westward movement.

(*iii*) *Thunderstorms*—It was seen that the passage of the trough line was frequently marked by thunderstorm activity. The maximum number of thunderstorms over Calcutta during the monsoon period was associated with the passage of the trough line over the station, with an appreciable number of them ahead of the trough line also. The thunderstorms generally coincide with the transit of the coldest portion of the trough over the station. The author has also seen the debriefing reports from aircraft (cruising level 10,000 to 20,000 ft) flying across the trough line indicating very rough weather with heavy thunderstorms, turbulence, icing and even clear air turbulence.

(*d*) *Surface synoptic situations*—The different sea level surface synoptic situations over northeast India and the northern half of the Bay of Bengal, during the periods of passage of the upper troughs, were classified under five headings: the number of trough passages associated with each type of synoptic situation is given in Table 3.

Out of the total number of 92 trough passages, only 7 were associated with break conditions and 71 with surface synoptic situations favourable for active monsoon conditions over Gangetic West Bengal.

It may be noticed that the two sets of figures under 'Yes' and 'No' in Table 3 are complementary, confirming the conclusions reached earlier in Section 5, para (*c*) that active monsoon conditions are caused by the passage of wave troughs. Conversely, lack of passage of troughs may produce weak or even "break" monsoon conditions. On the largest number of occasions, the passage of the wave trough was associated with the extension of the monsoon trough over the north Bay of Bengal or unsettled conditions there: under certain conditions (Koteswaram and George 1958), the passage of the troughs was also responsible for the formation of monsoon depressions.

6. Wind maxima

The flow pattern in this season over India at very high levels (above 200 mb) is mainly one of steady easterly flow, the only variation being the movement of jet maxima. Over the area under discussion, the easterly troughs do not extend to very high levels, if the winds at these levels are strong; in other words, jet stream troughs are rare, although they are common in the other seasons when the flow pattern is westerly. These characteristics of the easterly flow have also been reported by Koteswaram (1956).

For the purpose of discussion regarding strong winds, we will consider only wind speeds of 50 knots or more. The strong wind noticed in the high levels on the time-section for Calcutta could be classified into two types—

(*i*) Wind maximum of 50 knots or more transiting the station quickly and seen on the time-section only for 24 to 48 hours or so, and

(*ii*) Persistent strong winds of speed 50 knots or more, with an embedded maximum in it and seen on the time-section continuously for a number of days, sometimes of the order of a week or even ten days (for example, 28 July to 5 August 1955, 25 July to 29 July 1957). The number of swift moving wind maxima and the number of prolonged periods of fast winds in each year are given in Table 4.

TABLE 2

Number of days when Orissa and/or Chota Nagpur had half or more than half of the normal rainfall, with similar rainfall in Gangetic West Bengal on the previous day due to an easterly wave trough

Year (1)	Yes (2)	No (3)
1955	27	8
1956	33	2
1957	32	8
Total	92	18

TABLE 4

	1955	1956	1957
Number of periods of swift wind maxima	4	4	5
Number of prolonged strong winds periods	4	0	5
Monsoon rainfall* (Jun—Sep) in the subdivisions Percentage excess (+) or defect (—)			
Gangetic West Bengal	—16	+18	— 7
Orissa	+ 7	+28	—33
Chota Nagpur	—26	+12	—17
Bihar	— 8	+11	—26
East Madhya Pradesh	— 2	+15	—16

*From India Met. Dep. *Weekly Weather Reports*

TABLE 3

Year	Monsoon trough shifting south or over north Bay		Low pressure wave, low, cyclonic circulation or unsettled conditions		Depression or cyclonic storms		Monsoon trough shifting north		No significant synoptic situation
	Yes	No	Yes	No	Yes	No	Yes	No	
1955	11	2	3	4	2	1	4	6	6
1956	10	7	14	4	5	1	2	3	1
1957	10	3	9	4	7	0	1	7	7
Total	31	12	26	12	14	2	7	16	14

TABLE 5

Year	Period	No. of rainy days*	Rainfall		
			Actual	Normal	Departure from normal (%)
1955	Jul 2—6	3	2·6″	2·1″	+24
	8—14	2	1·3″	2·6″	—50
	21—24	2	1·6″	1·6″	0
	Jul 29—Aug 5	1	0·8″	3·5″	—77
1957	Jul 13—16	3	18 mm	39 mm	—54
	25—29	2	14 mm	62 mm	—77
	Aug 2—4	2	26 mm	29 mm	—10
	10—13	1	10 mm	41 mm	—76
	16—19	1	8 mm	41 mm	—80

*For definition, see para $c(i)$ of Section 5

It was seen that the latter type of strong winds was usually associated with the shift of the axis of the monsoon trough away from the normal position, towards the Himalayas. In the year 1956, when this wind type was absent, each subdivision had an excess of rainfall.

The rainfall over Gangetic West Bengal during the periods of prolonged strong upper winds, is given in Table 5. It is seen that on most of the occasions the rainfall had been in large defect.

Table 4 also contains the seasonal rainfall in each year over Gangetic West Bengal and the adjoining subdivisions which lie downstream with respect to Calcutta. It is rather striking to note that the seasonal rainfall in each year over these divisions was inversely related to the number of periods of prolonged wind maxima. Since the prolonged periods of wind maxima over Calcutta occur when there is a large scale northward shift of the easterly jet stream, it would appear that the break conditions are associated with the northward shift of the easterly jet stream, as pointed out by Koteswaram (1956, 1958).

7. Illustrative situations

(*a*) Two instances of the passage of easterly wave over Calcutta and the weather associated with it are illustrated in Figs. 1 and 2. The thermal structure of the trough is shown by the isopleths of thickness changes in Fig. 1 and by isotherms in Fig. 2 which indicate cold air near the trough line and warm air ahead of and to the rear. Thunderstorms occurred at the station when it was just below or slightly ahead of the trough line.

(*b*) In the earlier sections it has been pointed out as to how the activity of the monsoon is controlled by the upper divergence due to the passage of the easterly troughs. Fig. 3 shows the rainfall distribution over northeast India, East Pakistan and the adjoining areas on a typical occasion.

On 22 July 1957, the axis of the monsoon trough was shifting to the north and on 23 July the eastern end of the axis of the monsoon trough at 1·5 km lay close to the foot of the Eastern Himalayas and the pressures

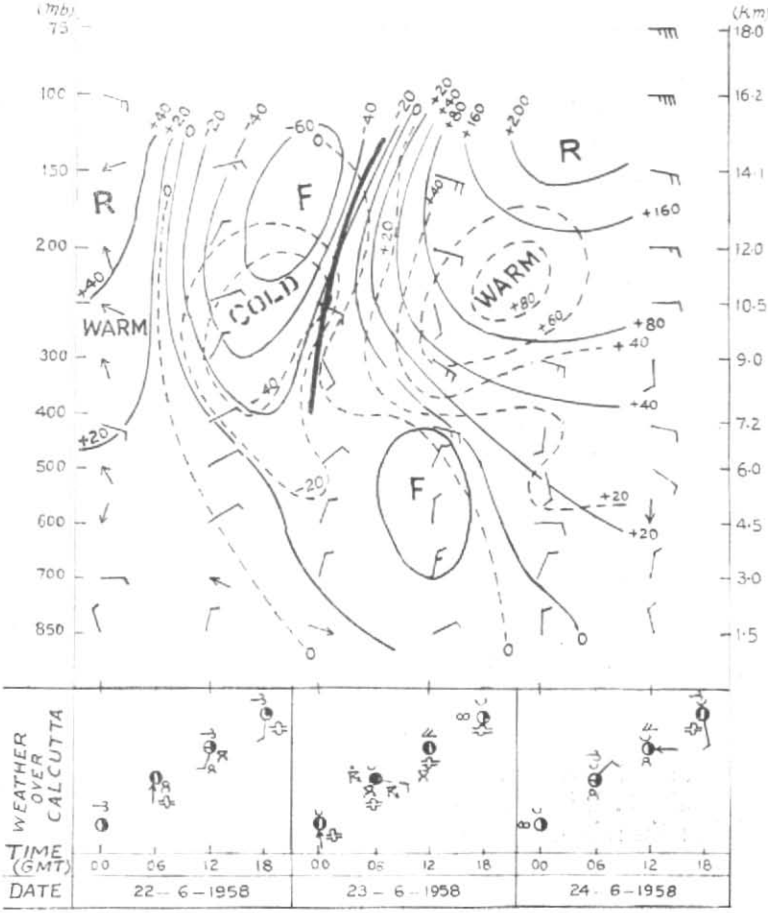


Fig. 1. Vertical time-section for Calcutta, 22—24 June 1958

Isopleths of 24-hour height changes (in gpm) are shown by thin continuous lines and of 24-hour thickness changes (in gpm) between successive standard isobaric surfaces by broken lines. Thick continuous line shows the position of the upper trough.

The maximum negative changes in thickness values (*i.e.*, temperature) are close to the trough line between 400 and 200-mb levels. Thunderstorm occurred near about the time of trough passage over the station.

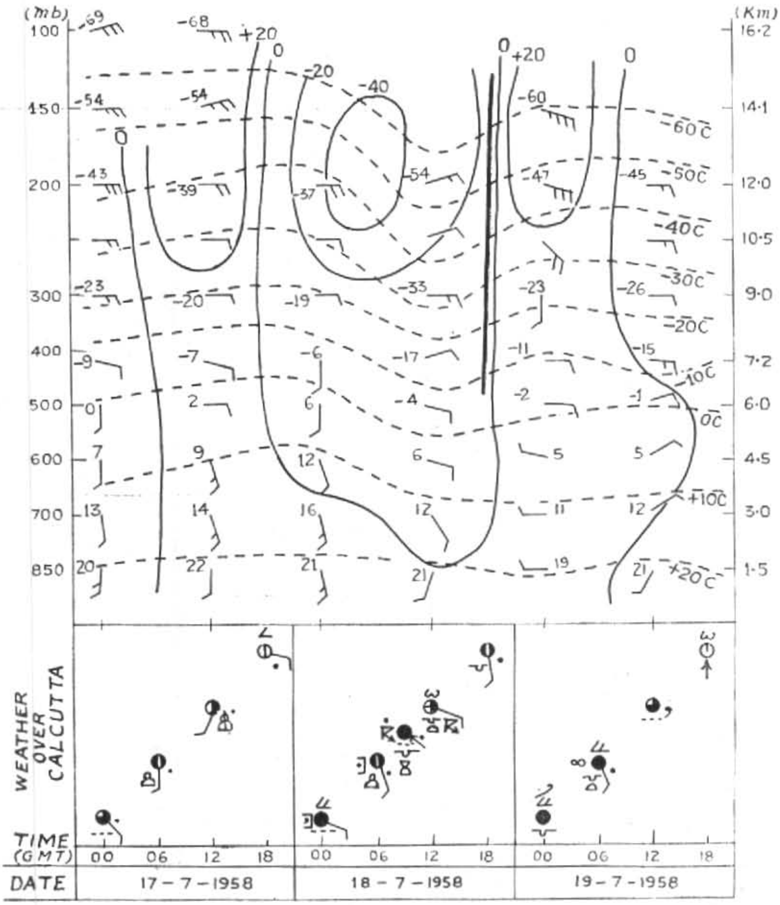


Fig. 2. Vertical time-section for Calcutta, 17—19 July 1958

Isopleths of 24-hour height changes (in gpm) are shown by thin continuous lines and isotherms by broken lines. Thick continuous line shows the position of the upper trough. Temperatures (°C) at standard isobaric surfaces are also plotted.

over northeast India were markedly above normal. However, the passage of an upper easterly wave (whose axis was close to Calcutta at 1200 GMT of 23 July 1957) caused widespread rain over Gangetic West Bengal, Chota Nagpur, East Pakistan, north Orissa and the adjoining areas. The area of rainfall and thunderstorms with respect to the position of the trough line during the 24-hour interval to which the rainfall amounts refer, may be noted. The streamlines of thermal winds between 9·0-km (300 mb) and 6·0-km (500 mb) levels (see Fig. 3c) show warm air both ahead and in the rear with relatively colder air close to the trough line. The thermal winds suggest almost a closed 'low' over Gangetic West Bengal, corresponding to the area of heavy rain and thunderstorms. The rainfall along the east coast of the south Peninsula was

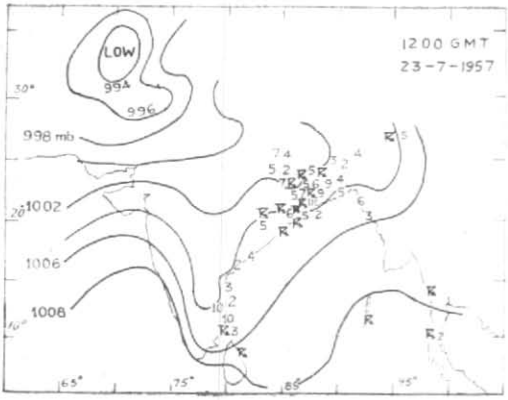


Fig. 3(a)

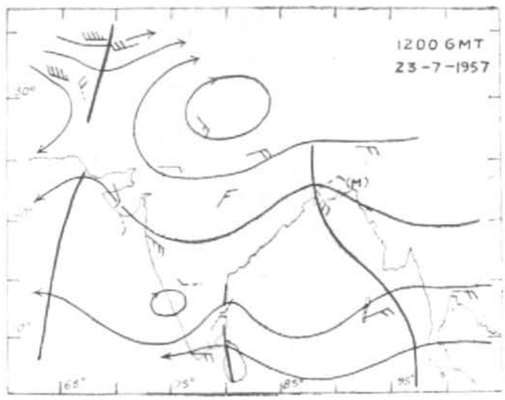


Fig. 3 b)

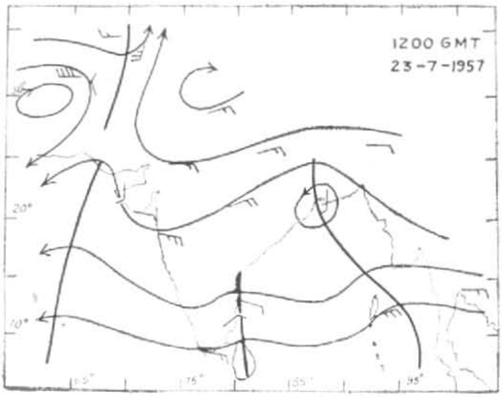


Fig. 3(c)

Fig. 3. Passage of an easterly wave trough over Gangetic West Bengal on 23 July 1957

Fig. 3(a)—Sea level isobars at 1200 GMT on 23 July 1957 and rainfall amounts (more than 1·5 cm) recorded at 0300 GMT on 24 July 1957 at stations in NE India, E. Pakistan and east coast of Indian Peninsula. Thunderstorms, wherever reported, are also shown.

Fig. 3(b)—Streamlines at 9·0 km (300 mb). Broken barbs indicate next lower level winds; M—Morning (0000 GMT) data. Continuous thick lines indicate the positions of the troughs.

Fig. 3(c)—Streamlines of thermal winds, 9·0–6·0 km (300–500 mb). Thermal winds (9·0–6·0 km) are also plotted. Trough lines are shown by continuous thick lines.

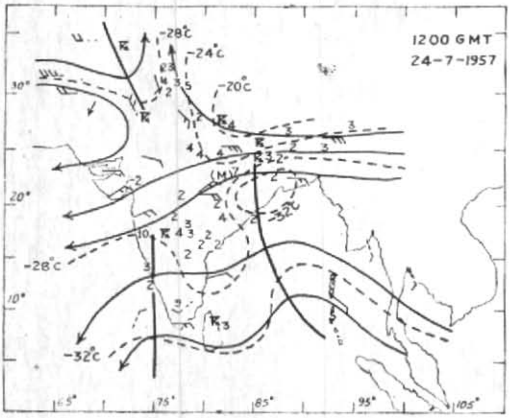


Fig. 4(a)

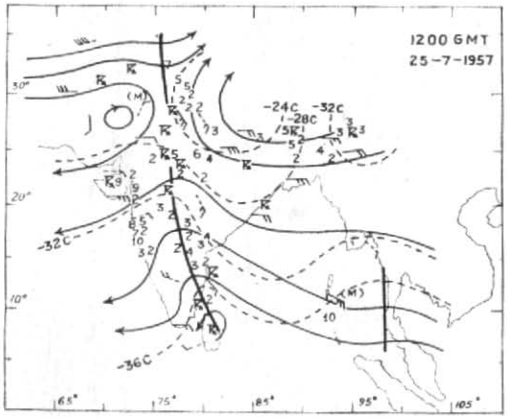


Fig. 4(b)

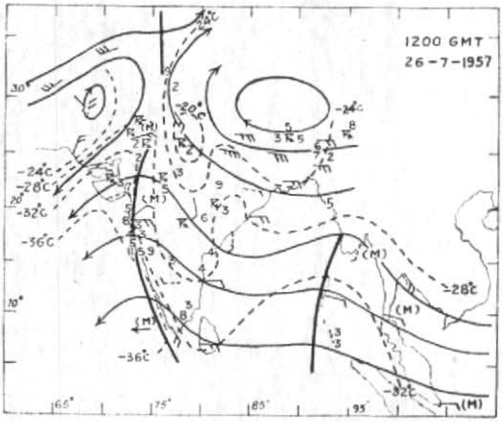


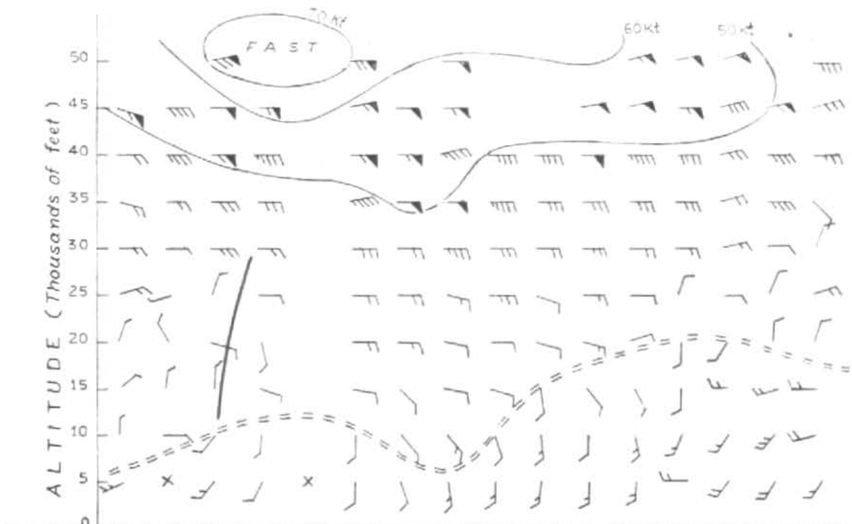
Fig. 4(c)

Fig. 4. Streamlines and isotherms at 9·0 km (300 mb) level, 24-26 July 1957

Streamlines are shown by thin continuous lines and isotherms by broken lines. Troughs are shown by thick lines. Rainfall (more than 1·5 cm) reported at 0300 GMT on next morning and thunderstorms, wherever reported, are included on these charts.

due to another trough over there. It is noteworthy that the coastal area between Lat. 17°N and 19°N which did not come under the influence of the troughs was relatively free from weather.

(c) Fig. 4 shows the movement of the trough illustrated in Fig. 3, subsequent to 23 July 1957. The trough was over East Pakistan and adjoining northeast Assam and Burma on 22 July and caused widespread and locally heavy rain there. The position of the trough on 23rd has been shown in Fig. 3. In Fig. 4 are given the charts for the period 24th to 26th. On the streamline charts for 9·0 km (300-mb level) at 1200 GMT of each day, the trough lines are marked and the rainfall recorded on the next morning (0300 GMT) plotted. Thunderstorms, wherever reported, have also been indicated. The positions of the trough lines have been checked from the vertical time-sections of the rawin stations in the path of the trough.



Rainfall over Calcutta (Inches)	0·27	0·01	0·01	0·06	0·25	0·06	0·54	0·36
Average Rainfall in Gangetic W. Bengal (Inches)	0·1	0·1	0·1	0	0·1	0·1	0·3	0·3
DATE	29-7-1955	30-7-1955	31-7-1955	1-8-1955	2-8-1955	3-8-1955	4-8-1955	5-8-1955

Fig. 5. Vertical time-section for Calcutta, 29 July—5 August 1955

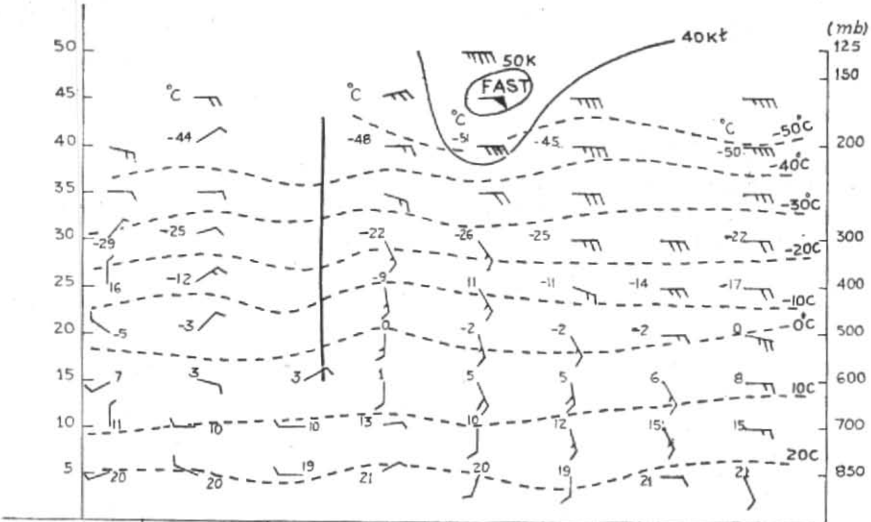
Thin continuous lines—Isotachs; Thick line—Trough line. The normal daily rainfall in Gangetic West Bengal during this period is approximately 0·4″ to 0·5″.

The sequence of charts given in Figs. 3 and 4, taken together, illustrates the downstream propagation of weather due to the movement of the easterly trough. The rainfall and the thunderstorm areas on each day in relation to the position of the trough and the shifting of the weather belt along with the westward movement of the trough are evident. The rear of the trough line is also seen to be an area of improving weather. The amplitude of the waves in the temperature field, as shown by the isotherms, is generally more than the amplitude of the streamlines. From these charts the average speed of the trough line is seen to be of the order of 10-12 knots.

During this period, on the surface chart a well-marked low pressure area which was over southeast Rajasthan and neighbourhood on the 22nd moved northwards into the Punjab where it filled up on the 25th. The axis of the monsoon trough was mostly to the north of the normal position and it shifted to the foot of the Eastern Himalayas by the end of the period. The sequence of weather and rainfall during the period becomes more understandable when we consider the movement of the easterly wave trough in the upper air.

It may also be noted that after the passage of the above trough, there was no other trough closely following it and affecting weather over northeast India. Consequently after the 24th the rainfall in Gangetic West Bengal and in Chota Nagpur, Orissa and northeast Madhya Pradesh which lie downstream, rapidly decreased resulting in a large deficit of rainfall.

(*d*) Fig. 5 shows the case of a prolonged spell of weak monsoon over Gangetic West



Average Rainfall in Gangetic W. Bengal (inch)	0·3		0·3		0·3		0·1	
Time (GMT)	03	15	03	15	03	15	03	15
DATE	17 – 9 – 1955		18 – 9 – 1955		19 – 9 – 1955		20 – 9 – 1955	

Fig. 6. Vertical time-section for Calcutta, 17-20 September 1955

Thin continuous lines—Isotachs; Broken lines—Isotherms; Thick line—Trough line.
Temperature (°C) at standard isobaric surfaces are plotted.

Bengal, Orissa and Chota Nagpur between 29 July and 4 August 1955. In this period except for a minor wave on 30 July, there was no easterly wave at high level where the winds were stronger than normal. The seasonal monsoon trough at sea level was not in the normal position and on many days, the axis could be located close to the Eastern Himalayas. This is in contrast to the instance given in Fig. 3 when the sea level monsoon trough temporarily shifted to the normal position, due to the passage of an easterly trough.

(*e*) Fig. 6 shows the occurrence of weather over Calcutta due to the passage of a swift jet maxima. The weather on such occasions can be attributed to the upper divergence on the right entrance and left exit sectors of the jet maxima. The number of passages of jet maxima over Gangetic West Bengal is small compared to the number of upper trough passages. Besides some of the jet maxima moved across with the simultaneous passage of the troughs in the levels immediately below the jet level. It has also been noticed that the movement of the 'jetlets' over Calcutta is associated with negative changes in the heights of the isobaric surfaces and relatively colder air in the levels below the 'jetlets'. Troughs in the temperature field, therefore, indicate the passages of both jet maxima as well as troughs. As such the importance of the wave motion in the temperature field and the 'cold' areas, is very significant in relation to the occurrence of weather.

8. Concluding remarks

From the present study it can be concluded that the monsoon rainfall over Gangetic West Bengal and by analogy, over a major portion of the Indian sub-continent outside the northwestern divisions, is primarily controlled by the passage of easterly wave troughs and jet maxima over the area. The "pulsating" nature of the monsoon current is caused by the periodicity in the passage of these perturbations. If the wave troughs and the wind maxima could be located and traced on the upper wind charts from day-to-day, aided by vertical time-sections of rawin-radiosonde stations, it will prove to be a great aid in the forecasting of weather downstream, and could considerably improve the accuracy of forecast for 12-24 hours ahead, if not more.

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REFERENCES

Holmboe, Forsythe and Gustin	1948	*Dynamic Meteorology*, p. 287.
Koteswaram, P.	1956	Dep. Met. Univ. Chicago, *Res. Rep.*
	1958	*Tellus*, **10**, 1, pp. 43-57.
Koteswaram, P. and George, C. A.	1958	*Indian J. Met. Geophys.*, **9**, 1, pp. 9-22.
Koteswaram, P. and Srinivasan, V.	1958	*Ibid.*, **9**, 4, pp. 306-307.
López, M. E.	1948	*Bull. Amer. met. Soc.*, **29**, 5, pp. 227-236.
Riehl, H.	1954a	*Tropical Meteorology*, p. 219, McGraw-Hill, New York.
	1954b	*Ibid.*, p. 222.