551·515·8 : 551·533·21

Influence of upper level troughs and ridges on the formation of post-monsoon cyclones in the Bay of Bengal

S. N. SEN

Meteorological Office, Poona

(*Received 14 November 1956*)

ABSTRACT. The upper air conditions at the formative stages of several depressions and cyclones in the Indian seas were studied by Desai and Rao in the light of Riehl's model for the formation of tropical cyclones. The recent introduction of twice daily radiosonde-rawin ascents at some stations in India provided additional facilities for similar studies in this area. The available upper air conditions associated with the formation of two post-monsoon cyclones of 1955 in the Bay of Bengal were accordingly studied with the idea of finding how far Riehl's theory of tropical cyclones could be applied in these cases.

The present study of the post-monsoon cyclones of 1955 reveals that two radiosonde ascents a day from a reasonable network of stations should be minimum requirement for studies of this kind. Time cross-sections showing 24-hour changes of heights at intervals of 12 hours are presented to illustrate the sequence of movement of upper troughs and ridges. As postulated by Riehl, the formation of both the cyclones was apparently associated with the passage of troughs in the westerlies across northeast India, *i. e.*, to the north of the area of cyclogenesis. But the upper air data from the available network of stations were too inadequate for drawing any definite conclusion as to whether the initial mass divergence at upper level was caused by the southward extension of the westerly trough and the superposition of its forward portion over the surface incipient low, or by the in-phase superposition of the upper trough in the westerlies with the upper tropospheric vortices moving across the Bay of Bengal. Dynamical development to the south of a confluent trough in the westerlies is suggested as a possible contributory factor for the cyclogenesis in the south Bay of Bengal.

The influence of the middle-latitude trough on the recurvature of one of the cyclones while out at sea and of another similar cyclone of October 1949 which had recurved only after crossing the coast, and the unexpected weakening of the former while out at sea, have been discussed.

1. Introduction

The latest theory on the mechanism of formation of tropical cyclones put forward by Riehl (1948a, 1948b and 1950) was based on the studies made by him of cyclones in the Pacific and the Atlantic areas. It is now widely recognised that the air mass and frontal techniques based on the theory of formation of shearing waves at density discontinuities (fronts), as formulated by the Norwegian meteorologists in 1920, cannot be satisfactorily applied to the development of tropical cyclones. According to the frontal theory, the denser air mass settles underneath the lighter air and this release of potential energy leads to an increase of the kinetic energy. While the cold air thus sinks in an extra-tropical depression, all air that enters a tropical cyclone near the surface ascends in the core, and temperature contrasts noticed at tropical discontinuities are very small. The frontal theory takes low level convergence as the starting point for cyclogenesis. Such convergence must lead to pressure rise and not fall at the centre, thus killing the beginning circulation. This is the well-known difficulty in cyclone theories. It has then to be assumed that upper outflow somehow becomes sufficiently large to overbalance the surface inflow. The actual mechanism for such outflow could not, however, be explained by the earlier theories of tropical cyclone formation.

According to Riehl's theory, the initial intensification of the incipient wave disturbance is brought about by mass divergence at high levels above 500 mb (300–100 mb), which imposes a pressure reduction on the surface layers. From the studies made by Riehl for the Pacific and Atlantic areas, the following alternative mechanisms have been suggested for the divergence at high levels.

(*a*) Superposition of anticyclonic northerly flow associated with the westward passage of upper tropospheric high (at levels 300–100 mb). Such an upper current must, from the conservation of absolute vorticity principle, be divergent. In such cases, it has been observed that deepening starts at the surface just as the upper high centre bypasses the low level trough.

(*b*) In association with the extension of a trough in the westerlies towards lower latitude, the divergence in the forward portion of the trough in the westerlies may be superimposed over the incipient tropical low at low level. The condition under which high-latitude troughs extend to low latitudes have been studied in detail by Cressman (1948).

(*c*) There is interaction at high levels between the tropical vortex train and the long waves in the westerlies. In-phase superposition will strengthen the meridional flow. If a northerly current at high level is accelerated due to such in-phase superposition, the Coriolis force no longer affords balance and the consequent cross-isobaric flow towards the low pressure leads to mass divergence to the right of the northerly current (looking downstream) and mass convergence to its left. If this region of divergence is superimposed over the incipient tropical low, surface pressure falls and the initial surface disturbance beigns to deepen.

Riehl further explained that once the starting mechanism causes initial lowering of surface pressure, the low level air is accelerated towards the area of reduced pressure, where it converges, acquires cyclonic vorticity, and begins to ascend. The ascent must transport enough mass upward to compensate for the lateral divergence above. Unless this happens, the pressure at high levels will fall and the east-west pressure gradient that generates the eastward outflow will be destroyed. Then the lower inflow exceeds the outflow and the circulation dies.

2. Application of Riehl's model of tropical storms in Indian seas

Some aspects of depressions and cyclones in the Indian seas were studied by Desai and Rao (1955) in the light of Riehl's model. In that study, formation of four cyclones of the post-monsoon season (October—November) in the Bay of Bengal were examined. They found evidence that each of these cyclones (October 1945, October 1949, November 1952 and November 1953) might have formed as a result of interaction of troughs in the westerlies with tropical perturbations corresponding to mechanism (*c*) of Riehl stated above. As the post-monsoon cyclones in the Bay of Bengal generally form in comparatively lower latitudes (south of Lat. 10°N), it would appear that chances of their formation due to interaction of troughs in westerlies should be less than those in the cases of Bay cyclones formed at higher latitudes. With a view to examining how far the upper troughs in the westerlies influence the formation of depressions in the south Bay of Bengal during post-monsoon season, two other such Bay cyclones have been studied on the basis of available upper air data. The cyclones in the Bay of Bengal of the year 1955 have been particularly chosen for this study, because twice daily radiosonde and rawin data available in 1955 for some of the basic stations were helpful for studying the movements of upper pressure systems. From the observed frequency and rate of movement of pressure systems, it is concluded that radiosonde data at intervals of twelve hours (*i.e.*, twice daily) should be the minimum observational requirement for studies of this type. While more frequent observations such as from four ascents a day would be still better, radiosonde data from only one ascent a day as used in the earlier study (Desai and Rao 1955) is considered to be definitely inadequate.

3. November (3rd to 8th) 1955 Severe Cyclone—Case I

On 2 November 1955, an easterly wave moved into south Andaman Sea. It concentrated into a depression on the 3rd evening centred near Car Nicobar (Lat. 9½°N, Long. 92½°E). After moving northwest, the

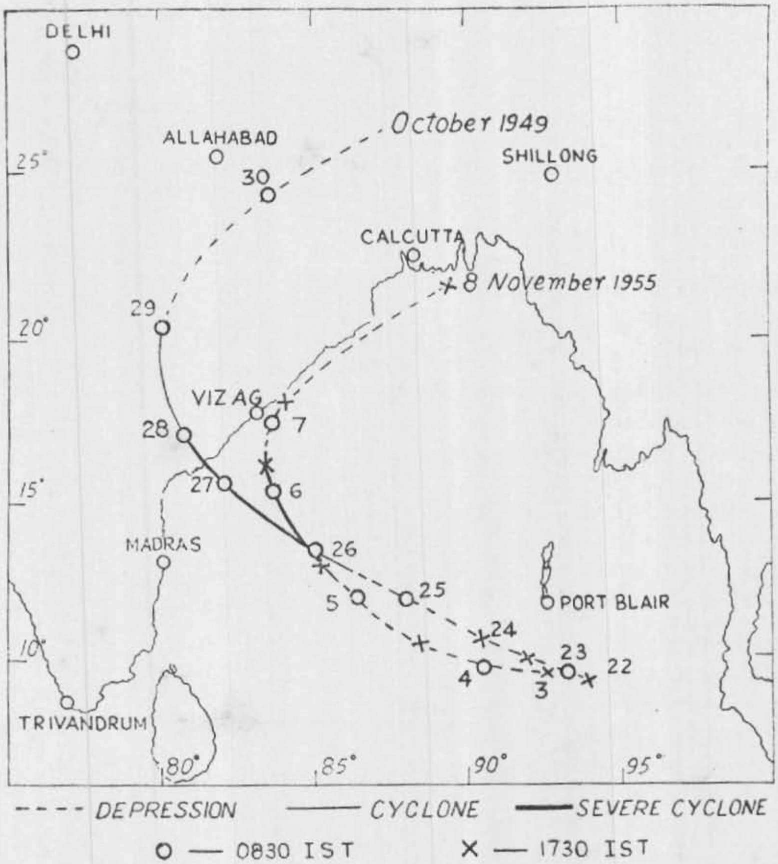

Fig. 1. Tracks of severe cyclones of November (3rd to 8th) 1955 and October 1949

cyclone recurved on the 6th and unexpectedly weakened while out at sea off Visakhapatnam and then moved northeastwards as a depression. The track of the cyclone is given in Fig. 1.

3·1. *Upper air conditions at the formative stage*—A study of the constant pressure charts as well as upper wind charts showed that troughs in the westerlies moved eastwards across north India at the time of the formation of the depression in south Andamans in the beginning of November 1955. The height values of the 700, 500, 300 and 200-mb levels at Delhi, Allahabad, Calcutta and Gauhati (40 miles N of Shillong) during the period 30 October to 7 November 1955 are shown in Table 1. While Delhi, Calcutta and Gauhati, had two radiosonde ascents (0300 and 1500 GMT) a day, Allahabad had only the evening ascents at 1500 GMT. The height values representing appreciable lowering of isobaric surfaces (since the observation at the same hour on the previous day) presumably on account of the passage of trough, have been given in bold figures in the table.

TABLE 1

Heights (in tens of feet) of isobaric surfaces

Pressure levels (mb)	Radiosonde ascent on 30 Oct 1955		31 Oct 1955		1 Nov 1955		2 Nov 1955		3 Nov 1955		4 Nov 1955		5 Nov 1955		6 Nov 1955		7 Nov 1955	
	0300 GMT	1500 GMT	0300 GMT	1500 GMT	0300 GMT	1500 GMT	0300 GMT	1500 GMT	0300 GMT	1500 GMT	0300 GMT	1500 GMT	0300 GMT	1500 GMT	0300 GMT	1500 GMT	0300 GMT	1500 GMT
DELHI (28°35′N, 77°12′E)																		
700	1033	1027	1027	1027	1027	1040	1040	1030	**1027**	**1024**	1030	1027	1027	1024	**1017**	1023	1017	**1001**
500	1910	1910	1906	1913	**1906**	1926	1919	1923	**1903**	**1903**	1916	1906	1913	1906	**1896**	1906	1896	**1870**
300	3130	3137	3130	3143	**3130**	3150	3133	3176	**3133**	**3133**	3163	3143	3163	3153	**3146**	3160	3143	**3100**
200	4028	4038	..	4029	**4000**	..	..	4091	..	..	..	4038	..	..	4048	..	4074	**4006**
ALLAHABAD (25°27′N, 81°44′E)																		
700	..	1033	..	1030	..	1030	..	1024	..	1017	..	1027	..	**1017**	..	1017	..	**1007**
500	..	**1919**	..	1929	..	**1926**	..	**1910**	..	1913	..	1916	..	**1903**	..	1910	..	**1896**
300	..	**3160**	..	3195	..	3179	..	**3160**	..	3179	..	3176	..	**3140**	..	3185	..	**3153**
200	..	**4061**	..	..	..	4085	..	..	..	4101	..	4091	..	..	..	4121	..	..
CALCUTTA (22°39′N, 88°27′E)																		
700	1037	1027	1030	1033	1033	1027	1030	1030	1027	**1017**	1033	1020	1024	1030	1030	1033	**1017**	1037
500	..	**1936**	**1919**	1941	1933	1923	1923	1919	1913	**1896**	1929	1906	1910	1926	1933	1930	**1919**	1949
300	..	3231	**3176**	3228	3195	3208	..	3189	3156	**3140**	3205	3192	**3166**	3192	3218	..	**3205**	3258
200	..	**4190**	**4068**	4177	..	4144	..	4111	4055	**4035**	4127	4141	**4075**	4091	4154	..	4160	4226
GAUHATI (26°11′N, 91°45′E)																		
700	1031	1020	1014	1014	1014	1027	1040	1034	1040	**1024**	1040	**1027**	1030	**1017**	1024	1024	1014	1014
500	1916	1900	**1886**	1892	**1880**	1903	1932	1926	1932	**1915**	1935	**1909**	1915	**1895**	1906	1918	1906	1909
300	3160	3137	**3084**	..	**3087**	..	3185	3182	3199	..	3221	**3179**	3188	**3146**	3166	3195	3192	..
200	4052	4029	**4009**	..	..	..	4101	4091	4104	..	4156	**4098**	4121	..	4078	4117	4123	..

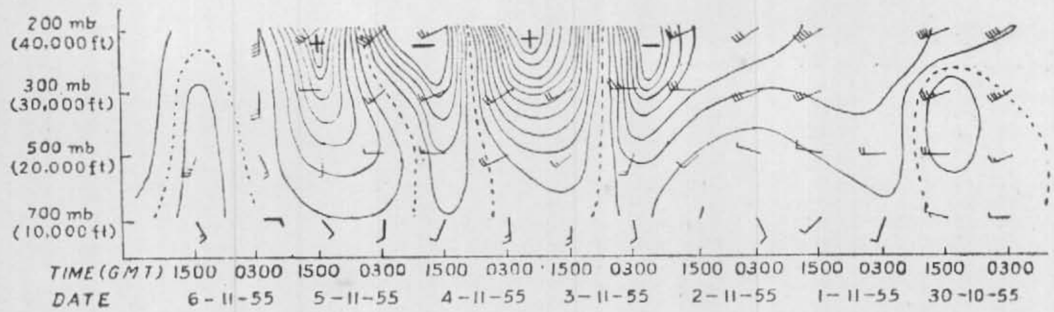

Fig. 2. Time cross-section for Calcutta showing 24-hour height changes

(Contours at intervals of 100 ft. Dotted line represents zero change)

An examination of the height values of isobaric surfaces at Delhi, Allahabad, Calcutta and Gauhati given in Table 1 would suggest that a trough in the westerlies moved across north India affecting Delhi on the 1st, Allahabad on the 2nd, Calcutta on the 3rd and Gauhati on 4 November. This was apparently followed by another trough affecting Delhi on the 3rd, Allahabad perhaps on 4th, Calcutta on the 5th morning and Gauhati on 5th evening. In the absence of more frequent radiosonde observations, the times of passage of the troughs through different stations can be estimated only approximately. It will be seen from Table 1 that 24-hour height changes observed at Calcutta in association with the passage of these troughs are appreciably larger, level for level, than those observed at Delhi or Allahabad. This apparently suggests that the troughs in the westerlies particularly the first one, got accentuated while moving towards the longitude of Calcutta. It will be seen that from 2nd evening to 3rd evening, 300-mb isobaric surface lowered by 490 ft and 200-mb surface lowered by 760 ft over Calcutta.

With a view to studying possible influence of the above troughs in the westerlies on the formation of the depression in the Andaman sea, a time cross-section for Calcutta showing 24-hour height changes was drawn as given in Fig. 2. Time is plotted from right to left, advantage being that assuming disturbances move eastwards at a fairly steady rate, the time cross-section then becomes equivalent to a space cross-section. 24-hour height changes are plotted against the middle of the 24-hour period, that is, observed change from 1st morning to 2nd morning is plotted against 1st evening and that from 1st evening to 2nd evening plotted against 2nd morning and so on. Contours through equal values of height changes are then drawn at intervals of 100 ft. The movement of the pressure centres are found to affect the heights of 500 mb and higher isobaric surfaces, the changes being much more pronounced at 200 and 300-mb levels. The time-section reveals that at 300 and 200-mb levels, one trough passed over Calcutta between 1500 GMT of 2 November and 0300 GMT of 3 November which was followed by a pronounced ridge and subsequently a second trough passed between 1500 GMT of 4 November and 0300 GMT of 5 November 1955.

The winds plotted in the time cross-section are from the rawin ascents made simultaneously with the morning and evening radiosonde ascents. Associated with the movement of the troughs and ridges, significant wind changes are not observed in the upper levels, the westerly wind there being generally very strong. However, strengthening of the wind to 55 kts at 200 mb on 2nd (1500 GMT) and change of the westerly wind at 500 mb to southwesterly after 2nd

TABLE 2
Heights (in tens of feet) of isobaric surfaces—Port Blair

Pressure levels (mb)	1500 GMT ascent on							
	29-10-55	30-10-55	31-10-55	1-11-55	2-11-55	3-11-55	4-11-55	5-11-55
700	1037	1924	1024	1027	1024	1014	1020	1030
500	1933	1916	1916	1916	1919	1910	..	1929
300	3195	3176	3182	3179	3185	..	..	..
200	4111	4084	..	4101	..	..	..	..

(0300 GMT) appear to be somewhat significant, being associated with the approach of the first trough.

It is seen from an examination of the surface synoptic charts that the initial concentration of the wave in the easterlies into a shallow depression in the south Andaman Sea took place on the 3rd evening as can be judged from the observations from the Andaman Island stations and available ships' reports from neighbouring sea areas. It can, therefore, be concluded that the first upper level trough in the westerlies which passed over Calcutta between 2nd evening and 3rd morning lay to the north of the easterly wave at the time of its initial deepening. It is, however, difficult to determine whether the upper level trough in the westerlies had extended southwards and if so to what extent, the greatest handicap being the complete lack of upper air data over the the entire Bay of Bengal. The radiosonde data over Port Blair, which is the only radiosonde station over the Bay of Bengal area, were also not available for the higher levels for some consecutive days during the period. A study of the upper wind charts for the lower levels based on available pilot balloon observations of 3rd evening, however, suggests that the upper trough in the westerlies might have had a southward extension over the Bay of Bengal. Assuming that the upper trough in the westerlies had extended sufficiently southward, the superposition of divergence in the forward portion of the upper trough over the surface incipient low might have contributed towards the latter's initial deepening. In the absence of necessary data, it is, however, not possible to say whether the superposition of divergence due to extension of the upper trough was more effective at 200/300-mb levels or not. It has, however, been observed (Riehl 1948a) that extra-tropical eastward moving perturbation usually extends to more southerly latitudes in the high troposphere than in lower levels. Cressman (1948) observed that superposition of a trough in the westerlies on a wave in the easterlies leads to an intensification of both perturbations. The observed accentuation of the trough in the westerlies near Calcutta and simultaneous intensification of the wave in the Andamans provide a possible indirect evidence of such superposition.

Let us now examine the height changes of isobaric surfaces over Port Blair during the period in question with a view to finding whether any upper tropospheric pressure systems had moved over the region of cyclogenesis. The observed height values during the period 29 October to 5 November are given in Table 2.

We are handicapped on account of having only one radiosonde ascent a day at Port Blair during the period. Further, data at 300 and 200-mb levels at Port Blair were not available during the period of depression formation, *viz.*, from 2 November onwards. The radiosonde data of Madras and Trivandrum (only one ascent at 1500 GMT) do not show any significant change in heights of isobaric surfaces during the period. From

TABLE 3

Heights (in tens of feet) of isobaric surfaces—Visakhapatnam

Pressure levels (mb)	1500 GMT radiosonde ascent on							
	1-11-55	2-11-55	3-11-55	4-11-55	5-11-55	6-11-55	7-11-55	8-11-55
700	1036	1017	1027	1017	1014	1004	1004	1017
500	1932	1913	1926	1906	1916	1919	1906	1916
300	3202	3173	..	3163	3192	3241	3182	3195
200	..	..	..	..	4130	4242	4098	4121

the available data over Port Blair, it appears that significant lowering of heights occurred at 700 and 500-mb levels on 3 November 1955 (data for higher levels not available), that is, the day of initial intensification of the easterly wave. With the inadequate data available, it is difficult to say whether the observed lowering of heights at lower levels might have been due to the intensification of the cyclonic circulation over the Andamans on the 3rd rather than due to southward extension of the trough in the westerlies upto Port Blair or westward movement of upper tropospheric low across the Andamans. The movement of upper tropospheric low is now supported by data over Madras and Trivandrum. The available data over Port Blair, Madras and Trivandrum do not also suggest passage of any upper tropospheric anticyclone over the Andamans near about the time of cyclogenesis.

3.2. *Intensification of the depression and associated upper air conditions*—As can be seen from the track shown in Fig. 1, the shallow depression which formed in the south Andaman Sea on 3 November 1955 commenced deepening after 4th evening and between 5th evening and 6th morning, it intensified into a severe cyclone.

It is now known that tropical storms are warm low-pressure centres and that outflow takes place in the middle and upper troposphere. At upper levels, tropical storms have been observed to be high pressure centres. Special hurricane soundings have revealed decrease of the pressure falls with height and rises at the higher levels. Above 300-mb level or so, pressure inside the hurricanes have been found to exceed those outside, which facilitates the outflow. It has been observed that severe tropical storms display great affinity for the 200-mb high pressure cell and that proximity of an upper ridge to an incipient storm leads to deepening of the storm to full strength. The high level ridges have also been observed to become more pronounced after typhoon formation, which apparently indicates that the storm helps to build up the large-scale high (Riehl 1948b). A recent study on the vertical structure of a few disturbances of Bay of Bengal (Rai Sircar 1956) also supports these ideas. In the case of the Bay cyclone under consideration, it is seen from a study of the height changes of upper isobaric surfaces at Visakhapatnam that when the disturbance intensified into a severe cyclone near Visakhapatnam on 6 November 1957, pressures over Visakhapatnam rose appreciably at 300 and 200-mb levels suggesting that the cyclone possibly had a high pressure cell at those levels. The heights of isobaric surfaces over Visakhapatnam during the period 1 to 8 November are given in Table 3.

It is seen that from 5th evening to 6th evening, 300-mb surface at Visakhapatnam had risen by 490 ft and 200-mb surface by 1120 ft whereas the 700-mb surface had fallen and 500-mb surface had risen only slightly on the 6th. It is significant that the severe cyclone was centred on the 6th evening within about 100 miles of Visakhapatnam. It is also significant that with the rapid weakening of the cyclone on the 7th close to Visakhapatnam, the heights of the 300 and 200-mb surfaces sharply decreased from 6th evening to 7th evening. It seems, therefore, that the cyclone at its matured stage was associated with a well-marked high pressure cell at 200-mb level above the cyclone, as has been observed in mature hurricanes.

It will be seen from the time cross-section at Calcutta (Fig. 2) that a ridge in the westerlies moved eastwards over Calcutta between 5th evening and 6th morning. It is possible that on the 5th when this ridge was to the west of Calcutta, it might have interacted with the high pressure cell at 200-mb above the cyclone (perhaps when the cyclone was near Long. 85°E) and their in-phase superposition might have contributed to further intensification of the cyclone between 5th evening and 6th morning.

3.3. *Comparison between severe cyclones of November (3rd to 8th) 1955 and October 1949*—The severe cyclone of November 1955 discussed above presents striking similarities with the Masulipatam cyclone of October 1949 (tracks given in Fig. 1) so far as the regions of formation, times of the year and their initial tracks are concerned. But the most significant contrast between the behaviour of these two cyclones was that whereas the 1955 cyclone recurved while it was about 200 miles off the coast and unexpectedly weakened out at sea off Visakhapatnam, the 1949 cyclone continued to move northwest, struck the coast near Masulipatam, and it weakened and recurved only after getting sufficiently inland. In view of the special importance in storm warning work of correctly forecasting the behaviour of cyclones while approaching the coast, it was worth examining the conditions which might have been responsible for the marked contrast in the later life-history of the two cyclones referred to above. The 1949 cyclone has been studied earlier by Sen and George (1952), Jordan (1953) and by Desai and Rao (1955).

3.4. *Recurvature of the cyclones*—It is noteworthy that in the cases of both the cyclones of November 1955 and of October 1949, recurvature took place under influence of pronounced trough moving eastward across northwest India. It is a well known fact that middle latitude influences determine recurvature of tropical cyclones (Riehl 1954). A study of the upper wind charts over India for periods corresponding to the recurvatures of the November 1955 and October 1949 cyclones clearly shows that in the case of November 1955 cyclone, pronounced trough moved across northwest India on 6 November 1955 causing recurvature while the cyclone was out at sea, whereas in the case of October 1949 cyclone, similar trough moved across northwest India on 28 October 1949 only after the cyclone had passed inland. The upper winds at 15,000 ft and 20,000 ft on 6 November 1955 (evening) and 26 October 1949 (evening) when the two cyclones were at comparable positions are reproduced in Fig. 3. Similar upper winds on 28 October 1949 (evening), corresponding to the time when the 1949 cyclone had recurved under influence of trough over northwest India, are also reproduced in the same figure. It will be seen that the trough moving across northwest India reached comparable position on 6 November 1955 and 28 October 1949, the dates on which the two cyclones commenced recurving, but the November 1955 cyclone at this time was well out at sea whereas the October 1949 cyclone had passed inland. The significant lowering of heights of isobaric surfaces on 5 November 1955 (evening) at Allahabad (Table 1) seems to be associated with the trough moving eastwards across northwest India. The cyclone in the Bay of Bengal commenced recurving on the following day. It is interesting to find that in the case of the 1949 cyclone also, heights of isobaric surfaces fell appreciably at Allahabad on 27 October 1949 (evening), that is one day before that cyclone commenced recurving,

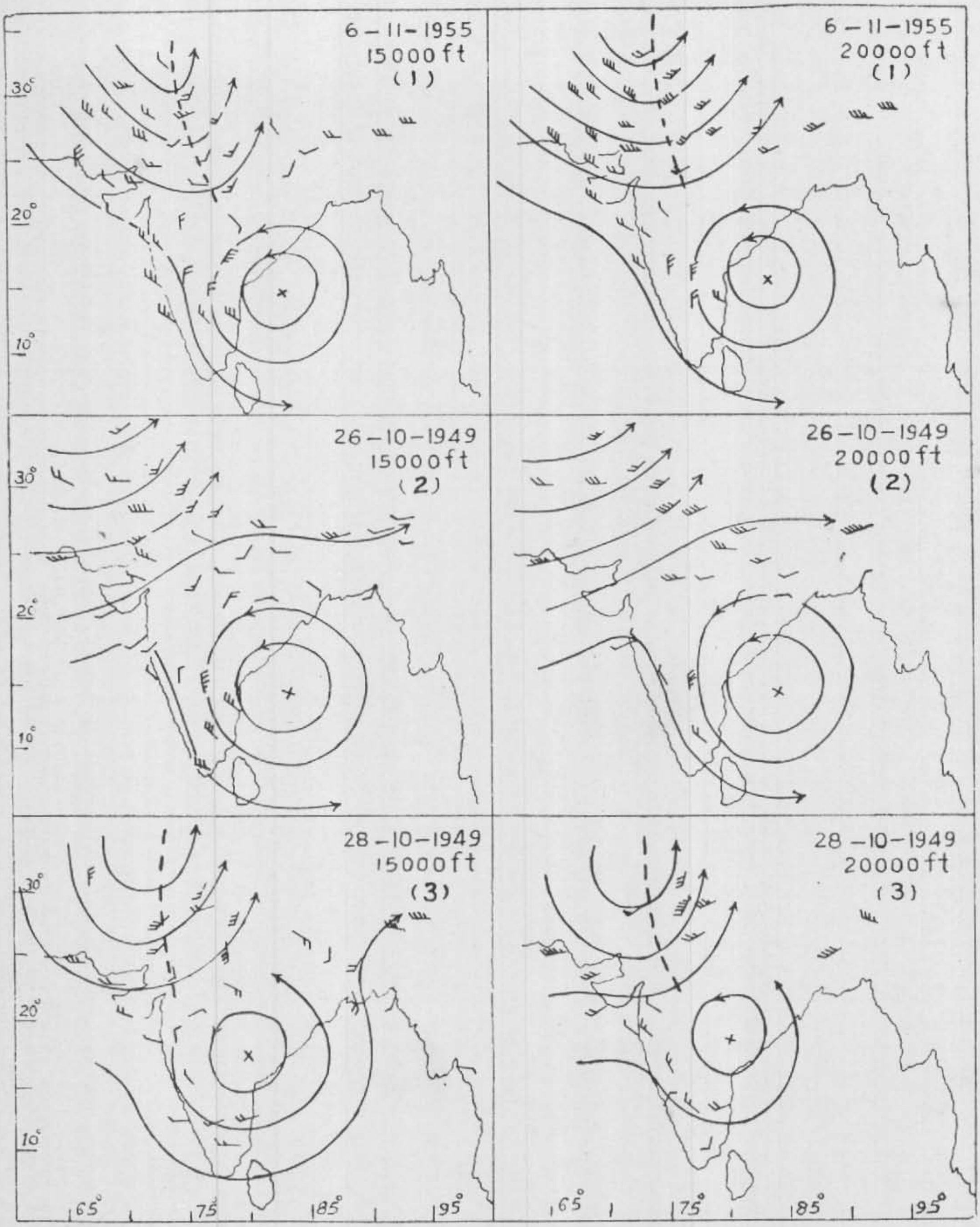

Fig. 3. Evening upper winds at 15,000 and 20,000 ft on (1) 6 November 1955, when the cyclone commenced recurving under the influence of trough in the westerlies, (2) 26 October 1949, when the cyclone located at comparable position as in (1) continued to move northwest—trough in westerlies had not sufficiently advanced and (3) 28 October 1949, when trough in westerlies advanced to similar position as in (1) and cyclone already passed inland commenced recurving

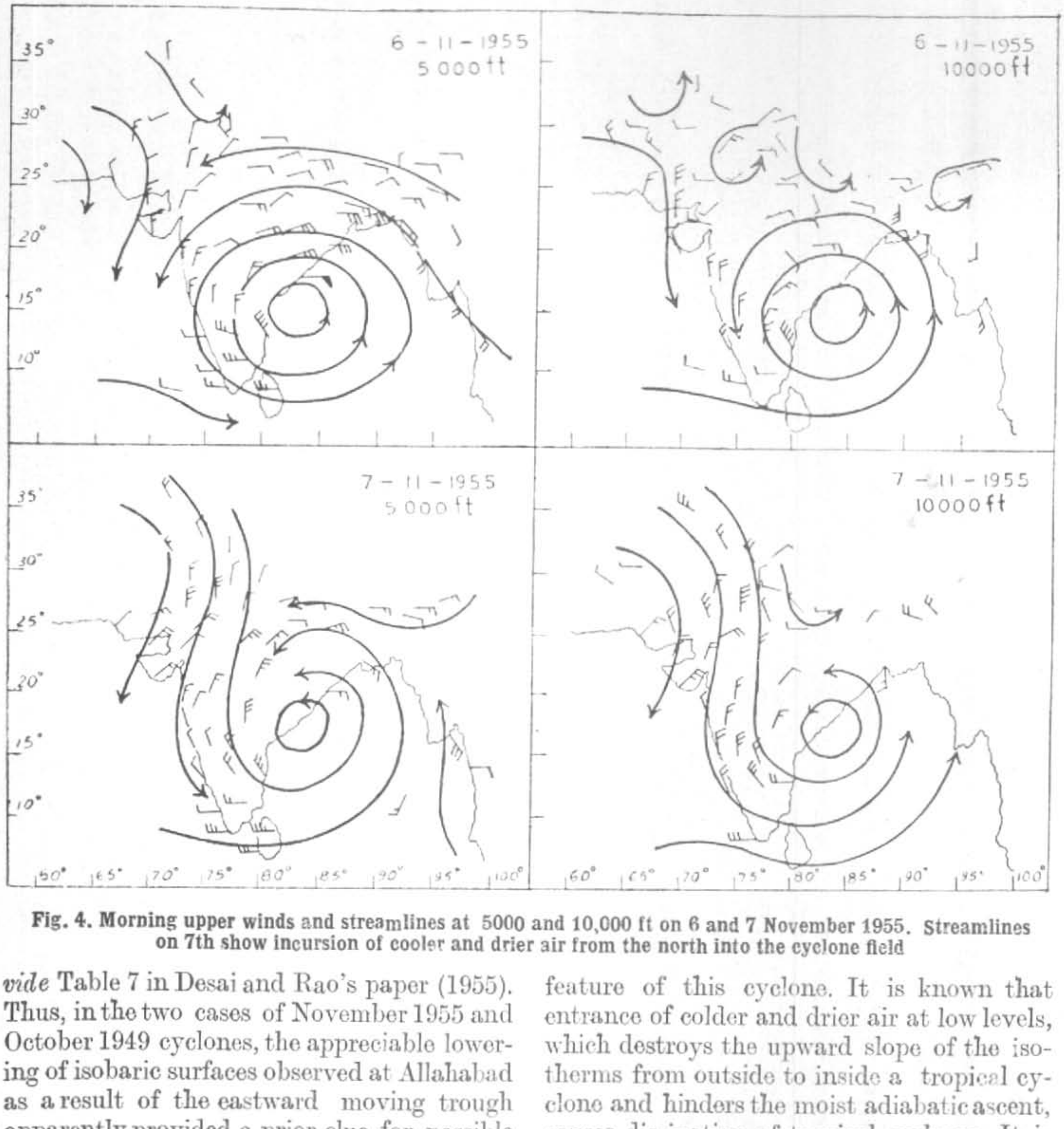

Fig. 4. Morning upper winds and streamlines at 5000 and 10,000 ft on 6 and 7 November 1955. Streamlines on 7th show incursion of cooler and drier air from the north into the cyclone field

vide Table 7 in Desai and Rao's paper (1955). Thus, in the two cases of November 1955 and October 1949 cyclones, the appreciable lowering of isobaric surfaces observed at Allahabad as a result of the eastward moving trough apparently provided a prior clue for possible recurvature of Bay cyclones from a region such as the 5-degree square bounded by Lat. 15° and 20° N and Long. 80° and 85°E in the post-monsoon season. This, however, cannot be generalised until recurvature of other cyclones from this regions are examined.

3·5. *Weakening of November 1955 cyclone*—The unexpected weakening of the severe cyclone about 100 miles off the coast, instead of its striking the coast, is an interesting feature of this cyclone. It is known that entrance of colder and drier air at low levels, which destroys the upward slope of the isotherms from outside to inside a tropical cyclone and hinders the moist adiabatic ascent, causes dissipation of tropical cyclones. It is seen from the upper air charts of 6 November 1955 (evening) and more particularly of 7 November 1955 (morning) that in association with the pronounced trough moving across northwest India, cold and dry polar westerlies were drawn into the cyclone at all levels up to 15,000 ft which must have caused the unexpected weakening of the cyclone. The upper winds at 5000 and 10,000 ft of 6 and 7 November 1955 (morning) reproduced in Fig. 4

clearly show the significant change from 6th to 7th leading to the incursion of such a current into the cyclone field by the 7th morning. This current could have caused complete dissipation of the cyclone, but for its recurvature and rapid northeastward movement which apparently resulted in the disturbance going outside the field of the colder and drier current and thus continuing to move as a depression for the rest of its life.

4. November (26th to 30th) 1955 Cyclone—Case II

On 26 November 1955, the seasonal trough of low over south Bay of Bengal became more pronounced and persisted like that till 28th. During this period, however, ships' observations were not available from the central region of the trough and it is hardly possible to say definitely whether the trough had not already concentrated into a shallow depression even before 29th. By the 29th morning, a depression was located in the southwest Bay of Bengal, centred about Lat. $9\frac{1}{2}$° N, Long. $83\frac{1}{2}$ °E. It intensified into a cyclonic storm on the 30th and crossed coast near Negapatnam in the early morning of 1 December 1955. The track of the cyclone is shown in Fig. 5. This cyclone had almost identical track as of 30 November 1952, which has been studied earlier by Krishna Rao and Sen (1953) and Desai and Rao (1954, 1955).

The heights of 700, 500, 300 and 200-mb surfaces at Delhi, Allahabad, Calcutta and Gauhati during the period 23 November to 1 December 1955 are given in Table 4. These data in Table 4 suggest that three troughs in the westerlies moved eastwards successively during this period, apparently reaching Calcutta on 26 November, 30 November and 1 December 1955 respectively. These troughs passed over Allahabad one day earlier, that is on 25, 29 and 30 November respectively. The passage of the troughs over Delhi a little earlier are also noticed, though in a somewhat diffuse form. A time cross-section for Calcutta is reproduced in Fig. 6 in the same way as in Fig. 2 for the other cyclone.

Even though a trough in the westerlies moved eastwards across Calcutta on the 26th and available upper winds and observed lowering of isobaric surfaces over Visakhapatnam also on the 26th (Table 7) had shown signs of extension of the trough southwards, the trough of low pressure in the south Bay did not intensify into a depression till perhaps 29th. There might have been various factors unfavourable for pronounced cyclogenesis on the 26th. The following possibilities are mentioned in this connection :

(*i*) It is seen from the upper wind charts for 20-30,000 ft levels that the westerlies over north India, south of Calcutta latitude, were rather weak on 26 November but they strengthened considerably on the 29th. This suggests that gradient on the southern side of the trough and the associated shear between winds on either side of the trough line was weaker on the 26th, which in accordance with the studies made by Cressman (1948) would indicate less chance of southward extension of the trough on the 26th. Southward extension was apparently more favourable for the trough on the 29th. It is noteworthy that in the case of November 1952 cyclone, which formed and rapidly concentrated into a cyclone on 26 November 1952, the associated westerlies over north India were strong and comparable to those on 29 November 1955.

(*ii*) There might have been out-of-phase superposition of the trough in the westerlies with upper tropospheric vortices moving westwards across the Andamans. Port Blair radiosonde data were not available on the 26th (see Table 5). It seems, however, that a high passed over Port Blair on the 24th, which apparently reached Madras on the 26th (see Table 6). It is possible that during the passage of this high across south Bay between 24th and 26th, it might had an out-of-phase interaction with the trough in the westerlies which moved eastwards across Allahabad on the 25th and Calcutta on the 26th.

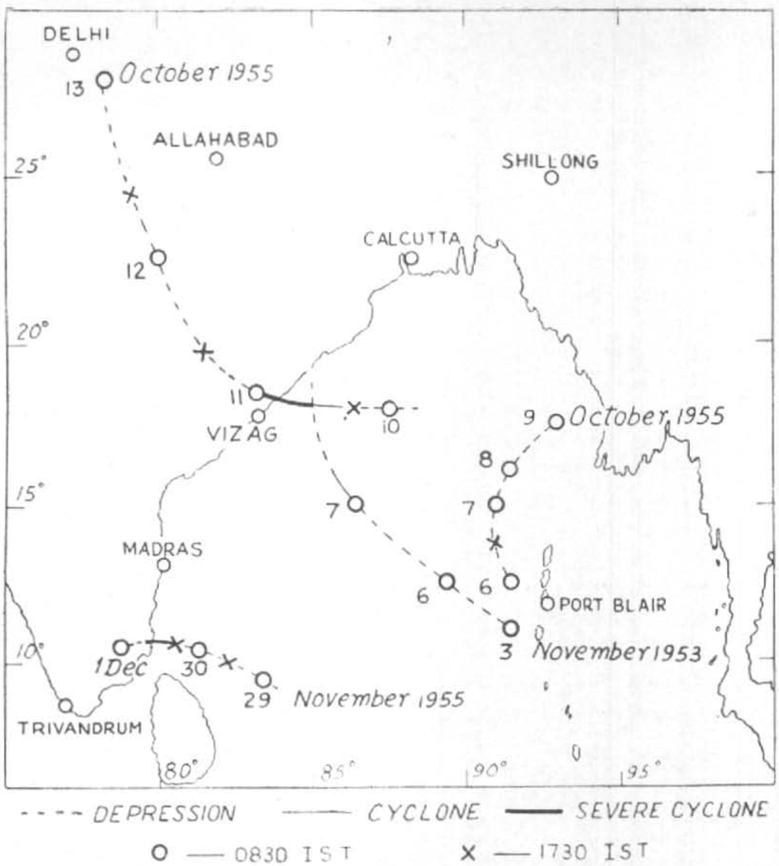

Fig. 5. Tracks of (1) November (30th) 1955 cyclone, (2) October 1955 cyclone and (3) November 1953 cyclone

TABLE 4

Heights (in tens of feet) of isobaric surfaces

Pressure levels (mb)	Radiosonde ascent on																	
	23 Nov 1955		24 Nov 1955		25 Nov 1955		26 Nov 1955		27 Nov 1955		28 Nov 1955		29 Nov 1955		30 Nov 1955		1 Dec 1955	
	0300 GMT	1500 GMT	0300 GMT	1500 GMT	0300 GMT	1500 GMT	0300 GMT	1500 GMT	0300 GMT	1500 GMT	0300 GMT	1500 GMT	0300 GMT	1500 GMT	0300 GMT	1500 GMT	0300 GMT	1500 GMT
DELHI (28°35′N, 77°12′E)																		
700	1043	1040	1033	1040	1040	1043	1033	1030	1030	1033	..	1033	1033	1030	1027	1033	..	1040
500	1932	1926	1926	1929	1929	1935	1929	1916	1919	1916	..	1913	1903	1913	1897	1913	..	1916
300	3173	3170	3176	3170	3173	3179	3179	3144	3166	3141	..	3163	3130	3176	3114	3150	..	3147
200	4088	4085	4088	4058	4078	4064	4085	4013	4078	4038	..	4085	4032	4104	4000	4065	..	4059
ALLAHABAD (25°27′N, 81°44′E)																		
700	1043	1043	1037	1040	1040	1043	1033	1033	1037	1033	1037	1033	1033	1024	1040	1033	1037	1037
500	1942	1945	1927	1930	1927	1933	1927	1923	1933	1923	1923	1920	1966	1896	1927	1899	1906	1913
300	3192	3208	3176	3156	3150	3173	3166	3169	3182	3163	..	3147	3091	3127	3166	3117	3130	3147
200	4111	4134	4085	4032	4016	4065	4055	4081	4081	4058	..	..	3976	..	4062	3984	4013	4055
CALCUTTA (22°39′N, 88°27′E)																		
700	1033	1027	1033	1037	1033	1033	1030	1020	1040	1030	1033	1033	1030	1030	1027	1033	1053	1040
500	1926	1917	1929	1923	1923	1926	1923	1906	1936	1923	..	1933	1919	1923	1903	1917	1933	1910
300	3169	3153	3172	3163	3166	3195	3160	3146	3189	3163	..	3179	3166	3169	3104	3163	3169	3130
200	4068	..	4078	4065	4078	..	..	4045	..	4065	..	..	4075	4078	..	..	..	4026
GAUHATI (26°11′N, 91°45′E)																		
700	1037	1033	1043	1033	1037	1027	1033	1033	1040	1030	1046	1030	1046	1030	1040	1030	1043	1033
500	1906	1912	1926	1912	1909	1897	1909	1906	1915	1912	1942	1900	1923	1900	1909	1880	1912	1906
300	3150	3166	3175	3140	3153	3117	3153	..	3156	3169	3238	3127	3156	3133	3127	..	3127	3127
200	4052	4085	..	..	4075	4006	..	..	..	4063	4190	4019	..	4032	4013	..	4048	4032

TABLE 5

Heights (in tens of feet) of isobaric surfaces—Port Blair

Pressure levels (mb)	1500 GMT radiosonde ascent on								
	22 Nov 1955	23 Nov 1955	24 Nov 1955	25 Nov 1955	26 Nov 1955	27 Nov 1955	28 Nov 1955	29 Nov 1955	30 Nov 1955
500	1936	1926	1946	1940	..	1933	1936	..	1919
300	3201	3189	3232	3202	..	3202	3202	..	3153
200	4121	..	4170	4127	..	4114	4124	..	4045

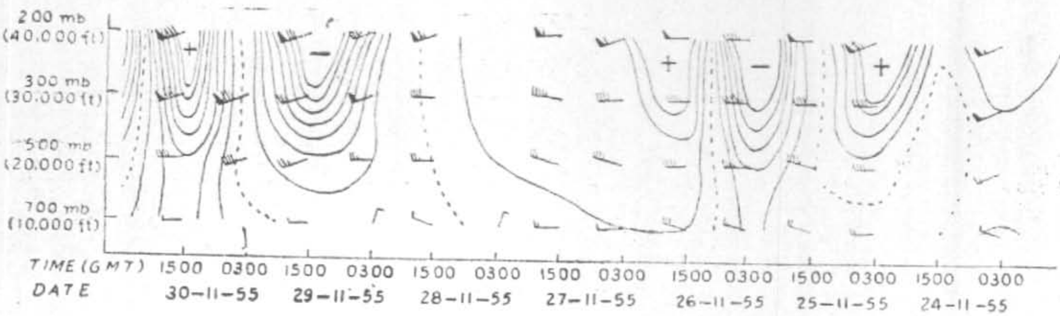

Fig. 6. Time cross-section for Calcutta showing 24-hour height changes
(Contours at intervals of 100 ft. Dotted line represents zero change)

The trough persisted in the south Bay for 3 days from 26th to 29th moving slowly westwards apparently without any appreciable intensification. Thereafter there was sudden development of the depression on the 29th which rapidly intensified into a cyclone on the 30th. The rapid intensification might have been due to interaction of the second trough in the westerlies which moved across Calcutta between 29 and 30 November 1955.

The passage of the two troughs eastwards across Calcutta on the 26th and 30th is also reflected in the height changes of isobaric surfaces over Visakhapatnam as shown in Table 7. Lowering of heights on the same dates at Visakhapatnam provides support regarding the southward extension of the troughs. The available data at Madras (Table 6) do not, however, show that the trough in the westerlies has extended as far south as Lat. 10°N. It is, therefore, doubtful whether the particular mechanism proposed by Riehl, namely, superposition of the forward portion of the trough over the area of cyclogenesis, had caused the required upper level divergence in this case. It is clear that to prove or disprove such mechanism, it would be necessary to have a much closer network of upper air observations around the area of cyclogenesis. However, the possibility of the trough in the westerlies becoming confluent over northeast India and resulting in cyclonic development to the south of the confluent trough is suggested as a possible contributory factor for cyclogenesis in south Bay of Bengal in such cases. This is explained later in the section under 'Conclusion'.

The heights of isobaric surfaces over Port Blair and Madras are reproduced in Tables 5 and 6. The passage of the upper tropospheric high westwards across Port Blair on the 24th which apparently reached Madras on the 26th, did not cause any accentuation of the surface trough over south Bay by the possible superposition of the eastern portion of the high over the surface low. With the available inadequate data, it is not possible to find definite reason for the same. However, the possibility of out-of-phase superposition of the upper tropospheric high with the trough in the westerlies has already been mentioned earlier.

It will be seen from Table 6 that the heights of pressure surfaces rose appreciably over Madras on the 29th and perhaps on 30th. The heights over Trivandrum had also risen slightly on the 29th and 30th. Passage of a high pressure centre from the east, which could reach Madras on the 29th or 30th, is not, however, noticeable in the Port Blair data on appropriate dates. The increase of heights at Madras in the upper levels might have been produced by the storm field itself as was noticed in the other November 1955 cyclone also.

5. Conclusions

The present study of the two cyclones in the Bay of Bengal reveals that in order to

TABLE 6

Heights (in tens of feet) of isobaric surfaces—Madras

Pressure level (mb)	Radiosonde ascent on													
	25 Nov 1955		26 Nov 1955		27 Nov 1955		28 Nov 1955		29 Nov 1955		30 Nov 1955		1 Dec 1955	
	0300 GMT	1500 GMT	0300 GMT	1500 GMT	0300 GMT	1500 GMT	0300 GMT	1500 GMT	0300 GMT	1500 GMT	0300 GMT	1500 GMT	0300 GMT	1500 GMT
500	1920	1929	**1949**	1926	1943	1920	1940	1920	**1962**	1917	1936	1940	1933	1936
300	3185	..	**3241**	3185	3208	3152	..	3176	**3241**	3192	..	**3208**	3195	3212
200	4104	..	**4180**	4098	..	..	..	..	..	4114	..	..	4117	..

TABLE 7

Heights (in tens of feet) of isobaric surfaces—Visakhapatnam

Pressure levels (mb)	1500 GMT radiosonde ascent on								
	23 Nov 1955	24 Nov 1955	25 Nov 1955	26 Nov 1955	27 Nov 1955	28 Nov 1955	29 Nov 1955	30 Nov 1955	1 Dec 1955
700	1037	1040	1046	**1033**	1033	1040	1046	**1040**	1040
500	1919	1933	1949	**1933**	1933	1930	1946	**1919**	1930
300	3169	3185	3222	**3179**	3179	3176	3205	**3163**	3182
200	4085	4098	4143	**4078**	..	..	4114	**4062**	4088

determine whether Riehl's theory is applicable to the formation of cyclones of the Indian Seas or not, it is necessary that we should have more frequent upper air observations from a fairly close network of stations. Examination of the 0300 and 1500 GMT radiosonde data in the present study has shown that significant lowering of heights of isobaric surfaces due to passage of upper troughs is often completed within 12 hours or so. That is, when such significant lowering is noticed at one hour, say at 0300 GMT, the observed heights 12 hours earlier or 12 hours later, are often not affected by the trough. It may, therefore, be concluded that to determine precisely the times of passage of upper troughs and ridges in the westerlies across a particular station, we should have 6-hourly radiosonde data (*i.e.*, 4 ascents a day), as were used by Riehl for his studies in the Pacific and Atlantic areas. Whereas 12-hourly radiosonde ascents (*i.e.*, 2 ascents a day) used in the present study appears to be the minimum requirement, data from single ascent a day, as used in the earlier study over the Indian area (Desai and Rao 1955), are definitely inadequate for such studies. The present study also suggests that unless we have a few additional upper air stations over the sea area (Bay of Bengal) besides Port Blair, such as by having ocean weather ships, it will perhaps be difficult to derive conclusive evidence regarding the mechanisms of upper level divergence which cause initial cyclognesis, such as are proposed under Riehl's theory.

It is found that the positions of the upper troughs and ridges in the westerlies moving across north India could be located with reasonable confidence with the available upper air data. Changes of heights of isobaric surfaces due to movement of troughs and ridges in the westerlies are most pronounced at 300 and 200-mb levels. The observed 24-hourly changes in heights are of the order of 300 to 500 ft at 300 mb and 500 to 1000 ft at 200-mb level. Available upper air data did not provide clear indication regarding movement of upper tropospheric vortices over the tropics and even if such vortices had moved, changes in heights of isobaric surfaces caused by such vortices are much less marked than those caused by troughs in the westerlies. This makes the precise location of the upper tropospheric vortices moving across the Bay of Bengal all the more difficult with scanty data over the Bay area.

It is found that in both the cases studied, the initial formation of the depression took place when an upper trough in the westerlies moved across northeast India, that is to the north of the region of cyclognesis in the south Bay of Bengal. It is notworthy that similar influence of the middle-latitude troughs on the initial formation of post-monsoon cyclones in the Bay of Bengal was also observed by Desai and Rao (1955) in each of the 4 post-monsoon cyclones studied by them. It would, therefore, appear that the middle-latitude troughs moving eastwards across north India and their southward extension influence cyclogenesis in south Bay of Bengal in the post-monsoon season. The mechanism by which these middle-latitude troughs interact so as to cause mass divergence above distant incipient lows in south Bay of Bengal is open to question. According to Riehl's theory, this can be effected either by the southward extension of the upper trough in the westerlies and superposition of its forward portion above the surface low or by the in-phase superposition of the upper troughs in the westerlies with upper tropospheric vortices moving above the surface incipient low. In the two cases studied it seems that the troughs moving across northeast India had extended southward into the Bay of Bengal, but there is no definite evidence that they had extended sufficiently southward so as to get superposed over the surface incipient low in the south Bay of Bengal. There is also no clear evidence for movement of upper tropospheric vortices across south Bay. However, a slightly different interaction of a trough in the westerlies, which extend southward but not well into south Bay, is suggested below as a possible explanation for the cyclogenesis in south Bay of Bengal in the post-monsoon season.

Normal upper wind circulation over India and neighbourhood at 10 km and above in November (Venkiteshwaran 1951) are reproduced in Fig. 7. If a trough in the westerlies moves eastwards across northeast India, the trough is likely to become confluent towards the east because of the anticyclonic circulation over the Bay of Bengal. With southward extension, the confluent trough may assume a pattern as shown in Fig. 8. Sutcliffe and Forsdyke (1950) have shown that in a confluent trough, the cyclonic development occurs to the south of the trough as a result of dynamical development, *vide* Figs. 18(a) and 22(d) of their paper. It is to be mentioned that confluent trough referred to in Sutcliffe and Forsdykes' paper relate to the *Thermal Field* (Thickness pattern). However, the dominant contour features, namely the trough and ridge patterns, at higher levels (10 km and above) are also similar to the thermal field, usually modified only to a small degree by the surface pressure pattern. Thus, interaction between the trough in the westerlies moving across northeast India and the normal upper air circulation over the Bay of Bengal and neighbourhood in the post-monsoon season could apparently lead to the development of a confluent trough and the associated cyclonic development to the south of the confluent trough as depicted in Fig. 8 may provide a possible explanation for observed cyclogenesis in south Bay of Bengal. The above suggestion is only tentative and its actual contribution in individual cases can be studied only when

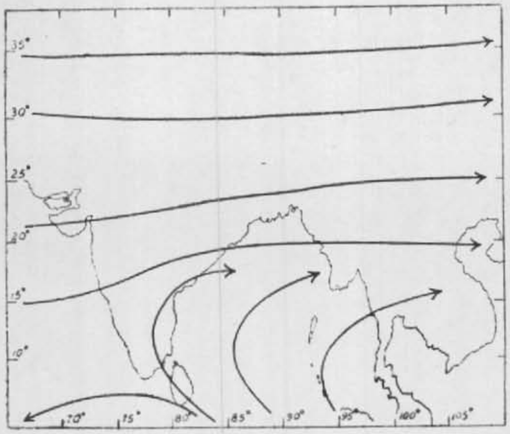

Fig. 7

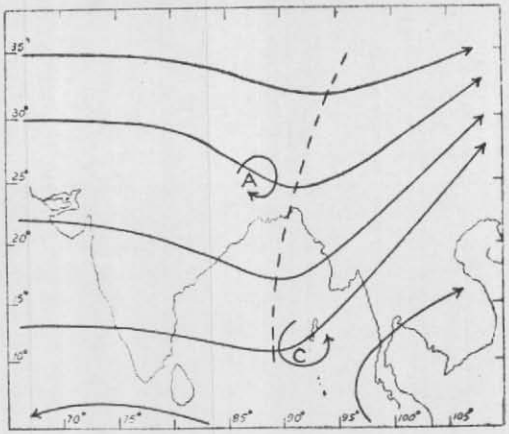

Fig. 8

adequate upper air data over and around Bay of Bengal are available.

In one of the two cyclones studied, the subsequent intensification of the depression into severe cyclone also appears to be associated with the passage of a fresh trough in the westerlies to the north of the disturbance in the Bay of Bengal. This might be just a coincidence. However, the present study suggests that in the post-monsoon season, if an incipient low such as a wave in the easterlies or accentuated seasonal trough of low exists in the south Bay of Bengal, eastward passage of an upper trough in the westerlies across north India, say across Delhi and then Allahabad longitudes, may provide a prior indication about possible cyclogenesis in south Bay of Bengal; and if a depression already exists in the Bay, passage of such upper troughs to the north of the depression might provide favourable condition for sudden intensification of the depression into a cyclone.

In both the cyclones of 1955, there is evidence of high pressure circulation at 200-mb level above the cyclones which is presumably produced by the cyclone field itself, as have been observed in the cases of matured hurricanes and also in other cyclones of the Bay of Bengal studied recently (Rai Sircar 1956).

Comparative study of the upper air conditions associated with the recurvature of the severe cyclone of November (3rd to 8th) 1955 and of October 1949 shows that both the cyclones recurved under influence of pronounced trough in the westerlies moving eastwards across north India and that recurvature commenced when the troughs in the westerlies reached comparable position. Weakening of the severe cyclone of November (3rd to 8th) 1955 while out at sea is found to be due to incursion of colder and drier air into lower levels of the cyclone in association with the passage of a trough in the westerlies.

The interaction of the middle-latitude upper troughs and ridges as postulated by Riehl are found to influence the formation of cyclones in the Bay of Bengal. But with the inadequate upper air data as are available at present, particularly over the Bay of Bengal area, it is hardly possible to establish which of the alternative mechanisms for the upper outflow contemplated in Riehl's theory is applicable in individual cyclone formation. For this purpose, radiosonde and rawin data, preferably 4 times a day, from selected stations in Burma, one or two other island stations besides Port Blair and also from a few stationary ships would be required. Till then, it may not be possible to determine the exact mechanism of the upper outflow causing cyclogenesis in this area or to detect any other sequence of events in the mechanism leading to cyclogenesis. In this connection, Riehl's concluding remarks on his model of tropical cyclogenesis (Riehl 1951) is quoted below, as it clearly brings out how his latest model of tropical storms stands today:

"At this time it is not possible to tell whether this latest model will withstand the test of experience. The sequence described is not the only one that can lead to cyclogenesis. Both in high and low latitudes, more than one synoptic pattern can lead to deepening. It is fair to say, however, that it is reasonable to attack the problem by placing emphasis on the upper divergence as an initiating mechanism. All efforts to explain deepening by low-level convergence have failed to date since none of them can explain the surface pressure falls. The future evidently must concern itself with further development of models that lead to cyclogenesis. It is probable that the inter-relation between different latitude belts will ultimately be recognised as an important factor."

6. Acknowledgement

I wish to express my sincere thanks to Dr. B. N. Desai for discussions on the subject and the interest he had taken during the preparation of this paper.

REFERENCES

Cressman	1948	*Misc. Rep.*, 24. Dep. Met., Univ. Chicago.
Desai, B. N. and Rao, Y. P.	1955	*Proceedings of the UNESCO Symposium on Typhoons*, pp. 175-198.
	1954	*Indian J. Met. Geophys.*, **5**, 2, p. 200.
Jordon, Charles L.	1953	*Ibid.*, **4**, 4, p. 339.
Krishna Rao, P. R. and Sen, S.N.	1953	*Curr. Sci.*, **22**, 4, p. 98.
Riehl, H.	1948(a)	*Misc. Rep.*, 24, pp. 1-64. Dep. Met., Univ. Chicago.
	1948(b)	*J. Met.*, **5**, p. 247.
	1950	*J. App. Phys.*, **21**, 9, p. 917.
	1951	*Compendium of Meteorology*, Amer. met. Soc., p. 910.
	1954	*Tropical Meteorology*, pp. 347-351.
Rai Sircar, N.C.	1956	*Indian J. Met. Geophys.*, **7**, 1, p. 36.
Sen, S.N. and George, C.A.	1952	*Ibid.*, **3**, 4, p. 264.
Sutcliffe and Forsdyke	1950	*Quart. J.R. met. Soc.*, **76**, p. 189.
Venkiteshwaran, S. P.	1951	*Mem. India met. Dep.*, **28**, Pt. II, p. 55-120.