551.509.312.: 551.515.2

Thermal thickness patterns and tropical storms

C. A. GEORGE

Regional Meteorological Centre, Calcutta

(*Received 2 December 1952*)

ABSTRACT. In this paper, an attempt is made to illustrate the utility of the thermal thickness patterns on constant pressure charts for forecasting the life cycles of a few tropical storms in the Bay of Bengal. The thickness patterns and the contour-thickness relationship seen on the 500-mb isobaric surface gave useful advance indications about the future movement and intensification or decay of the storms under study, at least 12 hours earlier than those evident from the synoptic charts. *Relative divergence* in accordance with Sutcliffe's development term was computed from the isopleths of $h_{500}+h_{1000}$ and the total thicknesses at the 500-mb surface and it was found that the patterns so obtained were *qualitatively* in good agreement with the subsequent movement and development of the storms. It is also shown that the storms under study were steered mainly by the thermal winds at 500-mb surface over the warm sector rather than by the actual winds at 6 kilometres.

1. Introduction

Two severe cyclonic storms developed in the Arabian Sea and the Bay of Bengal during November and December 1951 respectively. Another severe storm also developed in the Bay of Bengal during May 1952. Brief reports about these storms have been given elsewhere (*Ind. J. Met. Geophys.*, 1952). The May storm was a regeneration within the trough of low that remained after the decay of a deep depression over the east central Bay and neighbourhood a few days earlier. These disturbances are particularly interesting in view of the fact, that rather unusually, all of them *weakened rapidly while they were still out at sea.*

Forecasting the formation, movement and subsequent development of tropical storms, especially their decay over the sea, is by no means easy, owing to the uncertainties about the complete mechanism of cyclogenesis or anticyclogenesis, difficulties of applying to the study of problems in the tropics principles employed elsewhere and the inadequacy of forecasting factors available to the forecaster in the tropics. Whatever be the principles of tropical cyclogenesis—whether they are based on instability or frontal processes as suggested by various writers (Hines 1947, Sawyer 1947, Berry, Bollay and Beers 1945, Roy and Roy 1930, Ramanathan and Banerjee 1931, Mull and Desai 1931, Malurkar and Pisharoty 1948, Desai and Koteswaram 1951, Desai 1951 and Sen and George 1952), there is perhaps no doubt that convergence in the lower troposphere with an equalising divergence aloft leads to cyclogenesis and the reverse leads to anticyclogenesis (Sutcliffe 1947) in the tropics as elsewhere. For a reliable assessment of cyclonic development, it is essential to know the *relative divergence* occurring in a *deep layer* of the troposphere. Whenever upper wind data are meagre or completely absent for this purpose, as on occasions of cyclonic storms, only constant pressure charts built up by the differential method can render the *best possible* aid to the forecaster in this respect. Sutcliffe's (1947) theory of thermal thickness patterns on isobaric surfaces and the idea that the thermal divergence at 500-mb, which represents a mean pressure level in the troposphere, equals the surface divergence*, as given by him and Forsdyke (1950), have afforded a practical means of utilising the 500-mb chart for the assessment of cyclonic or anti-cyclonic developments.

The usefulness of upper air analysis for tropical forecasting has been pointed out by Ratcliffe (1950). The present study seeks to illustrate the utility of the 500-mb chart for prognosticating the significant epochs such as formation, intensification or decay and movement of the above-mentioned storms and deep depression in the Bay of Bengal on the basis of the thermal thickness patterns and the contour-thickness relationship (Petterssen 1945) seen on this pressure surface and Sutcliffe's development term computed from isopleths of $h_{500}-h_{1000}$ and $h_{500}+h_{1000}$.

---

* $\text{div}\ V_0 = (\text{div}\ V')_m$

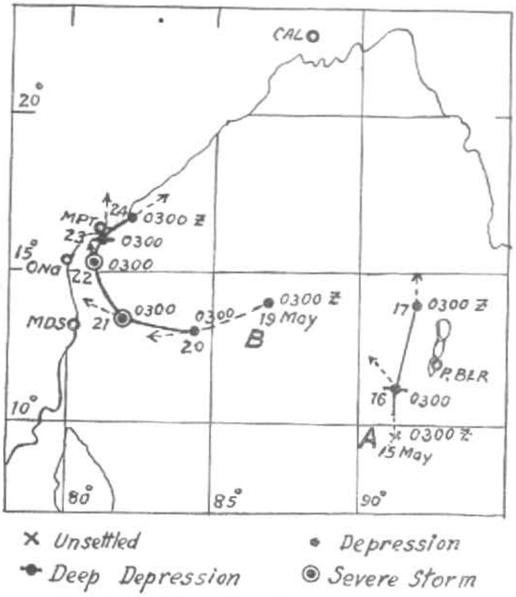

Fig. 1. Tracks of disturbances of May 1952

The 500-mb chart is built up by the differential method (Petterssen and Priestley) in the usual manner making use of the daily available radiosonde data at 1500 GMT and the pilot-balloon winds at 0900 GMT. The total thermal wind within the 1000/500-mb layer is computed as the *vector shear* between the 2000/3000 ft and 20,000 ft winds in the case of the December 1951 storm and between the 2000/3000 ft and 18,000 ft winds in the case of the May disturbances.

The relative divergence has been computed at as many points on the charts as necessary, especially within the depression field, in order to yield representative patterns. For this purpose, the square grid marked on a perspex overlay has been used, following Sawyer and Matthewman (1951). The magnitude of development so obtained is, however, only *qualitative* as the values have not been corrected for the variation with latitude of the coriolis parameter and gravity, so as to make the unit of divergence strictly 10^{-2} hr^{-2}. The grid length has been chosen to be 100 nautical miles at Lat. 20° on the I. Met. D. W-4 chart. Positive relative divergence indicates cyclogenesis and negative relative divergence anti-cyclogenesis. In the present analysis, the former is referred to as convergence and the latter as divergence for the sake of convenience. Figs. 2-10 and 12-16 give the 500-mb charts containing the thickness patterns, the thermal winds and the 'development' patterns pertaining to the Bay disturbances reviewed in this paper.

2. Discussion of the results

(*A*) *Bay storm and deep depression of May 1952*

The tracks of these disturbances are given in Fig. 1. Their intensity, position of centre and expected direction of movement indicated by the broken arrows attached to the tracks are in accordance with those given at 0300 GMT in the Indian Daily Weather Reports for the respective days in May 1952.

(*i*) *Deep depression on 16 May 1952*

Conditions became markedly unsettled in the southeast Bay of Bengal by 0300 GMT of the 14th and a depression probably formed by the evening of the 15th. It became a deep depression by 0300 GMT of the 16th. By the next morning, however, the deep depression *weakened over the sea itself*, after moving N/NE. It became unimportant later, giving rise to a residual extended trough whose axis was running from Nellore to Tavoy through Table Island at 0300 GMT of the 18th. Track A in Fig. 1 indicates the course of this deep depression.

The 500-mb surface and associated convergence patterns at 1500 GMT on 14, 15, 16 and 17 May 1952, which are relevant to this deep depression are given in Figs. 2 to 5. In the 500-mb surface charts lines have been drawn at intervals of 100 ft both for $h_{500}+h_{1000}$ and $h_{500}-h_{1000}$. The following features of the charts are noteworthy.

On the 14th (Fig. 2), a well-marked cold *thermal trough* extended from northeast India to the Comorin area across the Tenasserim coast and east central Bay. The difluence of this trough, though slight, yet apparent, over south peninsula and southwest Bay, might perhaps be taken as a sign of cyclogenesis on its cold side (Sutcliffe and Forsdyke 1950). The pattern of convergence or divergence on this day was generally consistent with the ascent or descent respectively

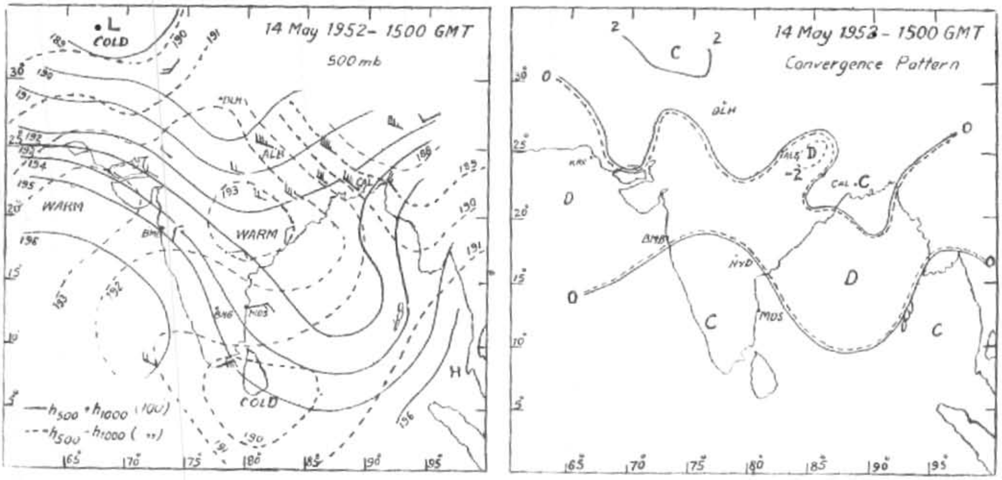

Fig. 2

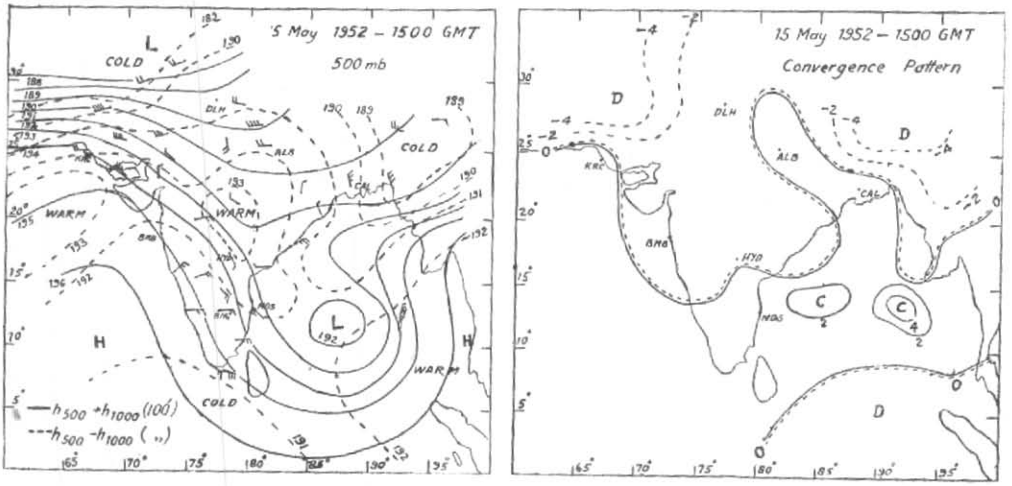

Fig. 3

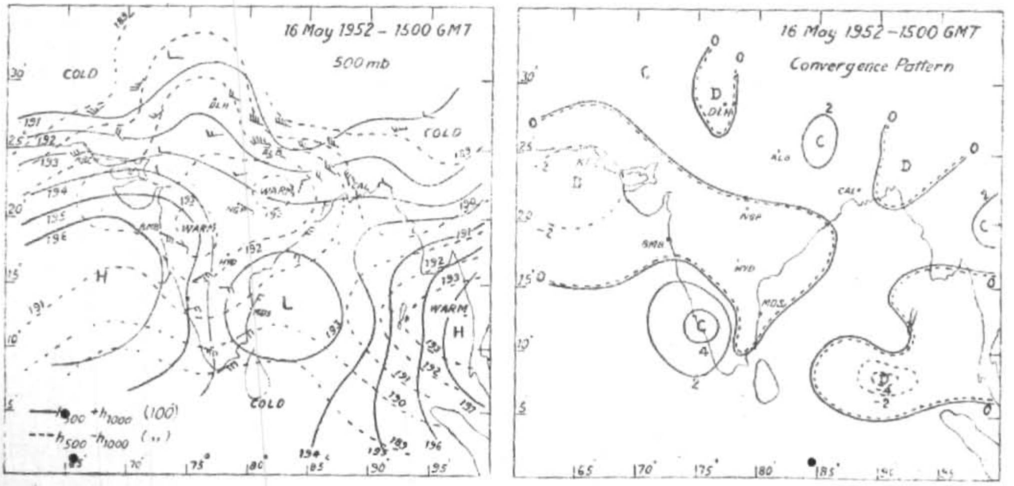

Fig. 4

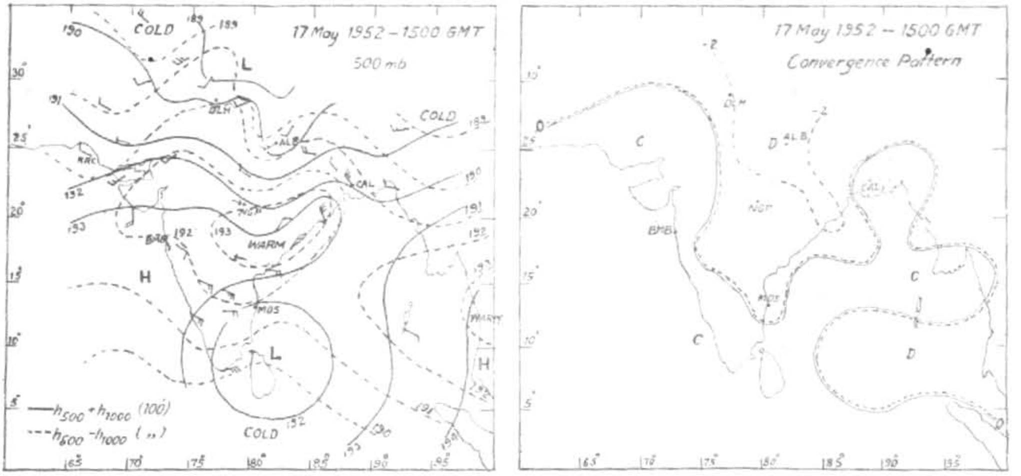

Fig. 5

of the thickness lines on the pressure surface. The convergence over southeast Bay and neighbourhood was suggestive of the unsettled conditions over that region. The divergence noticed over south Bihar and neighbourhood was apparently due to the anticyclonic shear (*Handbook of Meteorology* 1945) of the westerlies.

On the 15th (Fig. 3), cyclogenesis had taken place as indicated by the concentrated convergence of 2 to 4 units that developed over southeast Bay and neighbourhood ; a closed low also appeared near this region on the 500-mb surface. The ascent of the thickness lines over the contours (in the warm moist sector) over north Andaman Sea and east central Bay, indicating fall of pressure to the north and northeast of the depression centre and the consequent probable movement of the depression in that direction might specially be noted. Pronounced anticyclonic shear appears to have given rise to the divergence seen over northeast India.

On the 16th (Fig. 4), a well-marked *thermal high* (Sutcliffe and Forsdyke 1950) having the thickness lines descending the contours over the field of the depression and ascending over deltaic Burma had developed. Weakening, if not the complete reversal, of the pattern of convergence on this evening over this area was very significant. These two facts might be considered as a sure sign of the weakening of the depression and its further movement northeastwards. The large convergence along and off the west coast south of Lat. 15°N was consistent with the steep ascent of the thickness lines on the pressure surface over that area. It had also indirectly contributed to the weakening of the depression by causing a fall of pressure over that region and thereby attracting the ' monsoon ' air into this area far away from the field of the depression.

On the 17th (Fig. 5), conditions almost similar to those on the 14th were restored, so far as the convergence was concerned ; while on the isobaric surface a closed low, which had been absent on the 14th and which had had a westsouthwesterly shift from the depression area from the 15th onwards, had persisted on this day over the southwest Bay and neighbourhood.

(*ii*) *Severe storm in the Bay during 21 to 22 May 1952*

The extended trough on the 18th as mentioned under (*i*) above, was suspected at 0300 GMT of the 19th to be concentrating into a depression with its central region near the position marked for this time in track B of Fig. 1. The depression was definitely centred about 300 miles east of Madras on the next morning. By 0300 GMT of the 21st the depression had moved westnorthwest and *rapidly intensified into a severe cyclonic storm*, which was centred about 120 miles eastnortheast of Madras. The storm later moved NW/N and was centred at 0300 GMT of the 22nd about 50 miles east of Ongole (Lat. 15½°N Long. 85°E approximately). 22 May marked a significant epoch in the history of this storm, as it *weakened over the sea into a deep depression* by the morning of the 23rd, when it was close to coast near Masulipatam. The deep depression progressively weakened further, recurving northeastwards and degenerated into a trough over the west central Bay by 0300 GMT of the 25th.

The 500-mb charts and the associated convergence patterns on 18, 19, 20, 21 and 22 May 1952, which are relevant to this storm are reproduced in Figs. 6 to 10. The chief features of these charts are described below—

The closed low on the 500-mb isobaric surface for the 17th (Fig. 5), which was drawing the E_m air over the area east of Long. 85°E, moved further southwestwards, and by the 18th evening, it became a rather well-marked trough of low extending from the Comorin to the southwest Bay of the Coromandel coast. The contours on the 18th (Fig. 6), undoubtedly favoured greater influx of E_m air into the region where cyclogenesis took place on the succeeding day. The thermal thickness pattern seen on the 18th over south Bay and east central Bay

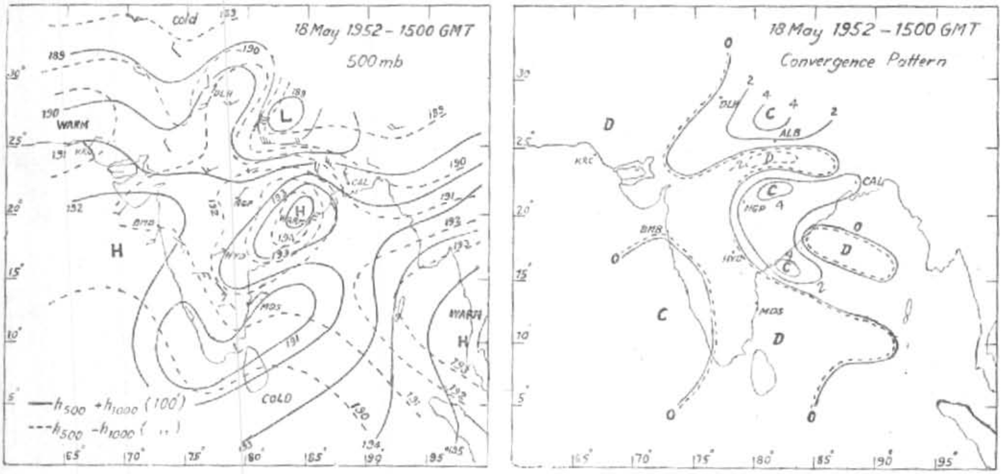

Fig. 6

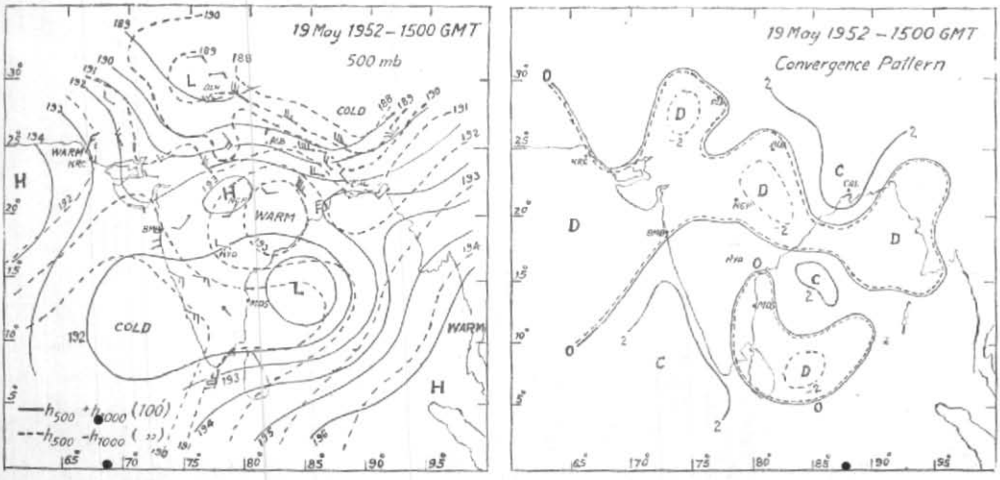

Fig. 7

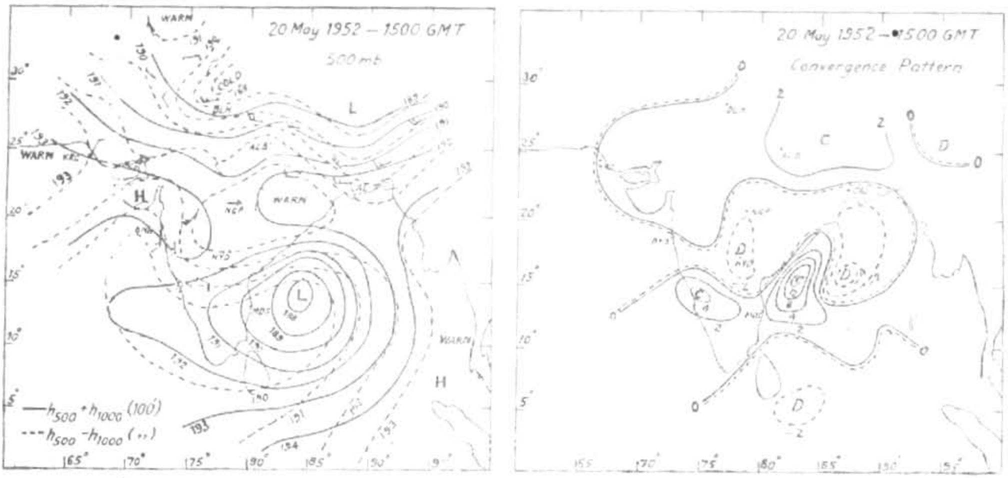

Fig. 8

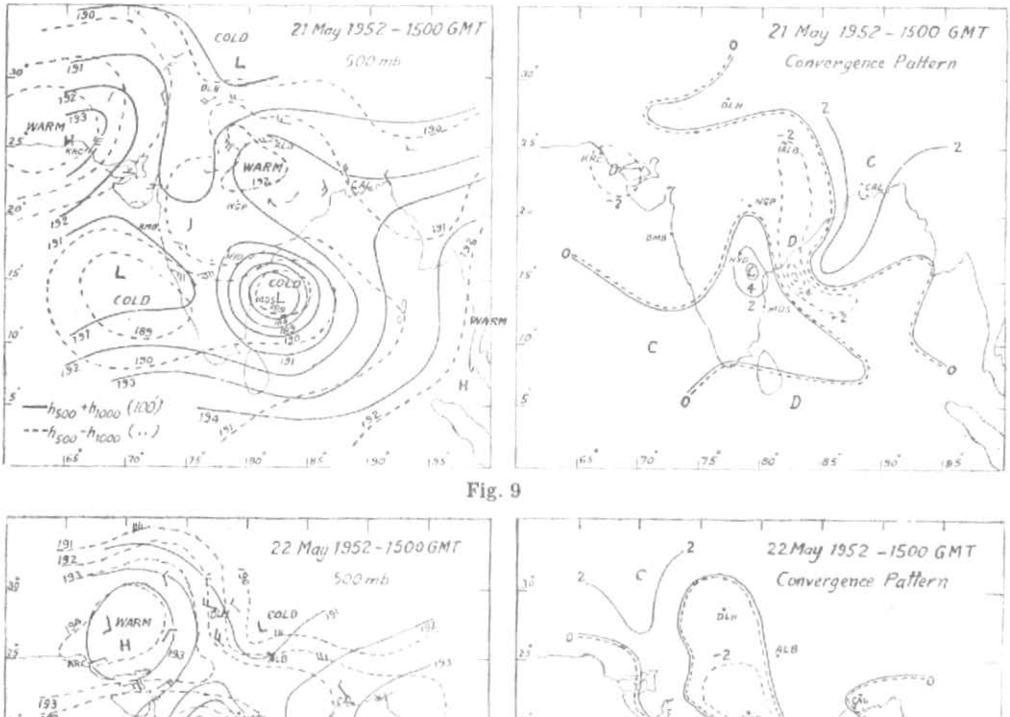

Fig. 9

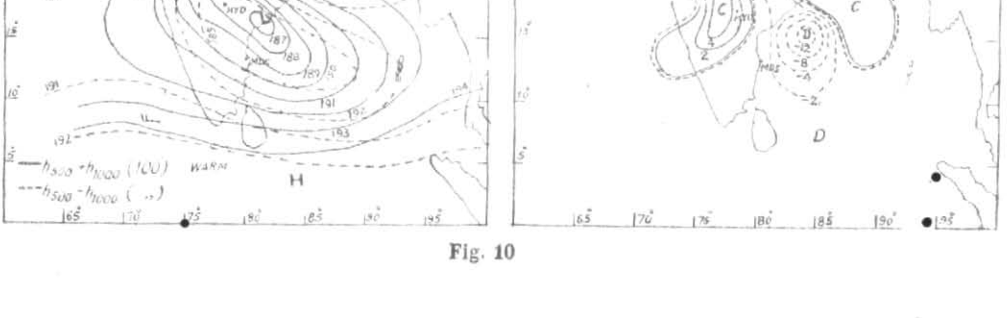

Fig. 10

was, perhaps, a *diffluent thermal jet* characterised by cyclogenesis on the cold side (Sutcliffe and Forsdyke 1950). The convergence pattern observed on this day was, however, not very conclusive in respect of cyclogenesis. Nevertheless, if the southeastern portion of the belt of convergence seen to the northwest of the depression field was taken to be in association with the probable ascent of the thickness lines of the contours over this region, under the influence of the developing cyclogenesis, then, the orientation of the convergence pattern from the region of cyclogenesis might have been helpful to infer the probability of a westnorthwest instead of a westerly movement of the depression centre, which will obviously move in the direction of the gradient of convergence. The convergence observed over north Andhradesa and Orissa was unaccountable by the thermal patterns descending the pressure surface over that region ; and this might have been caused by the observed cyclonic shear (*Handbook of Meteorology* 1945) of the NW/N winds over northwest Bay and neighbourhood.

On the 19th (Fig. 7), the diffluent jet continued to be the thermal pattern and a closed low also appeared on the isobaric surface over the region of cyclogenesis. The convergence on this evening, still oriented in a westnorthwesterly direction from the depression area was significant, although its magnitude was not large compared to the value observed on the 15th (*c.f.* Fig. 3). The disappearance of the convergence over north Andhradesa and Orissa on this day in contrast to the pattern on the previous day, adds to the significance of the convergence that persisted over the region of cyclogenesis. The deepening isobaric surface, the diffluent thermal pattern ascending over the westnorthwest sector of the former and the convergence observed on this evening, perhaps, left no doubt about the formation of a depression and its probable westnorthwesterly movement as had happened from 0300 GMT of the 20th.

On the next evening (Fig. 8), the thermal pattern undoubtedly intensified into a deep cold trough, on account of the fall in the thickness values at Trivandrum, Port Blair and Visakhapatnam since the 18th (data for the 19th for Trivandrum and Visakhapatnam were taken as the mean of values for the 18th and 20th). The contours of the 1000-mb surface had also obviously deepened owing to the fall of pressure at sea level in association with the depression. Both these factors, had, in turn, caused a very steep gradient of the 500-mb surface contours over the disturbance. The conspicuous increase of convergence of the order of 8 to 12 units, in sharp contrast with the values for the previous day, and the orientation of its gradient in a northwest to northerly direction, would certainly indicate a *rapid large intensification* of the depression, probably to the stage of a severe storm and its subsequent movement in a northwest to northerly direction, as had happened from 0300 GMT of the 21st and onwards. The increase of divergence over the northeast sector of the storm and of convergence along and near the Kanara coast on the 20th as compared to the values over these regions on the previous day were noteworthy.

On the 21st evening (Fig. 9), the thicknesses at Poona and Port Blair had decreased by 60 ft and 160 ft respectively, while at Trivandrum the thickness had increased by 60 ft since the 20th. These changes were not fictitious and doubtful as the same tendency was maintained at these stations on the 22nd as well (see Fig. 10). The thermal gradient had accordingly weakened and the resulting pattern on the evening of 21st was apparently a *cyclonic thermal involution* that preceded cyclonic occlusion (Sutcliffe and Forsdyke 1950). A ridge of divergence with a maximum value of 4 to 8 units over the region of descending thickness lines had appeared in the storm field for the first time on this evening. These appeared to have contributed to the gradual weakening of the storm. The convergence observed over south Andhradesa and adjoining areas had, perhaps, no obvious bearing on the storm, as it was probably an eastward shift of the belt of convergence seen over the Kanara coast on the previous evening. In any case, one could hazard the risk of ignoring this, in so far as its influence upon the movement of the storm was concerned, in view of the fact, that a westerly movement of the storm centre indicated by this convergence was quite unlikely as the storm had already moved in a northwest to northerly direction by the morning of 22nd. On the other hand, the wedge of convergence which extended from northeast India southwards upto Lat. 16°N and Long. 85°E appeared to be more significant, as this had appeared in replacement of the large divergence seen on the 20th over the warm sector to the northeast of the storm centre. These factors, together with the northwest to northerly movement which the storm had already had till 0300 GMT of the 22nd might help to indicate a northeastward recurvature as well as weakening of the storm from the morning of 22nd.

The thermal pattern on the 22nd evening (Fig. 10) appeared to have changed to an *anticyclonic thermal involution* characterising slow moving anticyclones (Sutcliffe and Forsdyke 1950). This was so, because, the thermal winds at Ahmedabad, Gwalior and Chittagong, which were mainly decisive of the change in the pattern, had changed from SSW to NE, from SE to WNW and from NNW to WSW respectively since the 21st evening. The 'development' computed for this day indicated still more marked divergence especially over the depression field, where it was of the order of 8 to 12 units as compared to that for the previous day. This, no doubt, indicated further weakening of the depression. The decrease of convergence to the northeast sector of depression was significant. The northwestward shift of the previous day's convergence area over south Andhradesa into west Hyderabad and neighbourhood on this day was also noteworthy.

It will be clearly seen from the foregoing, that the 500-mb isobaric surface and the associated thermal thickness patterns, together with the 'development' computed from them, were quite helpful to predict the various stages of development and movement of the disturbances reviewed above, at least 12 hours earlier than the symptoms on the morning synoptic charts of the next day. It may also be noted, that while the magnitude of convergence, however, qualitative the assessment of relative divergence might have been, indicated the intensity of the disturbances during their developing stages, the depression centre at sea level was found to have been steered in the direction of the gradient of convergence from the depression centre by the thickness lines over the warm moist sector.

(B) *Severe storm during 7 to 11 December 1951*

The seasonal trough of low over the extreme south Bay of Bengal was concentrating into a depression near Lat. 8° N and Long. 91° E by the morning of the 5th. By 0300 GMT of the 7th, it progressively intensified into a severe storm after having had a northwesterly movement. Thereafter, the severe storm moved gradually in a north to north-northeasterly direction until the 11th morning. Later, it *rapidly weakened over the sea into a depression* and moving northeastwards, the depression was centred near Lat. 19½°N and Long. 89½°E at 0300 GMT of the 12th. The depression progressively moved northeastwards and weakened further and by 0300 GMT of the 14th, it lay as a trough of low off the Arakan-Chittagong coasts. The track of this storm containing details as for the May 1952 disturbances is given in Fig. 11.*

The 500-mb surface and the convergence-divergence patterns on 6, 9, 10, 11 and 12 December 1951 are reproduced in Figs. 12 to 16. As no radiosonde data for Port Blair, which was nearest to the region of cyclogenesis was available for the 5th, the chart for that day has not been prepared. Charts for the 7th and 8th, being not very significant for the study of this storm are not given here. The thickness data for Port Blair and the Indian stations, particularly those along the east coast and the large number of thermal winds for the Indian stations for all the days and at Tavoy on the 11th have been made use of for drawing the thickness patterns as accurately as possible, over the Arakan-Chittagong and Tenasserim coasts, where

---

* *c. f.* Track of November 1951 storm in the Arabian Sea given elsewhere (*Ind. J. Met. Geophys.* 1952). These two storms were almost identical in respect of development and movement

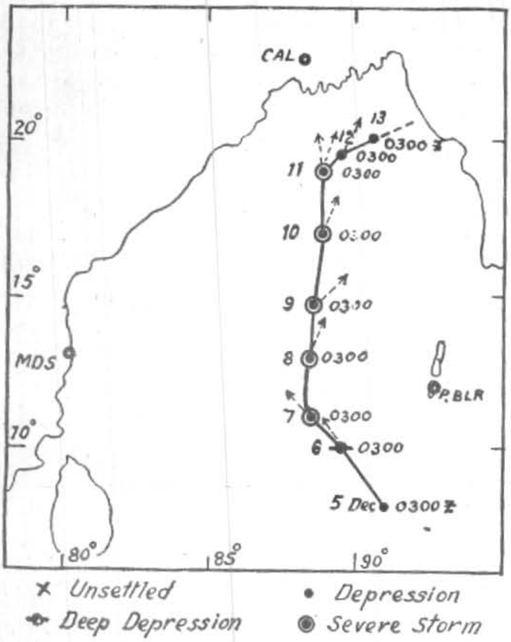

Fig. 11. Track of December 1951 Storm

both upper wind as well as radiosonde data were practically absent.

In the light of the discussion of the results obtained from the 500-mb surface and 'development' patterns for the May 1952 Bay disturbances, no detailed description of the patterns for this storm is perhaps necessary. The run of the thickness lines, mainly from a south to southwesterly direction over the contours over the warm moist sector to the east of the storm centre, the constancy of the values of convergence of the order of 4 to 6 units and the orientation of the gradient of convergence in a north to northnortheasterly direction from the storm centre on the 6th, 9th and 10th (Figs. 12 to 14) cannot escape one's notice. The storm after becoming severe by the morning of the 7th, as perhaps indicated by the 500-mb surface and convergence pattern on the evening of the 6th, continued to be severe and to move north/northnortheastwards, in the direction of the warm sector thermal winds till the 11th morning in accordance with these patterns. The pronounced divergence of the order of 16 to 20 units, which developed over the northwest Bay on the 10th evening (Fig. 14), in sharp contrast with the pattern over the same region on the previous day deserves special mention. The development of a significant patch of convergence over north Arakan coast and the tilt of the entire convergence pattern northeastwards were also equally conspicuous on this day. These patterns on the 10th evening might help to indicate northeastward recurvature as well as the weakening generally associated with recurvature of the storm from the morning of the 11th. On the 11th evening (Fig. 15), the convergence, still oriented northeastwards, however, *decreased in magnitude*, while the wedge of divergence over the northwest Bay seen on the previous day extended into the whole of north Bay of Bengal. In addition, a significant patch of divergence also developed over the south Arakan coast and over deltaic Burma. These unmistakably pointed to the further weakening and northeastward movement of the storm, as was observed on the 12th morning. It need hardly be mentioned that the development pattern on the 12th evening (Fig. 16) indicated northeast to eastnortheastward movement and further weakening of the depression.

3. Validity of the analysis

It is well known that there are various limitations, both practical and theoretical, for the use of the technique of constant pressure analysis in our country. The chief among them are lack of sufficient radiosonde data and the non-validity of the geostrophic equation in the low latitudes. The differential method of analysis and the correspondence of actual as well as thermal winds even at Lat. 10°N in the Indian area with the geostrophic values, as pointed out by Ratcliffe (1950), minimise these difficulties at least to some practicable extent.

As the sea level pressure gradient in our latitudes is generally weak, the changes in development caused by the variation in the vorticity of the geostrophic winds at the friction-free 1000-mb surface is likely to be small. It may also be noted that the major contribution for pressure variations is by the thermal winds, those by the geostrophic departure as well as the cyclostrophic component of the gradient wind being far too small (Petterssen 1945). Further, the thickness tendency (Sutcliffe and Forsdyke 1950) depends not only on the advective term based

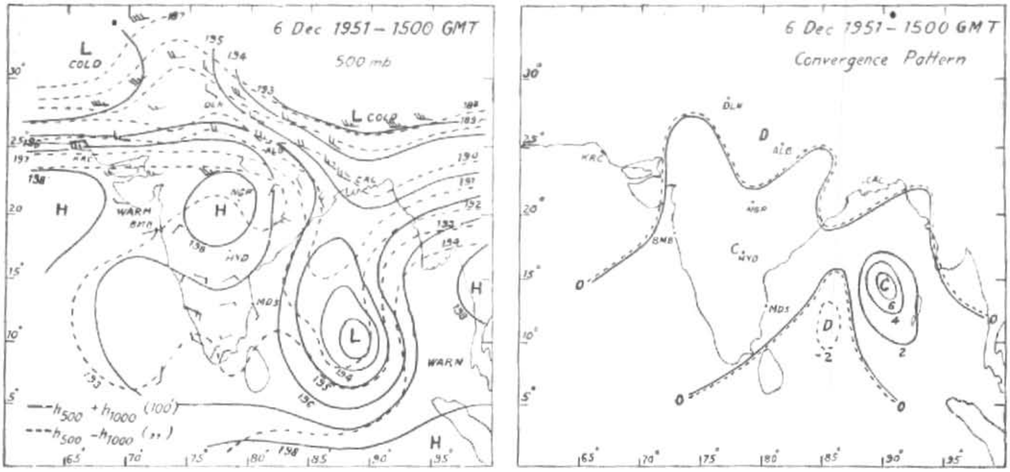

Fig. 12

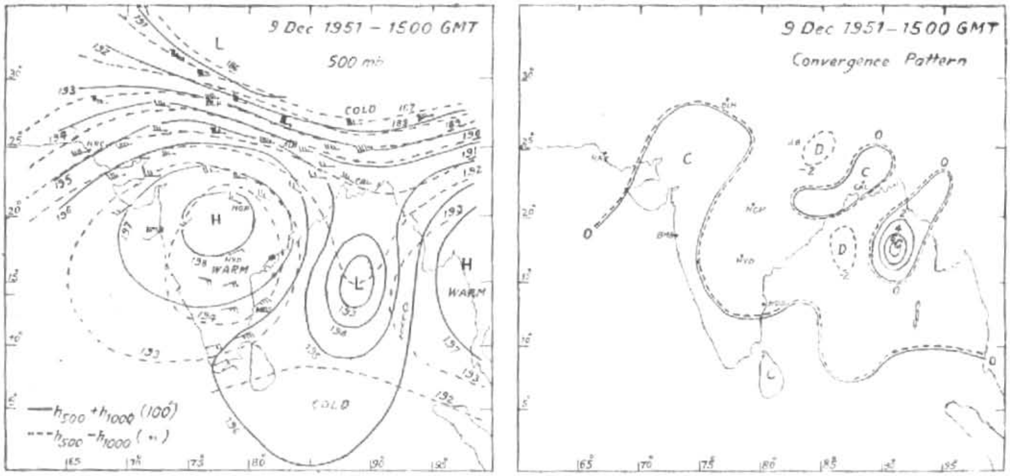

Fig. 13

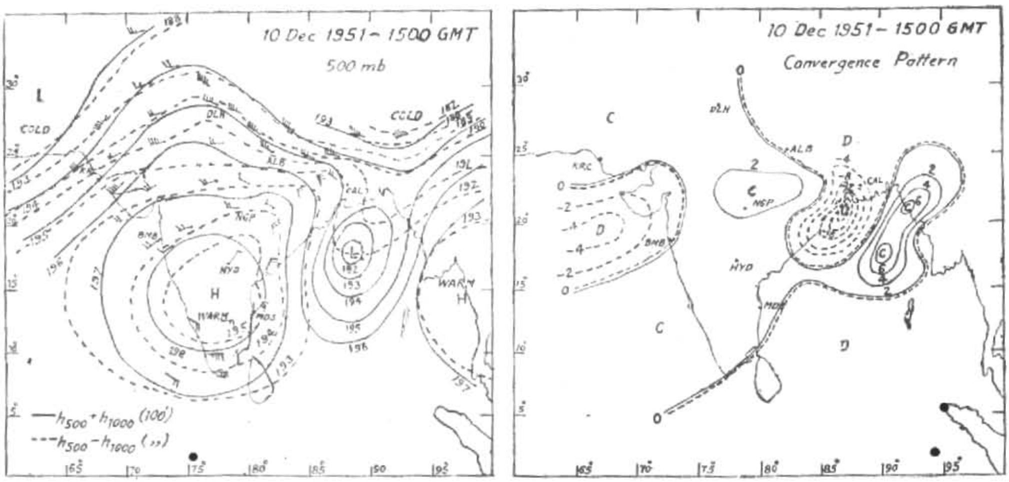

Fig. 14

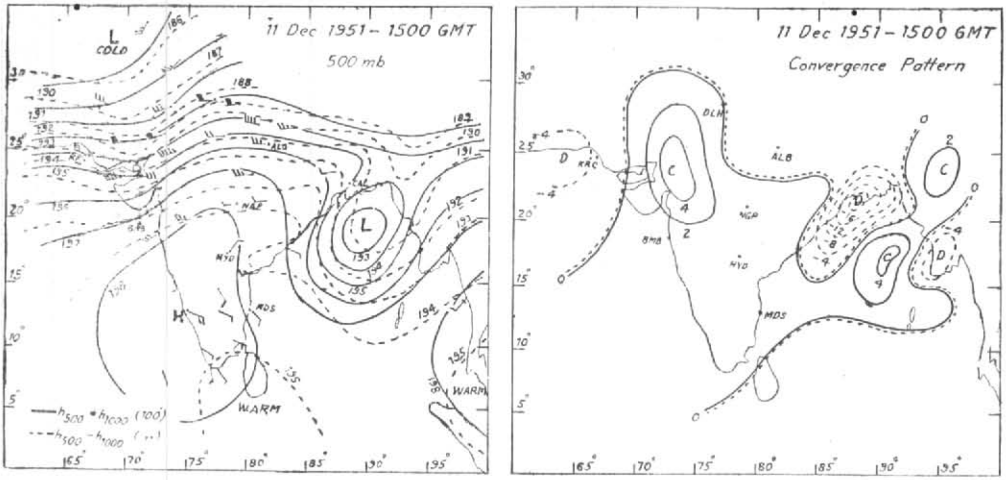

Fig. 15

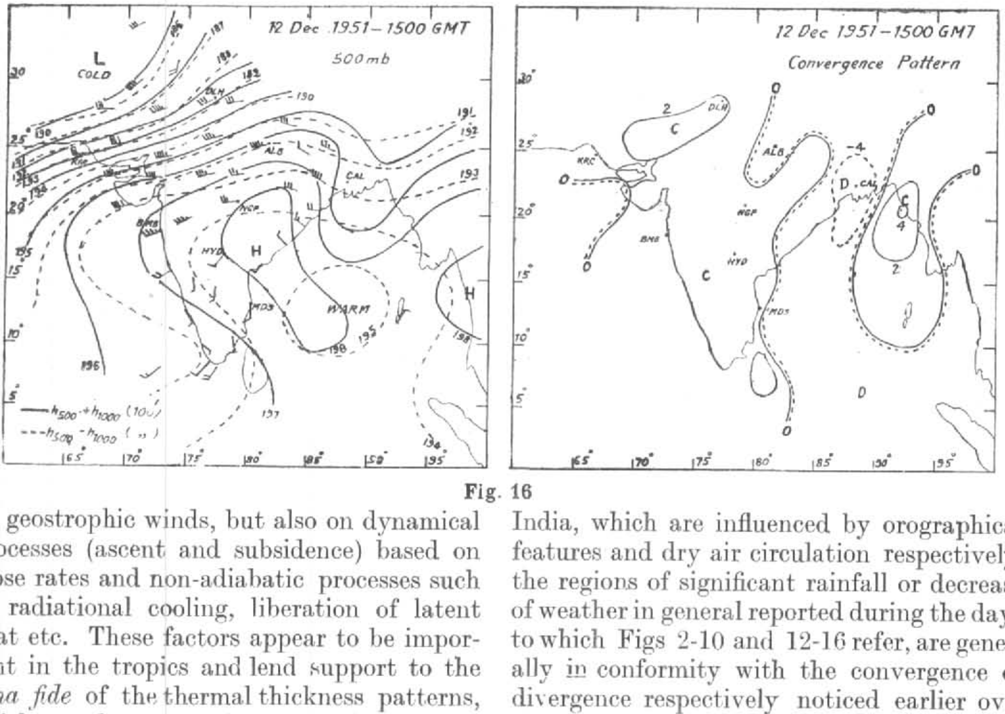

Fig. 16

on geostrophic winds, but also on dynamical processes (ascent and subsidence) based on lapse rates and non-adiabatic processes such as radiational cooling, liberation of latent heat etc. These factors appear to be important in the tropics and lend support to the *bona fide* of the thermal thickness patterns, which are also seen to be more or less conservative on the day to day charts. The above considerations suggest the overriding influence of the thermal thickness patterns over the development processes in the tropics as elsewhere.

Lastly, it may be mentioned as a fair proof of the validity of the analysis that, barring areas such as the Assam hill tracks and north India, which are influenced by orographical features and dry air circulation respectively, the regions of significant rainfall or decrease of weather in general reported during the days to which Figs 2-10 and 12-16 refer, are generally in conformity with the convergence or divergence respectively noticed earlier over the respective areas, as can readily be seen by a comparison of the patterns of 'development' with the weather elements reproduced on the 0300 GMT sea level charts given in the Indian Daily Weather Reports for the corresponding and/or succeeding days (December 1951 and May 1952).

4. Conclusion

The above analyses of three tropical disturbances in the Bay of Bengal, though too few to allow broad generalisations to be drawn from them, appear to show the utility of the thermal thickness patterns and the contour-thickness relationship observed on the 500-mb isobaric surface, together with the 'development' patterns obtained from them to be reckoned with as *an additional aid* over and above the symptoms on the usual synoptic charts for forecasting the life cycle of storms *even in the tropics.*

It may be seen, that the convergence associated with the disturbances during their developing stages (see Figs. 2-10 and 12-16) has occurred a little away from the surface centre of the cyclonic disturbances and that the sea level centre of the disturbance has moved in the gradient of convergence. It is also evident from the diagrams that, on most of the days, the convergence associated with cyclogenesis has occurred over the region in the warm moist sector, where the thickness lines climbed the pressure surface ; convergence can also be caused by the cyclonic shear of the actual winds, which, in a thermally symmetrical system, implies a similar shear of the thermal winds, even when the thickness lines are parallel to the contours over the warm sector. In either case, thermal steering of the storm centre at sea level appears to have been important, as stressed by Sutcliffe, although actual wind data over the depression field to prove the latter theoretical possibility of convergence are very meagre in the three cases studied.

Ramanathan and others (1930, 1931) have suggested that the warm moist winds at 4 to 6 km above the surface system are a valuable guide for deciding the direction of movement of the tropical depressions in the Bay of Bengal. The present study corroborates their conclusion in respect of cases in which the thermal winds at 6 km (500-mb surface) are in the same direction as the actual winds at that level, *i.e.*, whenever the winds over the concerned sector increases in speed with height up to 6 km, and at the same time, these winds have had cyclonic shear. In general, however, the thickness lines, or in other words, the thermal winds, in contradistinction to the contours or the actual winds at the 500-mb surface over the warm sector appear to have been primarily responsible for the steering of the surface low pressure systems, as illustrated in this paper.

5. Acknowledgement

I wish to express my grateful thanks to Dr. S. Mull, Director, Regional Meteorological Centre, Calcutta for his kind interest in the work and for affording all facilities for the above study. I am indebted to Mr. C. Ramaswamy, Meteorologist, for his inspiring guidance during the routine differential analysis of the constant pressure charts at the Meteorological Office, Calcutta Airport (Dum Dum). My warm thanks are also due to Mr. S. Mazumdar, Meteorologist, Calcutta (Alipore) for his helpful criticism of the manuscript of the paper.

REFERENCES

Desai, B. N. (1951). *Mem. Ind. met. Dep.*, **23**, Pt. 5.

Desai, B. N. and Koteswaram, P. (1951). *Ind. J. Met. Geophys.*, **2**, 4, pp. 250-265.

Berry, F. A., Bollay, E. and Beers, Norman R. (1945). *Handbook of Meteorology*, pp. 763-803.

Ibid, p. 819.

Hines, G. M. (1947). *Review of present methods of tropical forecasting*, Naval Met. Service, London.

Ind. Dly. Weath. Rep., Dec. 1951 and May 1952.

Ind. J. Met. Geophys. (1952). **3**, 2 and 4, pp. 148 and 295.

Malurkar, S. L. and Pisharoty, P. R. (1948). *Curr. Sci.*, **17**, p. 205.

Mull, S. and Desai, B. N. (1931). *Ind. met. Dep. Sci. Notes*, **4**, 39.

Petterssen, S. (1945). *Quart. J. R. met. Soc.*, **71**, 307-308, pp. 56-73.

Petterssen, S. and Priestley, C. H. B., Memorandum No. 2 (V.T.M. No. 2).

Ramanathan, K. R. and Narayana Iyer, A.A. (1930). *Ind. met. Dep. Sci. Notes*, **3**, 18.

Ramanathan, K. R. and Banerjee, H. C. (1931). *Ind. met. Dep. Sci. Notes*, **4**, 34.

Rateliffe, R. A. S. (1950). *Met. Rep.*, 8.

Roy, S. C. and Roy, A. K. (1930). *Beitr. phys. frei. Atmos.*, **16**, p 224.

Sawyer, J. S. (1947). *Quart. J. R. met. Soc.*, **73**, 315-316, pp. 101-126.

Sawyer, J. S. and Matthewman, A. G. (1951). *Quart. J. R. met. Soc.*, **77**, 334, pp. 667-671.

Sen, S. N. and George, C. A. (1952). *Ind. J. Met. Geophys.* **3**, 4, pp. 264-277.

Sutcliffe, R. C. (1947). *Quart. J. R. met. Soc.*, **73**, 317-318, pp. 370-383.

Sutcliffe, R. C. and Forsdyke, A. G. (1950). *Quart. J. R. met. Soc.*, **76**, 328, pp. 189-217.