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## On some aspects of the Tropical Cyclone of 20-29 May 1963 over the Arabian Sea

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**ABSTRACT.** This report discusses the development and structure of the Arabian Sea cyclone of 20-29 May 1963. The structure is discussed on the basis of special reconnaissance flights carried out by research aircraft of the U. S. Weather Bureau Research Flight Facility. Analyses of surface, 500-mb and 200-mb flow are used to illustrate the conditions associated with cyclone development and motion. They give, in addition, a good view of the circulation patterns during the transition from the pre-monsoon to the summer monsoon regime over the northern Indian Ocean.

The factors that seem to have influenced the development of this cyclone and the structure of the system during its life cycle were found to be quite similar to those in hurricanes in the Atlantic Ocean.

### 1. Introduction

During the years 1962 to 1964, a team of U. S. and Indian meteorologists, stationed at the International Meteorological Centre in Bombay, worked together in a program of analysis and research on Indian Ocean circulations, as part of the meteorology program of the International Indian Ocean Expedition (Ramage 1968). In connection with this program the research aircraft of the U. S. Weather Bureau, based in Bombay, carried out in the summer of 1963 a series of flights in the Arabian Sea and Bay of Bengal investigating various aspects of the weather circulations.

During the period 22-24 May 1963, the aircraft carried out two research missions into a tropical cyclone in the southeast section of the Arabian Sea. A flight on 22 May detected a cyclonic system with maximum winds of 60 knots and minimum central pressure of 984 mb in a position near 12°N-65°E (see Fig. 1). A second flight on 24 May revealed a more intense vortex with maximum winds of 100 knots and central pressure of

947 mb. A cyclone of such an intensity is labelled by the India Meteorological Department as a "severe cyclone", while in the Atlantic area it is labelled as a "hurricane" and in the Western North Pacific Ocean as a "typhoon".

This was the first aircraft reconnaissance of a tropical cyclone in the Indian Ocean and aroused considerable interest among meteorologists in India. The flights provided for the first time information on the inner structure of an Indian Ocean cyclone over water. The development of this cyclone also provided the group of U.S. meteorologists with the first opportunity to study at close range the formation and motion of an Indian Ocean cyclone.

The purpose of this report is to discuss the structure of the cyclone, with use of the aircraft data, and to illustrate some synoptic aspects of the circulation throughout the troposphere associated with its formation and motion. Attention is devoted also to the changes in circulation patterns associated with the initiation of the southwest monsoon regime of 1963.

For the study of the synoptic aspects of the circulation, charts at 12-hour continuity were available for various levels from surface to 200 mb, for the period 16–29 May 1963. More careful and complete analysis was carried out for the 24-hourly charts (1200Z) for the surface, 500 and 200-mb levels. Only a selection of charts, considered adequate to convey the pertinent aspects of the circulation, are illustrated here.

Streamline analysis was mainly used for all charts, although surface pressure charts were also studied. Most of the data available are included in the charts. Special comments on analysis and data problems are included later in the discussion.

The analysis and study of this situation was completed in Bombay in the fall of 1963 and winter of 1964. The first manuscript was prepared in 1964, but final preparation for publication was delayed for various reasons.

## 2. Synoptic history

The initial surface disturbance, which eventually developed into cyclone intensity, appeared first around 15 May 1963, as a weak cyclonic circulation near  $6^{\circ}\text{N}$ – $70^{\circ}\text{E}$  (Fig. 1), just north of the Maldivé Islands. The circulation was rather indefinite and the winds were light. There were widespread thunderstorm and shower activity and squally weather. The minimum pressure in the centre of the disturbance was about 1005 mb; pressure anomalies were about 2–4 mb below normal.

Fig. 2 shows the distribution of flow at the surface on 16 May, 1200Z, which is quite similar to the one in the previous day and is also to a large extent typical of the spring season. Anticyclonic centres are observed over the Arabian Sea and Bay of Bengal, with a broad belt of northeasterlies prevailing over the central Arabian Sea. The flow over northern India is essentially westerly; over the central and southern parts of the Peninsula there is a series of weak circulations, determined to some extent by local effects. The same is true also over the northwestern section of the chart.

The flow pattern in the equatorial belt is of special interest. North of the equator there is a major trough system, oriented in a general east-west direction, that extends from latitude  $5^{\circ}\text{N}$  on the east coast of Africa to latitude  $13^{\circ}\text{N}$  in the Indian Peninsula. Over the Bay of Bengal this trough is not too well defined. The cyclonic circulation of concern in this report appears embedded in this E-W trough, centered near  $7^{\circ}\text{N}$ – $70^{\circ}\text{E}$  and is

quite well defined by the available wind observations. Another cyclonic circulation analyzed near  $3^{\circ}\text{N}$ – $57^{\circ}\text{E}$  is not well supported by the data and was entered mostly on the basis of continuity. To the south of this trough there is a broad belt of westerlies straddling the equator and extending from the coast of Africa to the area south of India. Between this belt of westerlies and the southeast trades of the southern hemisphere there is another E-W oriented trough that extends along latitude  $3$ – $6^{\circ}\text{S}$  from the coast of Africa to Indonesia. Closed cyclonic circulations along this trough are indicated near longitudes  $68^{\circ}$ ,  $75^{\circ}$  and  $90^{\circ}\text{E}$ .

The analysis of the flow and weather distribution in the region to the south of India on 16 May was aided by a research aircraft mission between Bombay and Gan Island ( $1^{\circ}\text{S}$ – $73^{\circ}\text{E}$ ) (see reports along longitude  $72^{\circ}\text{E}$  in Fig. 2). The aircraft observations revealed a stronger equatorial westerly current than suspected. A belt of disturbed weather and winds of 35 to 40 kt at 2000 ft, was observed from the equator to about  $3^{\circ}\text{N}$ . This belt of strong winds was well to the south of the cyclonic centre and was apparently not directly associated with the perturbation itself.

This pattern of flow in the equatorial belt is quite typical in the Indian Ocean in spring and exists nearly every day. In summer the northern trough is displaced northward to northern India and the southwesterly current covers the Arabian Sea and the Bay of Bengal and Indian sub-continent forming the well-known southwest monsoon current. (The traditional interpretation of developments in the transition period from spring to the summer monsoon circulation is in terms of a displacement of the northern equatorial trough to northern India; however, a recent study by Raman (1967), claims that a trough system persists near the southern tip of India throughout summer and the trough along northern India forms there as a thermally induced system). In autumn and spring a pattern of troughs on each side of the equator, similar to the picture in Fig. 2, is usually present. In winter the southern hemisphere trough is generally displaced farther to the south than appears in Fig. 2 and provides the generating influence for tropical cyclone development in the southern Indian Ocean.

A similar pattern of flow exists also in other equatorial regions. In some areas, for example in the eastern Atlantic Ocean, the northern hemisphere trough is frequently located farther to the north and the clockwise turning zone between the southeast trades and the westerlies is located

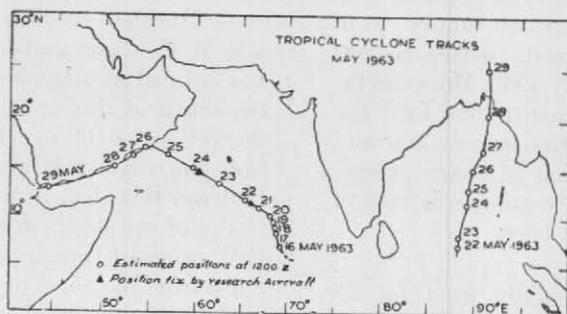


Fig. 1. Tracks of tropical cyclones of May 16-29, 1963 in the Arabian Sea and May 22-29, 1963 in the Bay of Bengal

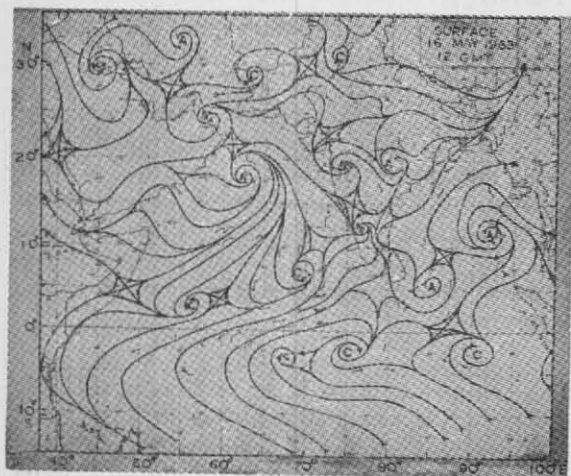


Fig. 2. Surface flow, 1200 Z, May 16, 1963

A stands for anticyclone and C for cyclonic centres, E stands for eddy circulation over or in close vicinity of equator

north of the equator, forming a ridge circulation rather than a trough.

The nomenclature in use for this system is rather confusing and controversial. Such terms as "Equatorial Convergence Zone", "Intertropical Convergence Zone", "Equatorial Trough Zone" and others have been used at times. There have been objections to the use of the word "convergence" since it is well established that convergence and associated disturbed weather do not always exist all along the trough. Furthermore, satellite cloud data has shown that frequently important cloud masses are associated with the westerly current and not with features along the trough (Sadler 1963). Regardless of the question of the propriety of the nomenclature, or whether the names applied conform to the physical processes involved, it is convenient and necessary that a name be adopted to refer to the system and that the name convey to the reader the correct notion of what one is talking about. For convenience, we shall refer to the northern hemisphere trough as the Northern Equatorial trough and to the southern one as the Southern Equatorial trough. This terminology may

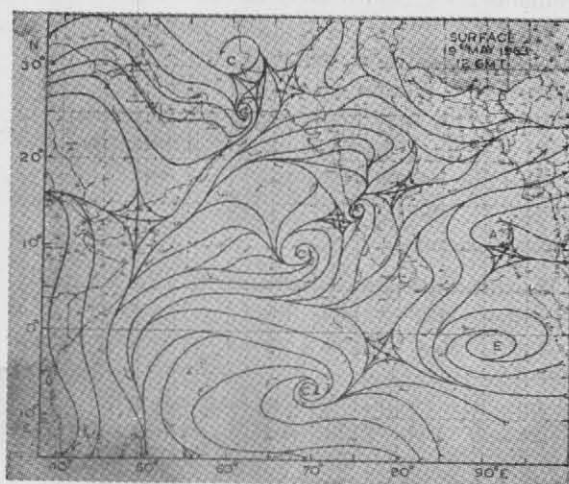


Fig. 3. Surface flow, 1200 Z, May 19, 1963

not be the most appropriate, but is convenient for the purpose in this discussion.

In the next few days the perturbation of interest moved slowly northward with gradual intensification. On 17 May (chart not shown) ship reports to the north and south of the perturbation indicated a somewhat stronger wind circulation; the central pressure was around 1004 mb. On 19 May (Fig. 3), the disturbance was centered near 9°N-69°E, with what can be labelled as "depression intensity". The northward drift of this system was accompanied by weakening of the anticyclonic centre in the north Arabian Sea and also a slight southward shift of the Southern Equatorial trough in the central part of the Indian Ocean. This brought about an increase in the area covered by the belt of equatorial westerlies.

A series of TIROS passes over the area gave excellent information on the weather distribution. TIROS observations on 19 May (Fig. 4) showed a very extensive mass of overcast cloudiness extending at least between longitudes 65° and 75°E and from latitude 15°N to about latitude 0-5°S.

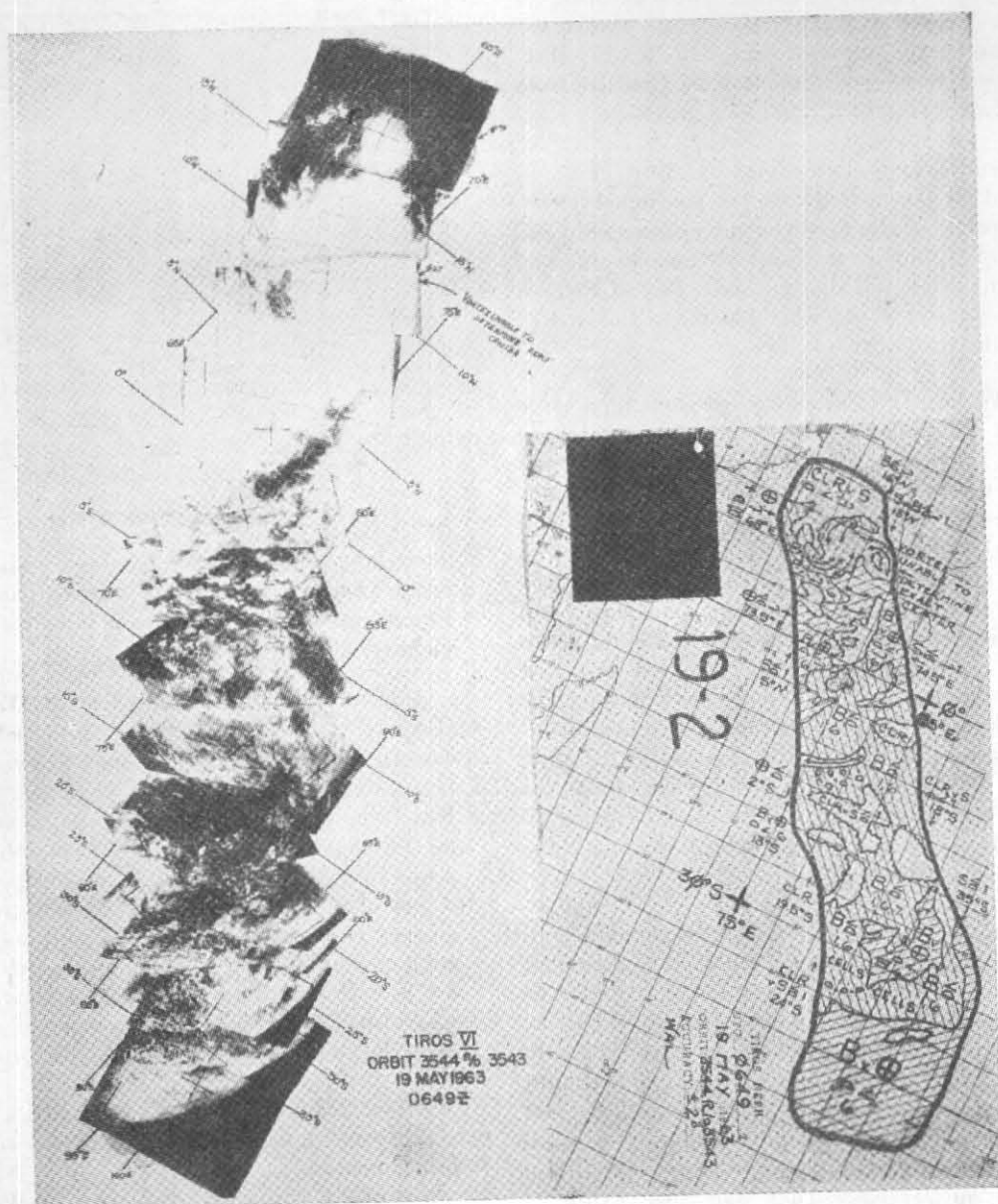


Fig. 4. Composite photographic representation of cloud distribution observed by TIROS VI on May 19, 1963. Orbit number and approximate time indicated in figure. The nephanalysis of the same cloud field transmitted by facsimile from the National Weather Satellite Center in Washington, D. C. is also shown.

Clear conditions existed north of latitude  $15^{\circ}\text{N}$ . Broken to overcast skies appeared over most of the belt between  $7^{\circ}\text{S}$  and  $12\text{--}15^{\circ}\text{S}$  and, at least, as far east as longitude  $90^{\circ}\text{E}$ . This zone of broken clouds covered a section of the southeast trades. Relatively clear conditions were observed between  $15^{\circ}\text{S}$  and  $20\text{--}25^{\circ}\text{S}$ .

Not all the mass of overcast cloudiness extending southward from latitude  $15^{\circ}\text{N}$  can be ascribed to the cyclonic perturbation of interest. Evidently, part of the cloud mass in the vicinity of latitude  $10^{\circ}\text{N}$  was associated with the perturbation (see

notes in TIROS NEPH chart, insert Fig. 4), but an observation of some interest is that the whole belt of westerlies was covered with clouds, which in the western edge of the picture extended well into the southern hemisphere. As mentioned previously, similar observations of extensive cloud masses associated with the equatorial westerly current were reported by Sadler (1963) in the eastern Pacific Ocean.

On 20 May (chart not shown) a north wind report of 30 kt by a ship on the western periphery of the

perturbation suggested further intensification to possibly cyclone strength, but no data was available close to the centre. From 20 to 21 May, there was a change in direction of motion from a north-northwest to a northwest course.

The surface circulation on 21 May (Fig. 5) indicated, in association with the continued northward motion of the perturbation, an eastward extension of the equatorial westerly current into the region of Ceylon and the southern Bay of Bengal. A weak cyclonic centre was defined to the east of Ceylon, in the southern Bay.

TIROS data (Fig. 6) continued showing a large mass of clouds extending from the equator to latitude 15°N. The perturbation was located near the eastern edge of the pictures in Fig. 6 and cannot be identified well in the cloud mass. The cloud distribution in the vicinity of the equator on 21 May (Fig. 6) indicated a complete separation between the cloudiness to north of the equator and the one to the south. The zone from about 1°N to 5°S was essentially clear; some isolated east-west oriented bands were visible near the equator. The whole belt of westerlies from the equator northward was covered with clouds, the same as on 19 May; most of it still apparently independent of the cyclonic perturbation. The main mass of clouds to the south of the equator coincided well with the Southern Equatorial trough.

In the analysis in the vicinity of the Southern Equatorial trough depicted in Figs. 2, 3 and 5, it is not possible to discern good continuity of the cyclonic cells embedded in the trough. With the inadequacy of the reports available it was extremely difficult to trace continuity and no attempt was made to follow each cell closely, since this part of the analysis was incidental and not too important for the main purpose of the study. It can be noted, nevertheless, that the few available reports defined the trough quite well and delineated its position within not too broad limits.

On 22 May the aircraft reconnaissance flight into the centre verified the existence of an intense and well organized cyclone. The aircraft observations, discussed in more detail in a later section, showed a circulation of near hurricane intensity, with maximum winds of 60 kt at 2000 ft and central pressure of 984 mb.

In the synoptic picture, the flow at the surface on 22 May (not illustrated) did not differ much from that shown in Fig. 5. With the northward motion and intensification of the cyclone the belt of westerlies continued expanding while the flow

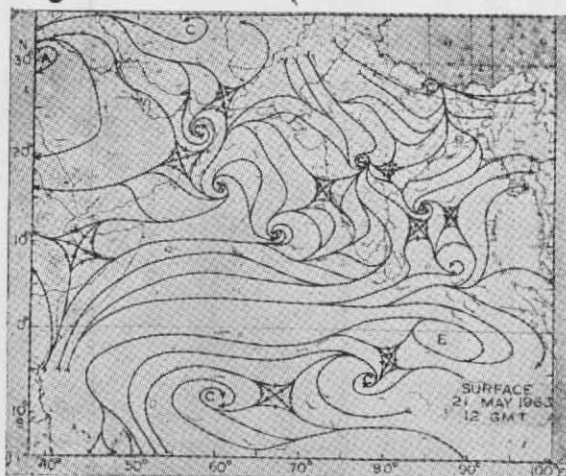


Fig. 5. Surface flow, 1200 Z, May 21, 1963

over the central Arabian Sea became better organized around the cyclonic vortex. The Southern Equatorial trough maintained its position in the vicinity of latitude 5°S.

Another TIROS path at about 0534Z, 22 May (Fig. 7), which unfortunately observed only the eastern half of the system, showed evidence of a better defined vortex formation in the cloud field. Fig. 7 shows also some further significant changes in the cloud distribution in the equatorial zone. Aside from the cloud mass of the cyclone there was a zone of clouds elongated east-west in the westerly current between 5°N and 10°N and another cloud zone in the southern hemisphere between 2°S and 4-6°S, with a distinct clear zone in between. There was also a significant decrease in the cloudiness over the southeast trades south of latitude 5°S.

After 22 May, the cyclone continued a northwest track over the central Arabian Sea with steady intensification, at a speed of around 8 kt. A second reconnaissance aircraft mission on 24 May (Fig. 8) revealed a fully developed severe cyclone with maximum winds of 100 kt and central pressure of 947 mb. With the continued intensification of the vortex, the surface flow over the Arabian Sea was influenced more strongly by the cyclone circulation and the southwesterly current spread northward, drawn by the vortex circulation. The chart for 24 May (Fig. 8) shows also the small cyclonic system in the Bay of Bengal, near 11°N-90°E. This system moved northward and intensified and eventually entered East Pakistan, as a severe cyclone, around 29 May.

The Arabian Sea cyclone struck the coast of Arabia near 17°N-55°E on 25 May and then recurved southwestward along the coast until it dissipated

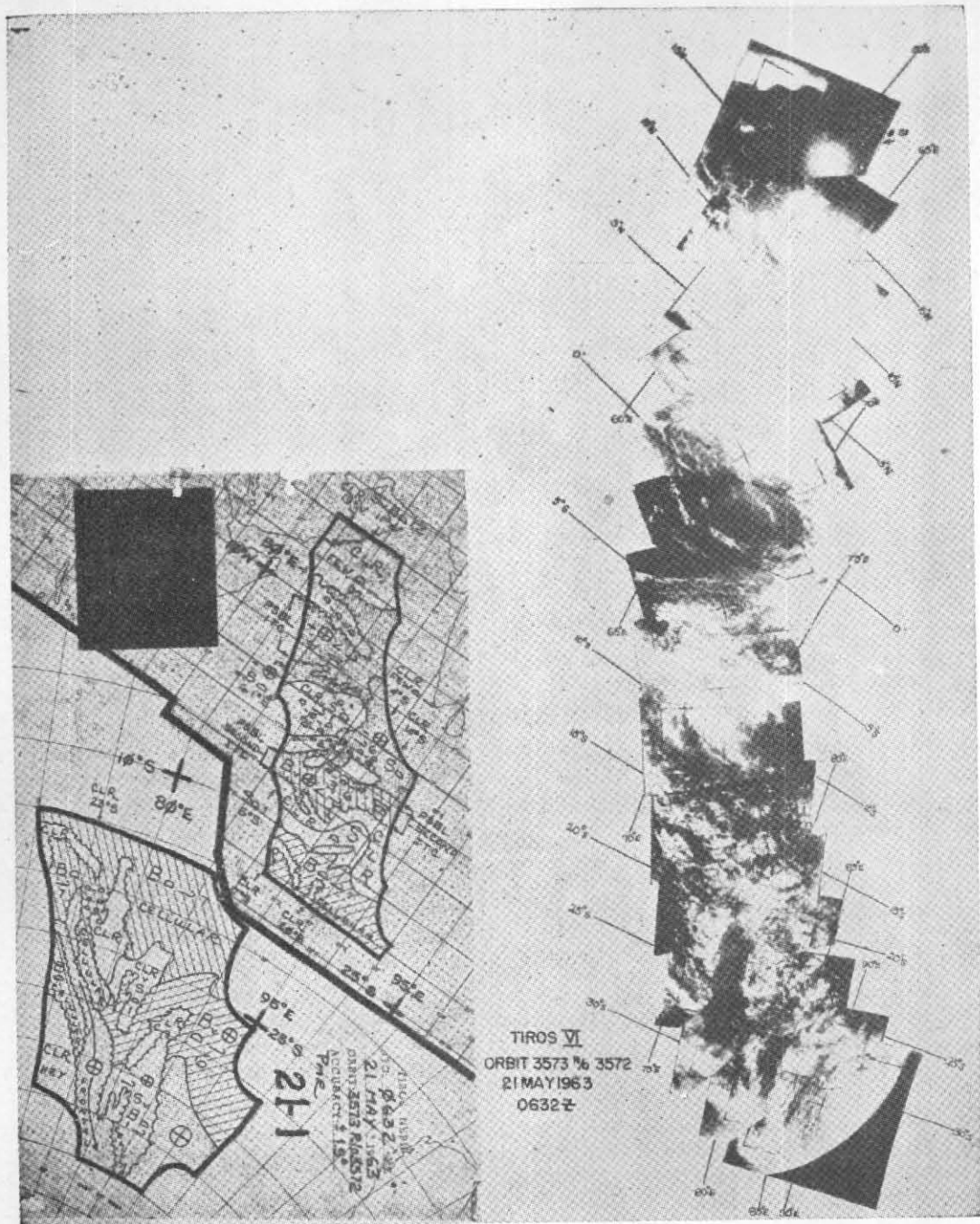


Fig. 6. Composite photographic representation of cloud field observed by TIROS VI on May 21, 1963

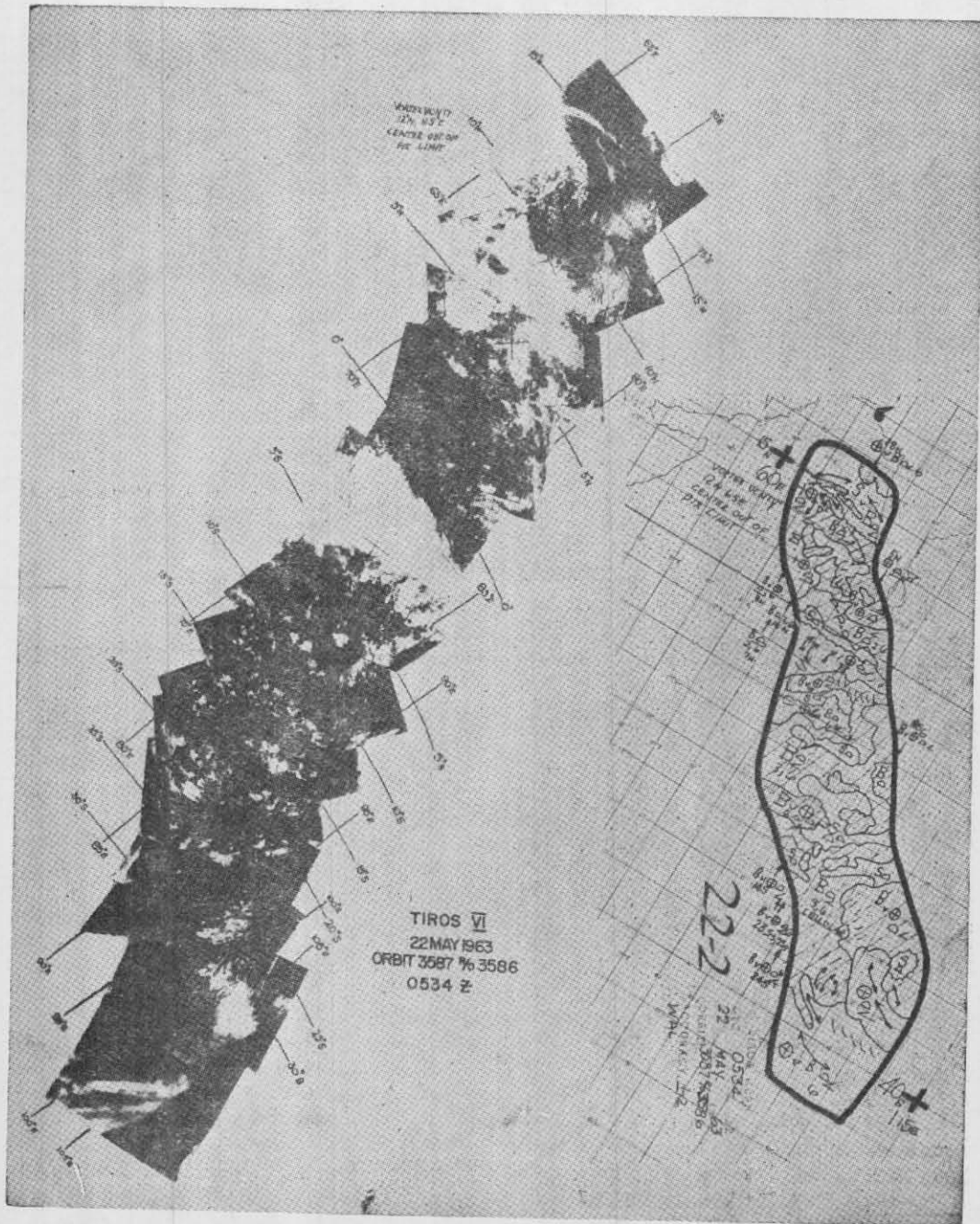


Fig. 7. Composite photographic representation of cloud field observed by TIROS VI on May 22, 1963

near Aden on 29 May (see Fig. 1). The surface picture for 26 May is shown in Fig. 9. The cyclone appears near  $17^{\circ}\text{N}$ - $54^{\circ}\text{E}$ , on the coast of Arabia. The flow in the western Arabian Sea is centered around the cyclone, but in the eastern part of the sea the southwest flow turns eastward into the trough in the western Bay of Bengal.

A comparison of the charts for 24 and 26 May (Figs. 8 and 9) with that for 16 May in Fig. 2 illustrates the profound change in circulation over the north Indian Ocean and Indian Peninsula triggered by the development and northward displacement of the cyclone. The flow in Fig. 9 depicts the typical summer monsoon circulation,

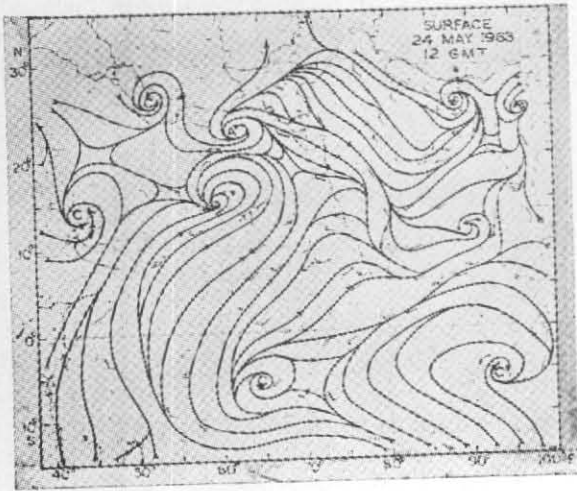


Fig. 8. Surface flow, 1200 Z, May 24, 1963

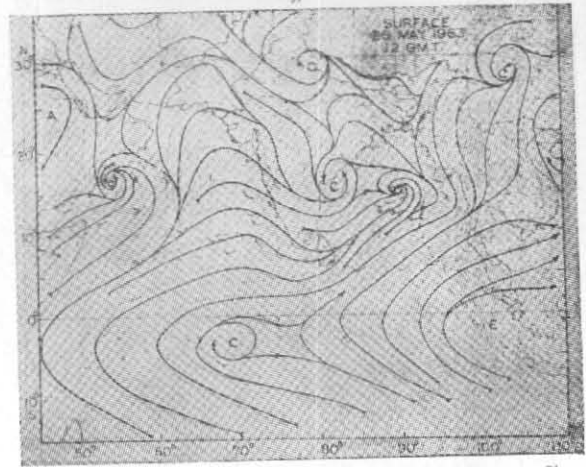


Fig. 9. Surface flow, 1200 Z, May 26, 1963

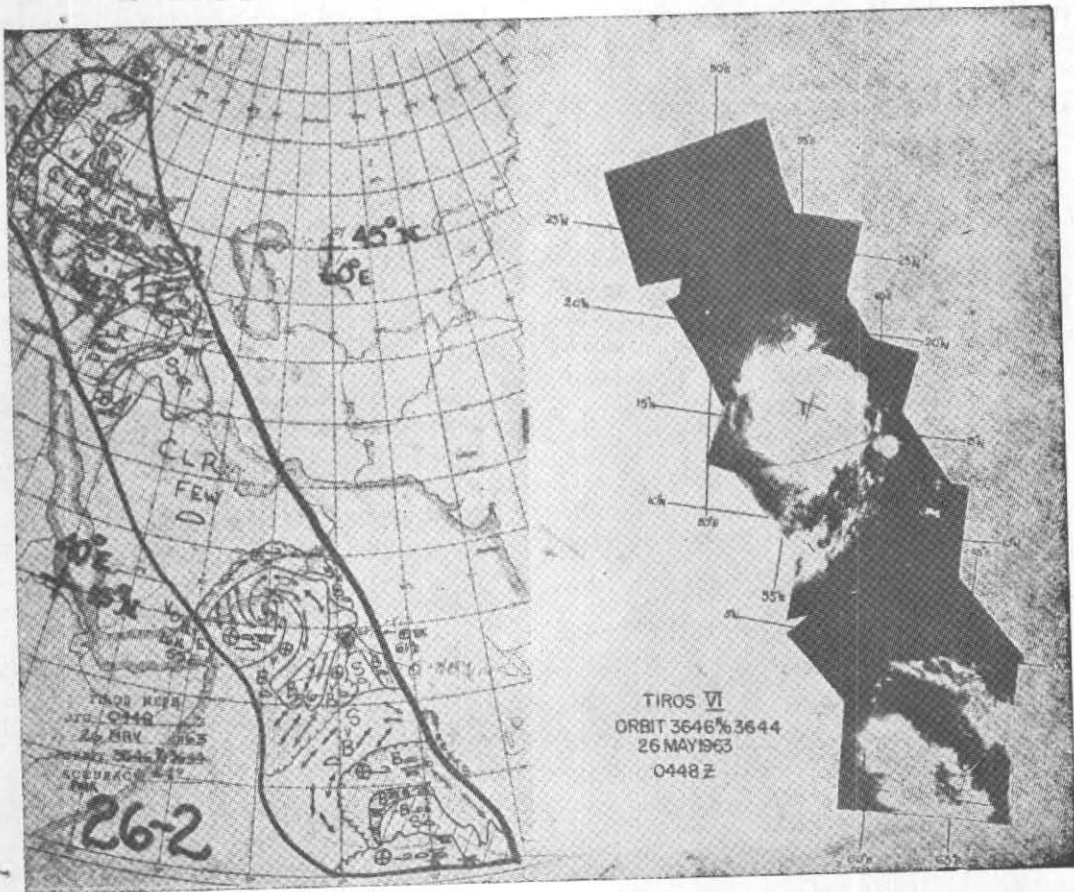


Fig. 10. Composite photographic representation of cloud field observed by TIROS VI on May 26, 1963



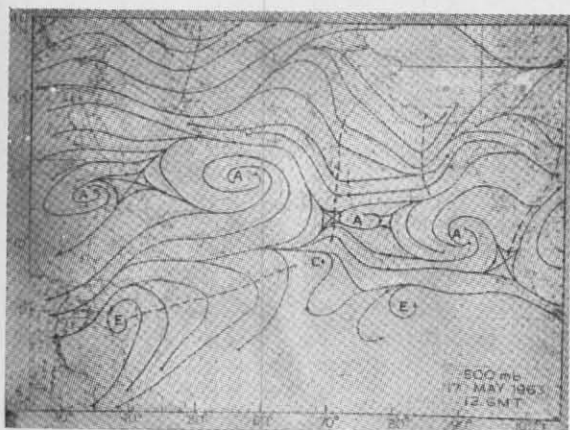


Fig. 11. Flow at the 500-mb level, 1200 Z, May 17, 1963

A stands for anticyclone, C for cyclone, E for eddy circulation  
Dashed lines delineate trough line



Fig. 12. Flow at the 200-mb level, 1200 Z, May 17, 1963

A complete view of the cloud mass of the Arabian Sea cyclone as seen by TIROS satellite was obtained on 26 May (Fig. 10). It shows a circular mass of 8 degrees-latitude in diameter. A centre is barely visible, but does not show the typical eye formation often seen in satellite photographs. On 26 May the cyclone had already been moving along the Arabian coast for at least 24 hours.

### 3. Flow patterns aloft and development and motion of the system

In studying the development of the cyclone and the conditions that may have influenced it, attention was devoted to two main points: the formation of the initial perturbation and the intensification to cyclone intensity. The initial perturbation originated on 15-16 May along the Northern Equatorial trough; the intensification to storm proportion occurred apparently around 20-21 May in the area near 10°N-67°E.

The scarcity of observations made the analyses at upper levels extremely difficult and uncertain. During the period 16-22 May 1963, we were fortunate in securing a series of reports from aircraft flying the routes Aden (13°N-45°E) to Gan (1°S-73°E) and Gan to Singapore (1°N-104°E), at middle and high levels, which were of invaluable help in arriving at an analysis in which we could place some confidence of it being realistic. Some flight reports were also available from commercial aircraft in the routes over the northern section of the Arabian Sea and the Bay of Bengal. The experience on this series indicated to us the dangers of drawing streamlines over the equatorial areas of the Arabian Sea based solely on wind reports from land stations on both sides of the sea.

Several upper levels were analyzed, but attention was devoted mainly to the 500 and 200-mb levels. These are the levels most commonly used in the Atlantic area to forecast hurricane motion and intensification. The flow at 200 mb has been found useful for determining conditions favourable for development, while the 500-mb flow has been found to be useful in forecasting motion. The upper level charts illustrated here are not all for the same dates as for the surface. The availability of data over the oceanic areas was partly used as a criteria for the selection of illustrations, and the dates with the best upper air data did not exactly coincide with those selected for the surface. This should not hamper the reader in interpreting the circulation changes throughout the troposphere.

The flow distribution at 500 mb at the beginning of the period is well illustrated by the chart for 17 May (Fig. 11). Westerlies dominated the region north of latitude 18°N, with major trough located along longitude 50°E and over India. The subtropical ridge line extended WNW-ESE from Ethiopia to Thailand, with major anticyclones over Africa, west Arabian Sea and Bay of Bengal. Easterlies prevailed over the equatorial section of the Northern Hemisphere. A series of inflight reports in a flight between Aden and Gan Island (1°S-73°E) were of considerable assistance in defining the flow over the south Arabian Sea. These reports show an ENE-WSW oriented trough located just north of the equator and extending from the location of the cyclonic perturbation in the southeast section of the Arabian Sea to a counterclockwise eddy over the equator in Africa.

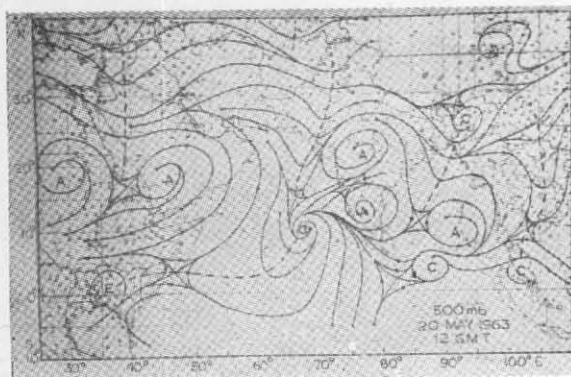


Fig. 13. Flow at the 500-mb level, 1200 Z, May 20, 1963

At 200 mb (Fig. 12) the flow over the tropics was characterized by cellular cells and appeared to be chaotic, but the following major features could be detected:

(a) A belt of westerlies, influenced by middle latitude circulations, north of latitude  $25^{\circ}\text{N}$ ; with main troughs located near longitude  $45^{\circ}\text{E}$  and over India.

(b) A ridge zone, split into a series of small anticyclones, extended approximately along latitude  $20^{\circ}\text{N}$  from Ethiopia to northern Burma.

(c) Immediately to the south there was an east-west oriented trough with cyclonic centres over the eastern Arabian Sea, western Bay of Bengal and over northern Thailand. This trough was a characteristic feature of the upper level flow during the early part of the series and for convenience in the discussion it will be referred to as the tropical E-W trough.

(d) South of this trough there was a second E-W oriented ridge zone extending along latitudes  $5\text{--}10^{\circ}\text{N}$  from the Arabian Sea to Malaysia. It was not well defined over the east coast of Africa.

(e) South of latitude  $5^{\circ}\text{N}$ , there was a belt of easterlies. A series of small anticyclones and weak N-S oriented troughs were observed to travel westward in these equatorial easterlies.

Most of the features in both the 500 and 200 mb charts were documented by the available data, but it would be possible to change some details of the analysis without violating the data. Continuity and data at intermediate maps were taken into consideration in the analysis.

The tropical E-W trough at 200 mb is of special interest. A somewhat similar feature is common

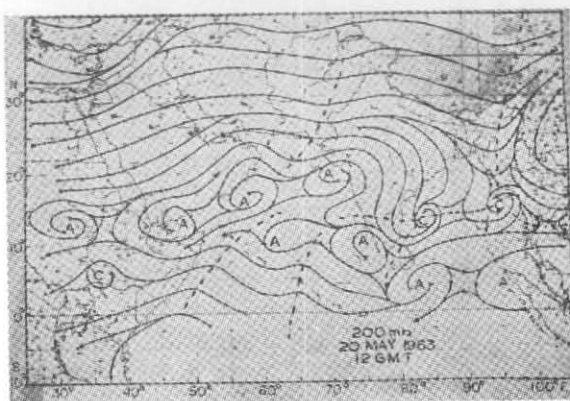


Fig. 14. Flow at the 200-mb level, 1200 Z, May 20, 1963

over the Atlantic and Pacific Oceans in summer. The equatorial trough at 500 mb is also an interesting feature of the circulation; it appears to be a reflection of the one at the surface, and is not present at the 200-mb level. The mean monthly charts from April to June, presented by Raman and Dixit (1964), suggest that the establishment of this 500 mb trough over the south Arabian Sea is one of first signs of the change over it to the summer monsoon circulation.

From 17 to 20 May the major features of the flow patterns depicted in Figs. 11 and 12 did not show much change. On 18 May at 500 mb (chart not shown) wind shifts to northwest were observed at both Gan and Minicoy Islands, ( $8^{\circ}\text{N}\text{--}73^{\circ}\text{E}$ ), indicating strengthening of a N-S oriented ridge line along longitude  $73^{\circ}\text{E}$ , just to the east of the cyclonic perturbation. The equatorial trough continued in about the same position. In the westerlies in the northern section of the chart the troughs continued progressing eastward.

The next charts shown (Figs. 13 and 14) are for 20 May. At the 500-mb level (Fig. 13), aircraft reports in a flight Aden to Gan, plus a shift to southerly winds at Gan and Minicoy indicated a more pronounced cyclone system in the southeastern Arabian Sea. A rather intense westerly trough was located along longitude  $70^{\circ}\text{E}$  and extended southward toward the cyclonic system in the eastern Arabian Sea. This trough had moved eastward from a position at longitude  $50^{\circ}\text{E}$  on 17 May. Anticyclonic flow was present over western India and another deep N-S trough appeared over the Bay of Bengal. The equatorial trough persisted over the southwest Arabian Sea joining the Arabian Sea cyclone with the

counterclockwise eddy that persisted near the equator over Africa.

At the 200-mb level on 20 May (Fig. 14) aircraft reports over the south Arabian Sea showed evidence of westward motion of the weak N-S troughs in the equatorial easterly current. The trough located near longitude  $65^{\circ}\text{E}$  is the same located near longitude  $80^{\circ}\text{E}$  on 17 May; while the one oriented NE-SW near longitude  $50^{\circ}\text{--}55^{\circ}\text{E}$  makes good continuity with one located near longitude  $65^{\circ}\text{E}$  on 17 May. The motion of these troughs was also supported by the wind changes at Minicoy. In the extratropical westerlies motion of troughs eastward was observed; the trough located near longitude  $70^{\circ}\text{E}$  made good continuity with the one located at longitude  $45^{\circ}\text{E}$  on 17 May. The other major features of the circulation—the subtropical ridge, tropical E-W trough and tropical ridge—can be identified in Fig. 14 with only slight changes in position. Cyclonic centres embedded in the tropical E-W trough were observed progressing eastward; centres are shown in Fig. 14 over the west and east sections of the Bay of Bengal.

On 17 May (Fig. 12) the 200-mb analysis showed the position of the surface perturbation underneath easterly flow on the south side of an upper anticyclone; on 20 May (Fig. 14) the surface perturbation was also located underneath easterly flow on the south side of the ridge line or southwest side of an anticyclone.

After 20 May, no more aircraft reports were available at 200 mb over the Arabian Sea; the analysis, therefore, became very uncertain. Fig. 15 shows the 200 mb chart for 21 May, analyzed over the Arabian Sea on the basis of continued westward motion of perturbations. With this westward motion, and on the basis of the winds at Gan and Minicoy an expansion of the anticyclone was indicated. The reports over south India on this and later maps also supported the analysis. The surface perturbation appeared then underneath the western side of the anticyclone and east side of the trough. On that day the system was probably on the stage of intensification to cyclone proportions.

In spite of the limitations in the data, it appears that the gradual development from 16 to 20 May and the more rapid intensification to cyclone strength which evidently took place around the 21st, were associated with anticyclonic flow aloft. Such an association has been found to be a necessary condition for development by various researchers (Desai and Rao 1954,

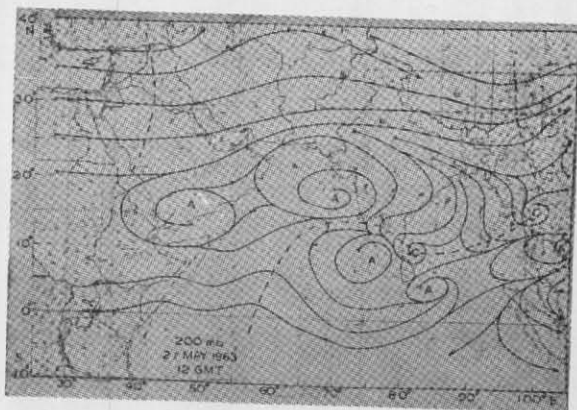


Fig. 15. Flow at the 200-mb level, 1200 Z, May 21, 1963

Koteswaram and George 1957, Yanai 1964). Furthermore, as suggested by the 200-mb flow on 20 and 21 May (Figs. 14 and 15), intensification to cyclone intensity took place while the surface system was under the western side of the upper anticyclone, which has also been found to be favourable for intensification (Ramage 1959; Colon and Nightingale 1963). Another point of interest in regards to the intensification to cyclone intensity was that it did not occur until the system had moved  $10^{\circ}$  away from the equator. Cyclogenesis at positions closer to the equator has been recorded, but is a rare occurrence.

It appears also that the initial development of the perturbation around 15-16 May occurred in association with a regime of travelling perturbations aloft moving westward in the easterly current near the equator.

From the point of view of operational forecasting, the motion of this cyclone did not offer difficult problems. There were two important changes in the direction of motion from NNW to WNW around 20 May and, a more interesting and unusual one from NW to SW on 25-26 May. The problem of predicting hurricane motion can be reduced to that of ascertaining the characteristics of the basic current in which the system is embedded and to foresee how these properties will change with time. The basic current is generally represented by a layer of the troposphere rather than by a single level. However, over the Caribbean area certain levels, for example, 700 and 500 mb, have been found to depict well the properties of rather thick representative layers of the troposphere that are important in relation to hurricane motion.

In the case of the cyclone under study the scarcity of data made it difficult to identify

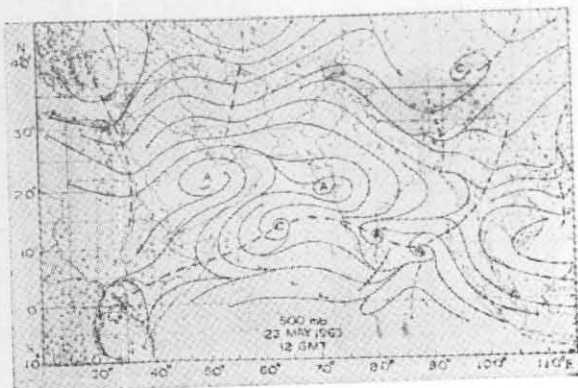


Fig. 16. Flow at the 500-mb level, 1200 Z, May 23, 1963

properly the layers that provided the main steering. In the initial period, prior to 20 May the system drifted slowly northward, apparently steered by the flow at low levels. The 500 mb charts for 17 and 20 May (Figs. 11 and 13) suggest a prevailing net southerly flow in the area surrounding the surface cyclone. There seemed to exist also a northward effect acting on the whole Northern Equatorial trough system.

On 20 May the 500-mb flow (Fig. 13) showed well pronounced anticyclones over Arabia and India with the ridge line over the Arabian Sea near latitude  $15^{\circ}$ - $20^{\circ}$ N, well to the north of the cyclone position. The anticyclonic cells over the Indian Peninsula had built up during the previous 48 hours (see also Fig. 11). One doubtful feature in the analysis is the precise nature of the flow in the oceanic area just to the north of the cyclone. The analysis shows pronounced cyclonic turning in the flow in the N-S trough that extends southward in the central Arabian Sea. However, it appears quite evident that the E-W ridge is located at least about  $5^{\circ}$  latitude north of the cyclone position.

In map discussions carried out in the Bombay analysis centre at the time, the forecasters anticipated a probable motion with a more westerly component than had been observed in the previous days. This forecast was based on the position of the ridge line well to the north of the cyclone, and expected continued eastward motion of the N-S trough. As mentioned previously the trough had moved steadily from a position near longitude  $50^{\circ}$ E on 17 May to the position near west India indicated on 20 May. The expected eastward motion of the trough would indicate a strengthening of the E-W ridge.

On the following day, 21 May, the system showed motion toward the northwest, while the

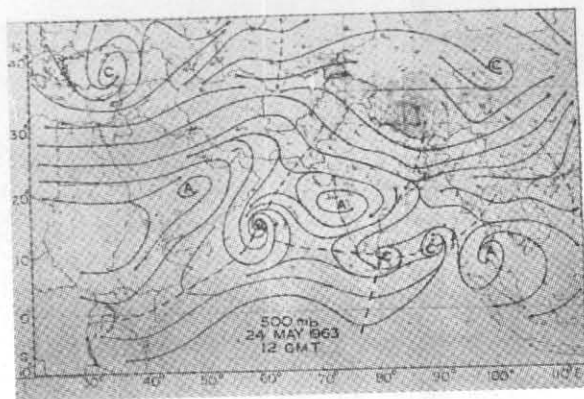


Fig. 17. Flow at the 500-mb level, 1200 Z, May 24, 1963

circulation at 500 mb (not illustrated) indicated strengthening of the anticyclone and ridge line to the north of the cyclone. After 21 May a continued northwestward track became more evident. The 500-mb chart for 23 May (Fig. 16) shows the cyclone embedded in a fairly strong trough that extended E-W across the Arabian Sea and south India. The ridge line appears along latitude  $20^{\circ}$ N with anticyclones over Arabia and west India. The N-S trough was then located over east India. On 24 May (Fig. 17) observations from the reconnaissance aircraft provided a good centre-fix on the cyclone and confirmed the northwestward motion. The 500-mb circulation showed an intense and extensive cyclonic system still associated with the equatorial trough. The winds over south India and Ceylon showed the E-W trough across the southern tip of the Peninsula, in a position farther to the south than in the preceding day. The trough over the southwest Arabian Sea (Fig. 17) was drawn following continuity from the previous day.

An interesting aspect of the flow in Fig. 17, also evident in Fig. 16, is the pronounced northeasterly flow over the Arabian coast ahead of the cyclone. The 30-kt wind at Aden suggested the presence of a rather strong current. This anticyclone over Arabia was maintained in a quasi-stationary position through the whole period since 17 May (see Figs. 11 and 13). During 24 and 25 May it appeared evident that the flow over the Arabian coast would have a pronounced effect on the cyclone motion. In the map discussions held at the Bombay centre, the implication of the persistence of the anticyclone ahead of the cyclone track, and a possible change in track toward the left (or southwest) was brought to attention. The maintenance of the ridge line about  $5^{\circ}$ - $10^{\circ}$  latitude to the north of the cyclone and absence of any intense troughs

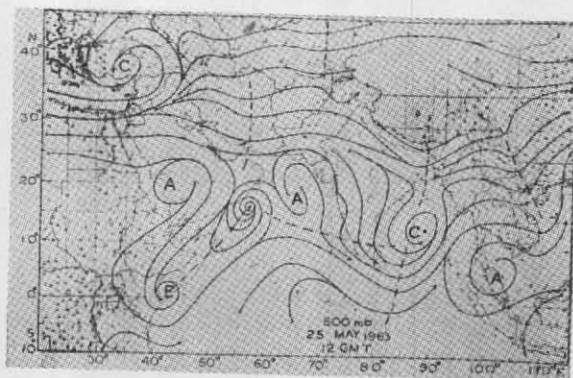


Fig. 18. Flow at the 500-mb level, 1200 Z, May 25, 1963

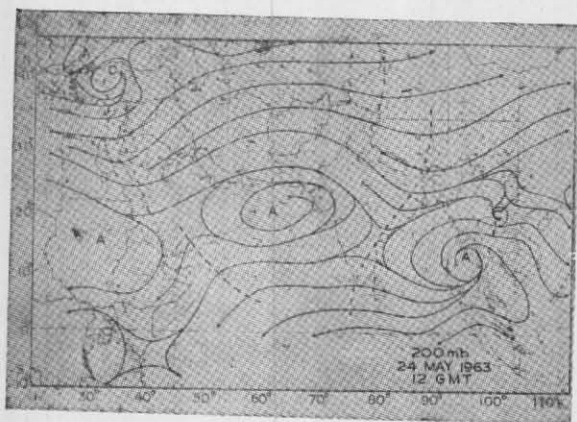


Fig. 19. Flow at the 200-mb level, 1200 Z, May 24, 1963

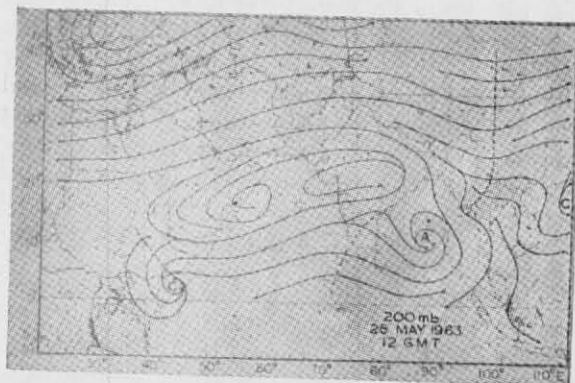


Fig. 20. Flow at the 200-mb level, 1200 Z, May 26, 1963

in the westerlies (see Figs. 17 and 18) made a turn toward the north more unlikely. The cyclone struck the coast of Arabia late on 25 May and then took a southwesterly course. It continued a southwestward drift along the coast.

At the 200-mb level the data over the oceanic area was quite scarce after 20 May and it was quite difficult to evaluate the influence, if any, of the flow at that level on the cyclone motion. The circulation pattern shown in Fig. 15, with anticyclones over Arabia, the north Arabian Sea and over the Indian Peninsula; and an E-W trough over south India, was maintained until 23 May; the analysis was based mainly on continuity supported by winds over the Indian Peninsula. By 24 May (Fig. 19) the available winds over India suggested the disappearance of the south India anticyclone and the establishment of a broad easterly current over the central and south Arabian Sea. The flow over the cyclone is drawn in the broad synoptic scale and mesosynoptic scale circulations that undoubtedly existed over the

cyclone are ignored. By 26 May (Fig. 20) the establishment of the easterly current was more evident. It does not appear from Figs. 19 and 20 that the 200-mb flow had much influence in the turn of the cyclone track from NW to SW.

One other factor that perhaps had a significant bearing on the behaviour of the cyclone was the topography over the Saudi Arabian coast. There is a fairly large mountain range near the coast, with the 1200-ft contour starting a few miles inland from about 20°N southwestward and then a gradual increase in height to about 6000-9000 ft in the vicinity of Aden. The effect of terrain on storm movement has been discussed occasionally in the literature.

No direct information on the intensity of the cyclone was obtained after 24 May, but the few reports available indicated a well organized and strong circulation until at least 28 May. TIROS data showed a well defined circulation on 26 May (Fig. 10). A 60-kt surface wind was reported on the east side of the cyclone on 28 May. The cyclone finally dissipated near Aden on 29-30 May.

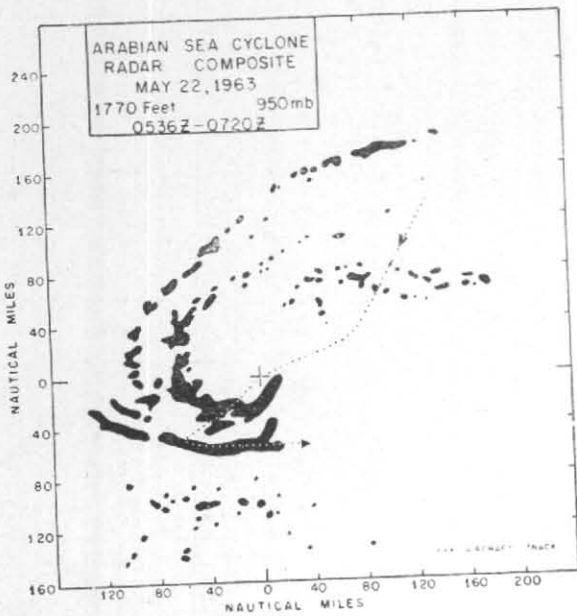


Fig. 21. Radar composite for Arabian Sea cyclone, May 22, 1963 (0536-0720 Z)

Dotted line indicates aircraft path during period of observation. Top of the chart is north. Cyclone was moving in a direction 300° at 8 knots

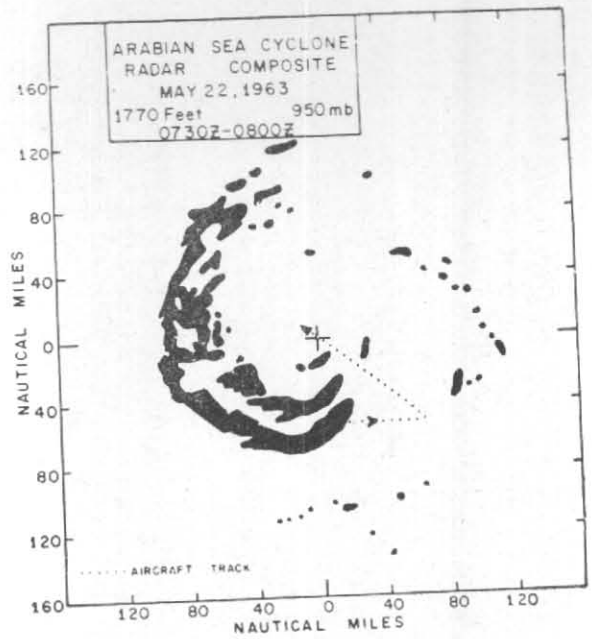


Fig. 22. Radar composite for Arabian Sea cyclone, May 22, 1963 (0730-0800 Z)

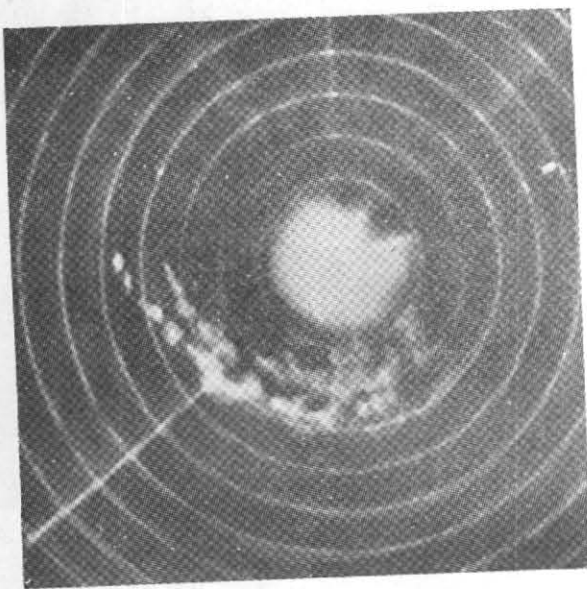


Fig. 23. Photograph showing main radar bands of Arabian Sea cyclone at 0800 Z, May 22, 1963. Top of the photograph is north. Range markers are 20 miles apart. Photograph taken by U.S. Weather Bureau research aircraft flying at 2000 feet

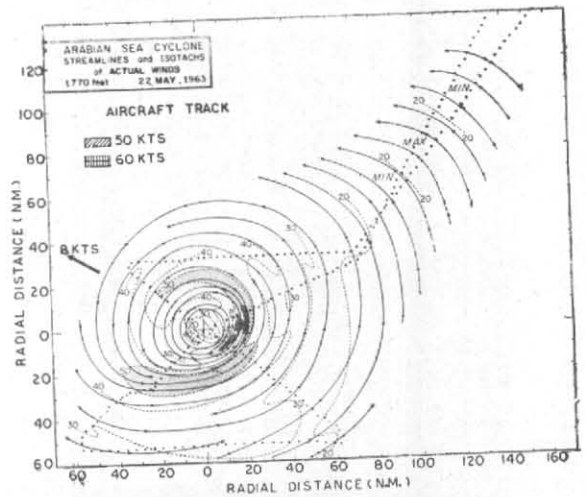


Fig. 24. Horizontal wind field at 1770 feet (950 mb), May 22, 1963

Streamlines in solid, isotachs (knots) in short dashed line. Dotted path shows track of the aircraft relative to the storm centre. Heavy arrow at left indicates the cyclone motion. Shaded areas indicate speeds above 50 and 60 knots.

#### 4. Structure of the cyclone—22 May

As mentioned previously, the investigation of this cyclone by reconnaissance aircraft was the first that had ever been carried out in Indian Ocean cyclones. Data collected at land stations have revealed many details of the structure of these systems as they enter land, but over water, only the surface structure as revealed by ships' observations has been available (Koteswaram and Gasper 1954). Although one would expect tropical cyclones in all areas to have the same basic characteristics, it is necessary to verify that that is actually the case. It is also important to establish that whatever principles are developed on cyclone theory in a given ocean, are valid also for those in other areas.

The flight on 22 May 1963 was made at an altitude close to 2000 ft. The aircraft flew out of Bombay and approached the cyclone from the northeast. It made two passes across the centre, from NE to SW and from SE to NW in a track shown in Fig. 24. This investigation fixed the circulation centre quite well and gave a representative view of the distribution of properties around the centre. The wind, temperature and radar data were positioned relative to the centre of the wind circulation. The data were analyzed in a composite horizontal field and also in radial profiles. The temperature data was adjusted to a reference level of 1770 ft (950 mb). This is normally done in order to eliminate temperature changes due to the vertical oscillations in the aircraft motion and emphasize the horizontal gradients. Information on the processing of the RFF aircraft data in hurricanes is given in various reports from the National Hurricane Research Project in Miami, Florida (Hilleary and Christensen 1957, Hawkins *et al.* 1962, Reber and Friedman 1964).

(a) *Radar field*—Two composite views of the distribution of radar echoes are shown in Figs. 21 and 22; the first was composited from pictures obtained (by APS-20 radar) from 0635 to 0730Z in the path from NE to SW across the centre and from W to E about 50 miles to the south of the centre (throughout this discussion the term "miles" refers to nautical miles). The second was composited from data recorded in the SE to NW penetration.

There were two main bands associated with the cyclone (Figs. 21, 22, 23); they spiraled sharply from the northeast, around the west, south and southeast sides of vortex. This picture in many ways resembles what has been observed in young formative storms on the Atlantic area, but an interesting feature of this radar distribution is that the bands were located in the left and front

quadrants of the circulation, with a radar-void sector on the right and right rear quadrants. In tropical storm development in the trade wind belt of the Atlantic Ocean, it is more common to see the main bands curving around the centre on the right side of the circulation. In developments in the Western Caribbean Sea and Gulf of Mexico radar distributions like in Figs. 21 and 22 are sometimes observed.

The most important portions of the bands were located a short distance to the southwest and south of the circulation centre. In the second path across the centre, approaching from the southeast quadrant, the two bands appeared to be closer to each other and farther away from the circulation centre (Fig. 22) than in the first penetration. Another interesting variation was the tendency for development of a third band in a position inward from the others. Fig. 22 shows also the tendency for the isolated echoes about 100 miles away from the centre on the east side to be oriented in a continuous line curving around the centre.

(b) *Wind field*—The low level wind field (Fig. 24) showed a band of maximum winds over 50 kt extending in a slightly spiralling configuration around the rear and right semicircles. The radial position of this band varied considerably in the different quadrants. On the right side, it was located between the 15 and 25-mile radii; on the left side between 30 and 40 miles, on the rear side between 10 and 25 miles and on the forward side between the 25 and 30-mile radii. The strongest measured winds were about 62 kt on the right rear sector of the circulation. This distribution is quite similar to what has been observed in developing young storms in the Atlantic area.

On the right side of the circulation the winds were nearly constant at about 20 kt from the outer edge of the data at the 200-mile radius to about the 60-mile radius (*see* Fig. 26). In the sector from the 110 to 140-mile radius the flow was slightly higher than in the inward and outward vicinities; these slightly higher speeds were recorded while the aircraft was crossing a radar band. Inward from the 70-mile radius the speed increased steadily to a peak maximum of 60 kt at the 20-mile radius; then the winds decreased sharply in strength to a minimum in the centre of the circulation. In the left semi-circle there was a minor maximum recorded near the 5-mile radius and a major zone of stronger winds at the 35 to 40-mile radius.

On the rear side of the storm (Fig. 27) winds of 20 kt were recorded outside the 60-mile radius.

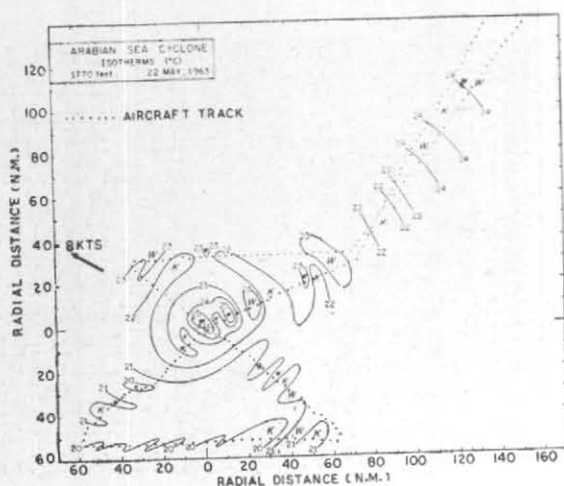


Fig. 25. Temperature field at 1770 ft (950 mb), May 22, 1963

W stands for warmer, K for colder. Dotted path shows track of aircraft relative to centre. Heavy arrow at left indicates cyclone motion

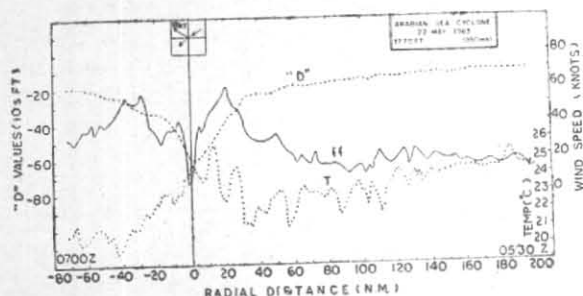


Fig. 26. Data profile (D-values, wind speed & temperature) at 1770 ft (950 mb), May 22, 1963

Small insert at top is a horizontal diagram showing the approximate path of the aircraft (dashed) and the cyclone motion (solid). The same format is followed in all profiles illustrated

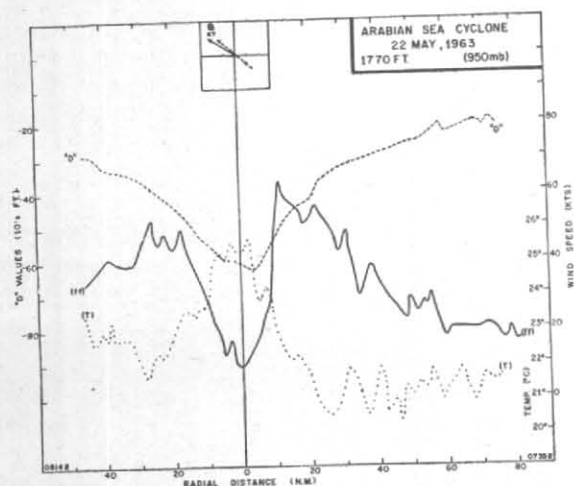


Fig. 27. Data profile at 1770 ft (950 mb), May 22, 1963

The stronger winds, around 62 kt, were recorded in a peaked maximum at the 12-mile radius. The winds were rather weak in a larger area around the circulation centre than was recorded in the earlier penetration through the eye. This suggested an elliptical eye elongated along the direction of motion. On the forward side (Fig. 27) there was a broad zone of maximum flow, close to 50 kt. No penetration was made into the rainbands located from the 70 to the 110 mile radius on the forward (northwest) quadrant, a secondary speed maximum probably existed in association with those bands.

The cyclone was at the time quite small in areal extent; winds of 30 kt or more extended only inside the 55-mile radius. The maximum winds, about 60 kt, were somewhat lower for the observed central pressure of 984 mb than is normally observed in the Atlantic area. Otherwise, the system had a distribution quite similar to that found in the Atlantic and Pacific areas in systems of similar intensity and stage of development. This was a well developed circulation relatively small in size, but of close to "hurricane" intensity. The eye was well defined in the wind field; definite wind maxima existed all around the periphery of the central area of weak winds. The strength of the maximum winds was about the same in both the right and left quadrants of the system. Since the centre was moving at a speed of 8 kt, the relative wind field (actual winds minus the vector motion of the centre) apparently showed stronger flow in the left semicircle. Similar observations have also been noted in Atlantic storms.

(c) *Thermal field*—The distribution of temperature showed a picture not much different from what has been observed in similar systems in the Atlantic area. There was a region of warm temperatures in the centre surrounded by a ring of cold air (Fig. 25). From about the 30 to the 100-mile radius temperatures were colder than in the outside undisturbed atmosphere. The maximum temperatures in the centre were around  $25.5^{\circ}\text{C}$ , about  $2^{\circ}$  above the normal for that level in the undisturbed atmosphere (Pisharoty 1959). Temperatures of this magnitude were recorded on both traverses across the eye. The coldest temperatures in the rain area,  $19.6^{\circ}\text{C}$  or about  $4^{\circ}$  below normal, were recorded in the left semicircle at the 43-mile radius (see left side of Fig. 26). This section coincided with the pronounced precipitation band in that side of the system. Temperatures of about  $25.5^{\circ}$  were also recorded by the aircraft in the surrounding atmosphere 200 to 250 miles northeast of the centre



in both the approach to and departure from the cyclone.

The temperature distribution (Figs. 26 and 27) showed also pronounced oscillations, with changes of about  $2^{\circ}$  over rather small horizontal distances. Fig. 26 shows some at the 111, 87, 56, 33 and 20-mile radius; others appear in the right side of Fig. 27. The oscillations near the 110-mile radius in the right side of Fig. 26 were associated with a radar band, but the ones closer to the centre were not. Experience in the analysis of hurricane data in the Atlantic area (Colon 1961, 1964; Gentry 1964), shows that such oscillations are a characteristic feature in the hurricane rain area and appear to be closely associated with convective cells.

The temperature profile in the SE to NW pass (Fig. 27) was more typical of well developed tropical cyclones than the one shown in Fig. 26. The warm core in the centre is more symmetrical and more pronounced than the previous one. The characteristic warm centre surrounded by a ring of relatively cool air is clearly represented in Fig. 27.

The distribution of temperatures, as well as winds, showed some interesting features when viewed in relation to the distribution of radar bands. For example, in spite of the glaring asymmetry in the distribution of precipitation bands (Figs. 22 and 23), the isotach field showed a more typical distribution, with a band of strong winds bordering the eye around the right semicircle. Thus the band of strong winds on the right side did not coincide with a pronounced precipitation band as is usually the case. Also there were very important small scale oscillations in temperature in the region inside the 90-mile radius on the northeast side (right side of Fig. 25) with no important convection bands noticeable in that area. These features, although certainly unusual, are not unknown or unexpected in Atlantic systems of similar intensity and stage of development.

(d) *Pressure field*—Figs. 26 and 27 also contain profiles of D-values (in reference to U. S. Standard Atmosphere). The magnitudes might differ some if they were referred to an Indian Ocean mean atmosphere; the gradients, on the other hand, would remain unchanged.

Fig. 26 shows an almost insignificantly small horizontal gradient outside the 30-mile radius; from the 30-mile radius to the centre there was

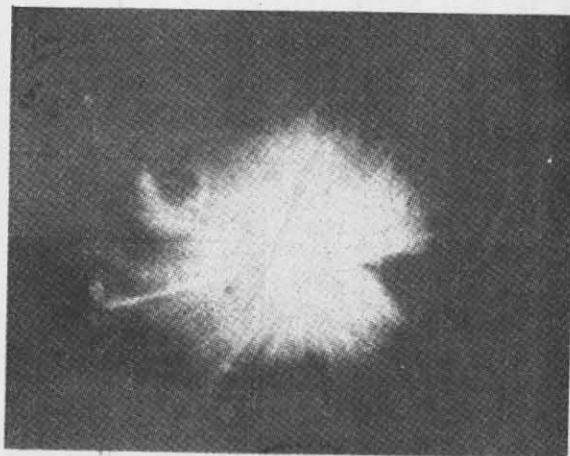


Fig. 28. Photograph showing the eye of the cyclone at 0800Z, May 24, 1963

a steady drop to a minimum of -610 ft. On the left side the gradient was more pronounced near the 10-mile radius, in association with the wind peak in that vicinity. The pressure distribution differed in the two sides of the centre, in accordance with the differences in wind flow.

The minimum "D" value at the centre was -600 which, on the basis of the studies by Jordan (1957), corresponds to a central pressure of about 988 mb. Although Jordan's study was made with Atlantic data the results should apply well in the Indian Ocean. The observers aboard the aircraft estimated a central pressure of 984 mb. The difference between the two estimates is within the limits of accuracy of the computation schemes.

#### 5. Hurricane structure—24 May

On 24 May the research aircraft departed Bombay and penetrated into the centre from the SE side at an altitude of about 3000 ft. Then it ascended in the vicinity of the centre to 500 mb and departed across the eye eastward towards Bombay. Data was, therefore, available only on two radial passes, at 900 and 500 mb, both on the right semicircle. Although the data was not plentiful, it nevertheless gave a fairly good view of the intensity and organisation of the cyclone.

(a) *Radar field*—The radar pictures obtained were not too good, due mainly to the large amount of "noise" in the centre of the scope, and did not give a good view of the complete distribution of bands. Fig. 28 shows the eye-wall band in a photo of the radar scope taken at around 0800Z

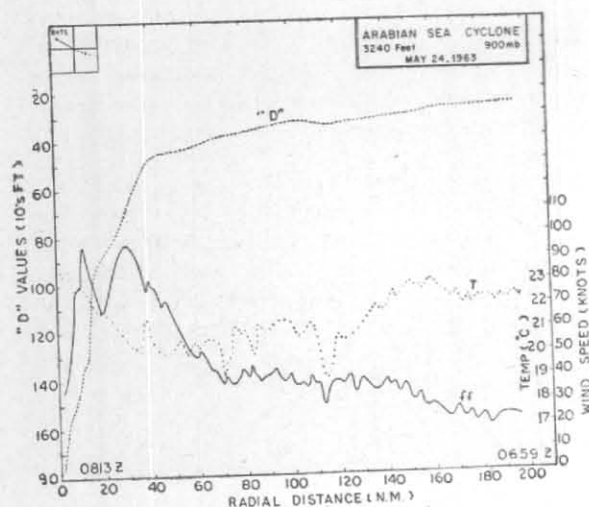


Fig. 29. Data profile at the 900-mb level, May 24, 1963

on 24 May. The radar eye appeared as a small, well-defined ring, with an inner diameter of 12 miles. The band itself had a thickness of about 8 miles on the south side. The ring appears open on the north side, but in view of possible attenuation of the radar signal, that feature may not be realistic. There was a definite and radical change in the configuration and structure of the eye band between 22 and 24 May as can be observed from a study of Figs. 21, 22, 23 and 28. These changes are typical of what has been recorded in Atlantic hurricanes. It is not known with certainty whether the changes observed between Figs. 23 and 28 occur as an evolutionary continuous process from one form to the other, or by a revolutionary discontinuous process of dissipation and reformation. Most probably it is the second one.

(b) *Wind field*—On the approach toward the centre at low levels, winds of 20-30 kt were measured 180 to 200 miles away (Fig. 29). The winds increased only slightly inward in the outer regions; winds of about 40 kt were measured between the 120 and the 70-mile radii. From the 70-mile radius inward there was a greater rate of increase in wind speed. A maximum wind of about 95 kt was recorded at the 32-mile radius. There was then a decrease to 65 kt at the 18-mile radius, followed by another peak of 96 kt at the 12-mile radius. The decrease in wind speed at the 18-mile radius was quite unusual. Somewhat similar features have been observed in going through the eye wall band of hurricanes, but not with the characteristics shown on Fig. 29. In this particular penetration the aircraft started climbing a few minutes before the maximum wind at the

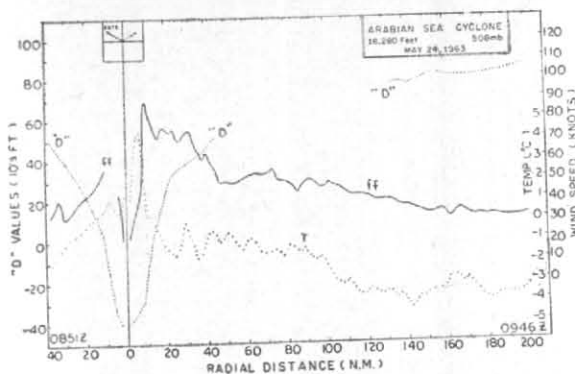


Fig. 30. Data profile at the 500-mb level, May 24, 1963

32-mile radius was recorded and continued on a climb throughout the approach into the eye. Occasionally the accuracy of the wind measurement suffers while the aircraft is climbing or descending; for this reason one should be careful in accepting as realistic such an unusual feature. In spite of this uncertainty, the profile in Fig. 29, in addition to the one in Fig. 30, gives an excellent representation of the intense hurricane vortex. Experience with Atlantic hurricanes indicates that the zone of maximum winds is generally located near the centre or on the outer section of the eye-wall radar band. In view of the dimensions of the radar eye system (Fig. 28) (12 miles in diameter and 8 miles band thickness) one would expect the radius of maximum winds near the 10-mile radius; Fig. 29 shows it at the 12-mile radius at the 900-mb level while Fig. 30 shows it at the 10-mile radius at the 500-mb level. This indicates a relationship between the size of the wind eye and of the radar eye quite similar to what has been recorded in Atlantic hurricanes. It also indicates no appreciable change between the radius of maximum winds at the 900-mb and 500-mb levels; an observation that had also been noted in some Atlantic hurricanes.

At the 500-mb level the aircraft crossed the eye close to its centre. The wind profile (Fig. 30) showed very weak flow in the centre; followed by a sharp increase in strength to a peaked maximum of 86 kt at the 10-mile radius on the right side. It then decreased at a fairly large rate to a value of 48 kt at the 55-mile radius. From there on outward the wind strength decreased more gradually. Winds of about 35 kt were still observed 180 miles from the centre.

The profiles in Figs. 29 and 30 were obtained in approximately the same sector of the system, so that comparison of the two profiles gives a realistic picture of vertical variations in wind strength. The maximum winds were about 98 kt near the 900-mb level and 85 kt at 500 mb, for a reduction of about 13 per cent. This is twice the percentage reduction between these two levels reported by Hawkins (1962). One interesting feature is that between the 60 and 140-mile radius the wind speed is about 5-10 kt larger at the upper level, contrary to what is normally expected in warm core systems such as tropical cyclones; but nevertheless, a feature not infrequently observed in Atlantic hurricanes.

(c) *Thermal field*—The temperature profile (Fig. 29) showed temperatures of around 24°C, about 3° above normal in the centre decreasing gradually to 20-21°C, slightly below normal, at the 30-mile radius. Values of 20-21°C, with short period oscillations of 1 to 2°C, prevailed throughout the rain area to the 120-mile radius. From the 150 to the 200-mile radius temperatures were about 22-23°C. This general distribution was similar to that observed at low levels on 22 May but the positive anomaly in the eye was higher on 24 May.

At the 500-mb level (Fig. 30) there was a narrow zone near the right (or east) edge of the eye with maximum temperatures of 4-3°C, or 9-4°C above normal. From the centre outward there was a sharp decrease to values of -1.5°C at the 20-mile radius in the right side; followed by a more gradual decrease to minimum values of -4°C, still about 1°C above normal, at the 140-mile radius. The distribution at 500 mb did not show too well the cool zone close around the eye that was recorded at low levels. Short period oscillations of 1-2°C range were observed at both middle and low levels. These oscillations are generally associated with convective scale cells embedded in the cloud system of the cyclone (Gentry 1964).

A temperature drop-sounding was recorded during the pass across the eye at 500 mb. This sounding (Fig. 31) resembled very much others that have been made in the eye of hurricanes. It showed a layer near the surface with lapse rate somewhat larger than the moist-adiabatic and large moisture content, relative humidity over 90 per cent. A stable layer, close to isothermal, extended from 825 to 675 mb. Drier air, relative humidity of 65 per cent existed near the top of the stable layer and above. The temperature anomaly was about 5°C in the

moist layer from surface to 825 mb, it increased to 10°C at the 700-mb level, at the 600-mb level it was 7°C and at 500 mb 9°C. This distribution of temperature with height compares quite well with eye conditions observed in Atlantic and Pacific tropical cyclones (Jordan 1957).

(d) *Pressure field*—The D-value distribution at low levels on 24 May (Fig. 29) showed the intense pressure vortex extending only to the 40-mile radius. Outside the 40-mile radius the horizontal gradients were relatively small and practically insignificant in comparison to those recorded in the central core. The minimum values at the centre were -1800 ft, corresponding to a central pressure of about 945 mb (Jordan 1957). At 500 mb the minimum D-value was around -400 ft. The horizontal profile at the upper level had a data-void sector from the 40 to the 130-mile radius, but the distribution seemed to have characteristics similar to those in the lower level.

## 6. Summary and Conclusions

This study of the important events associated with a tropical cyclone in the Arabian Sea made use of data gathered by all techniques of observation available presently for analysis in the tropics. Surface and aerological reports at land stations, surface observations by ships at sea, cloud distribution as observed by satellites, aerological reports by commercial aircraft and detailed reports by specially instrumented aircraft have all been combined to discuss the development and structure of this cyclone. Definite and reliable statements about the synoptic and physical factors that determined its formation, intensification and motion, could not be made due to problems imposed by the scarcity of data at sea.

Although the aircraft data collected in the interior of this cyclone were not really plentiful and covered only two short periods in its life history, they provided an adequate picture of the properties of the system and their changes with time during the intensification stage.

The investigation on 22 May took place at about the time that the cyclone was reaching "hurricane" intensity. There was a very well defined wind vortex, with definite wind maxima present around the eye. The areal extent of the strong winds was relatively small; winds over 30 kt extended only 50-60 miles from the centre. The thermal field showed a warm core around the centre with maximum temperatures of about 25.5°C, or 2°C above normal, at the

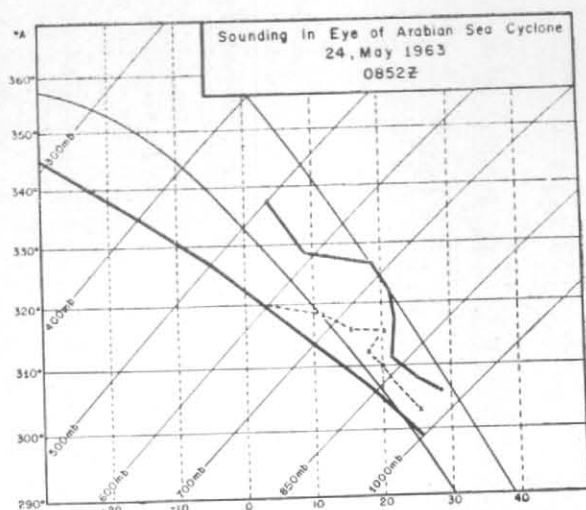


Fig. 31. Temperature sounding in the eye of the Arabian Sea cyclone, 0852 Z, May 24, 1963

Temperature shown in solid, dew point in dashed line.  
Temperature curve to the left is the May mean  
in the Arabian Sea area.

950 mb surface. This warm eye core was surrounded by a ring of cooler air; warmer temperatures existed further outside in the periphery of the circulation. The pressure field showed the typical picture for a tropical cyclone of nearly circular concentric isobars with steep pressure (D-value) gradients concentrated in a small narrow zone close to the centre. The radar data showed two main precipitation bands in a spiral configuration around the north, west and south sectors of the storm. There were little or no radar echoes on the east to southwest quadrants.

On 24 May the cyclone was investigated at or close to the period of maximum intensity. The data revealed a wind vortex of very deep intensity with central pressure of about 945 mb. From 22 to 24 May the central pressure decreased by about 40 mb and the maximum winds increased from 60 kt to at least 105 kt (stronger winds probably existed in sections of the circulation not investigated by the aircraft). The most significant changes associated with the intensification occurred in the inner core of the system, around the eye. The main radar band around the eye evolved into a characteristic circular ring band of small diameter. The distribution of winds, pressure and temperature showed that the process of intensification was characterized by a reduction in the radius of maximum winds; increase in wind speed greater in the eye-wall and much less in the rain area;

deepening of the pressure field more pronounced in the central core; and temperature increase larger in the middle and upper levels of the eye.

All these observed features revealed that Indian Ocean cyclones have essentially the same properties and go through a process of evolution similar to cyclones in other regions of the globe. Therefore, all the ideas developed elsewhere on genesis, development, motion and dynamic processes that operate during their life cycle should hold equally well in the Indian Ocean.

There were indications also that the circulation patterns near the surface and aloft in the Indian Ocean are basically no different than what has been observed in other tropical oceanic areas. The circulation at low levels in the initial phase of this cyclogenetic period that preceded the 1963 Indian summer monsoon hinged around the equatorial trough. A double trough, one in the southern and one in the northern hemisphere, was found to be a characteristic feature of the daily charts. A belt of westerlies existed along the equator between the two troughs. Cyclonic perturbations along the Northern Equatorial trough, generated spontaneously or in response to the influence of travelling perturbations that move across the equatorial belt at high levels, provided the nucleus for development of cyclones. During the period of study two such developments took place, one in the Arabian Sea and one in the Bay of Bengal.

The series of charts illustrated in this report presented a good view of the evolution of the flow patterns throughout the troposphere in going from the spring to the summer type of circulation. In this series the evolution was accomplished in association with deep cyclone development, but the evolution can take place also without cyclone development. Careful analysis and study of several series depicting this evolution with both the presence and absence of cyclones, might help in clarifying some of the dynamic and thermodynamic processes that govern it.

The structure of the upper level tropical troposphere over the northern Indian Ocean in the pre-monsoon period resembled very much that of summer in Atlantic and Pacific regions in that it showed a cellular structure with travelling cyclones, anticyclones and troughs. These high level systems appeared to act in conjunction with low level perturbations to alter the intensity of the low level perturbations along the ideas of super-position that have had wide acceptance in other areas.

At the 500-mb level the evolution of the flow patterns seemed to follow in association with developments near the surface. In the upper troposphere (200-mb level) the flow patterns changed from the cellular and highly irregular circulations of spring to a remarkably steady regime of zonal easterlies which extended over the entire tropical belt from the equator to

about 30°N and from Africa to the Pacific. The physical principles that guide these changes and their relation to events near the surface are not yet fully understood and warrant further analysis and study.

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