Some Large-Scale Characteristics Associated with Tropical Cyclone Development in the North Indian Ocean during FGGE

CHENG-SHANG LEE, ROGER EDSON AND WILLIAM M. GRAY

Atmospheric Science Department, Colorado State University, Fort Collins, Colorado

(Manuscript received 17 September 1987, in final form 16 August 1988)

ABSTRACT

This paper discusses the meteorological conditions associated with tropical cyclone formation in the north Indian Ocean during the 1979 FGGE year. Seven developing systems are composited together using FGGE III-b analyses to show the common circulation features surrounding developing cloud clusters. Three systems are further discussed to show different environmental influences on the low-level buildup of circulation during formation. The characteristics of these three disturbances' 200 mb outflow patterns and a general discussion of north Indian Ocean tropical cyclone activity are also given.

Results show that tropical cyclone formation generally follows the initial increase of strong low-level winds on one side (either equatorial or polar) of a pre- cyclone disturbance. This early buildup of wind appears to result from environmentally forced asymmetric wind surge action. Some of this increase appears to result from inward advection of velocity, but part of the increase seems to occur in situ. These initial strong azimuthal wind asymmetries are gradually reduced as the winds spread more evenly around the disturbance. A basic cyclone development process is the evolution of the low tropospheric flow from initial asymmetrical flow (shear vorticity) to a more symmetrical circulation (curvature vorticity).

1. Introduction

About five to six tropical cyclones form in the north Indian Ocean (N.I.O.) every year. This accounts for about 7%–8% of the 80 or so tropical cyclones that form per year about the globe (Gray 1968). In general, tropical cyclones in the N.I.O., which includes the Bay of Bengal and the Arabian Sea, have weaker intensities than those which form in the northwestern Pacific and the North Atlantic Oceans (Lee and Gray 1984). However, because there is a huge, densely concentrated population that lives and farms along the tidal basins of the northern portions of the Bay of Bengal, some of the greatest disasters involving the loss of human life due to natural causes can be attributed to these N.I.O. tropical cyclones. In some instances over 100,000 lives have been lost in these areas (Southern 1979).

There have been many studies regarding the climatology of these N.I.O. cyclones (e.g. Bansal and Datta 1972; Mooley 1980; WMO IWTW Workshop 1985). Unfortunately, extensive studies concerning the important large-scale circulation patterns associated with the formation and intensification of these cyclones have been scarce. This is largely due to the scarcity of standard observations in these regions for the following reasons:

1) There are few island or land stations to the equatorial side of tropical cyclones in the N.I.O. This hinders the proper analysis of certain large-scale effects from the south, such as those caused by cross equatorial flows.

2) Although routinely made in the Atlantic and the western North Pacific, there has been only one aircraft reconnaissance flight into a N.I.O. tropical monsoon depression (Houze and Churchill 1987). Thus, to obtain intensity or maximum wind estimates of N.I.O. cyclones, one must rely on either estimates from the Dvorak (1975) satellite technique or from the availability of surrounding wind and surface pressure data. In either case, accurate ground truth is rarely obtained.

Over the past decade, rawinsonde compositing techniques have been developed to study the large-scale characteristics associated with tropical cyclone activities over the somewhat more data rich areas of the western North Pacific, the North Atlantic and the South Pacific/Australian regions (e.g., McBride and Zehr 1981; Holland 1984). However, in the N.I.O. the lack of an evenly distributed rawinsonde network has made it impractical to develop composites for this region. Fortunately, the 1979 FGGE (First Global GARP Experiment) level III-b dataset analyzed by the European Centre for Medium-range Weather Forecasts (ECMWF) appears to be suitable for a thorough study of the large-scale characteristics associated with tropical cyclone activities in the N.I.O. (Bengtsson et al. 1982).
In this study, we have used the ECMWF analyzed FGGE II-b data to study changes in the large-scale circulation patterns associated with N.I.O. tropical cyclones and intensifications. There were seven tropical cyclones which formed in the N.I.O. during the FGGE year, as reported in the best track analyses of the Joint Typhoon Warning Center (JTWC) Annual Typhoon Report (ATR) (1979), and a composite analysis for all seven of these cyclones will be shown. (JTWC is the official forecast center for the U.S. Department of Defense for all tropical cyclones between long 180° to the African coast.) Also, individual case studies will be presented for three of these cyclones. The focus of this study will be on the upper and lower tropospheric large-scale divergence and vorticity fields where the FGGE data appear to be at their best. Similarities and differences between individual cases will be noted.

2. Utilization of FGGE III-b data

The major data source used in this study is the ECMWF FGGE III-b analyses of horizontal winds. These data were extracted directly from the initial analysis of the pressure levels and have not been subjected to any vertical interpolation or model initialization. Satellite imagery from the polar orbiting TIROS satellite were also available on mosaics twice a day in both IR and visible images for most of the days during the period that tropical cyclones were present. The official "best track" as indicated in the Joint Typhoon Warning Center Annual Typhoon Report (JTWC ATR 1979) was used to determine the position and intensity of each of the cyclones while for the outer wind fields the primary source were the flow features and satellite pictures from the summer MONEX, Quick Look Summer MONEX Atlas (Krishnamurti et al. 1980).

The FGGE data, which were initially on 1.875 deg lat/long cartesian grids at 15 pressure levels, were linearly interpolated onto cylindrical grids with grid spacings of 1° lat in radius and 22.5° in azimuth. In order to study the rotational and divergent flow patterns associated with the tropical cyclones, the zonal and meridional wind components were converted to radial and tangential wind components with respect to the moving cyclone center (as determined by the JTWC best track). The radial wind was then mass balanced vertically from 100 to 1000 mb at every radius. Although there were 15 vertical levels in the original analyses, this study used only ten levels (100, 150, 200, 250, 300, 400, 500, 700, 850, and 1000 mb) and relied heavily on analyses from the upper and lower troposphere where the original data were more numerous.

The satellite-derived cloud winds and aircraft data that went into the upper levels of the FGGE III-b dataset appeared to be very useful information. However, to account for variability of the actual heights of the satellite-derived winds and to combine the differences in heights typically found in the mean outflow layers from the poleward to equatorial side, the upper two layers (150 to 200 mb and 200 to 250 mb) were averaged and treated as one single outflow layer. Likewise, the low-level circulation was represented by the layer average from 800 to 1000 mb.

By comparing the FGGE analyses with our rawinsonde composites in other ocean basins, Lee (1986) has shown that the FGGE analyses can well represent the rotational part of the circulation of the tropical cyclone, especially beyond 4°–5° radius from the cyclone center. Furthermore, at the early stages of the tropical cyclone's development, the FGGE analyses seemed to be able to resolve the rotational part of the circulation as close in as 2° latitude from the cyclone center. The FGGE analyzed radial winds, on the other hand, did not appear as good. Reasons for these characteristics are multifold and have been discussed in many other compositing work. Fortunately, in the upper troposphere beyond 4°–5° radius from the center, the resulting divergent part of the layered-averaged winds seemed comparable to our rawinsonde studies and were used in this study. This allowed the FGGE data to be quantitatively used to study certain large-scale influences on the tropical cyclones as long as certain precautions in interpretation were taken.

One important advantage of using the FGGE data was that continuous time series of any important parameter could be constructed for each individual tropical cyclone throughout its life cycle. A continuous trend in time of parameters also added credibility to the FGGE data. Time series of the 6° radius upper- and lower-level tangential winds were thus constructed. These were especially helpful for studying the genesis period of each tropical cyclone, in a manner similar to that described by McBride and Zehr (1981). In addition, time series of upper- and lower-level radial winds at 6° radius were analyzed in order to study transverse circulation changes.

3. Favorable environmental setting for N.I.O. tropical cyclone formation

Unlike tropical cyclone formation in the other ocean basins which occur sometime in the late summer, tropical cyclones of the N.I.O form primarily in the monsoon transitional seasons of spring and autumn because it is only during these periods that the monsoon trough is located sufficiently over the open water of the N.I.O (−5°–15°N) to develop into mature cyclones before they make landfall. During the summer period of late June through early September, the monsoon trough is typically located much further to the north over the Ganges Valley and at the head of the Bay of Bengal.

As discussed by Gray (1968, 1979), tropical cyclones also form only when the tropospheric vertical wind
shear directly over the incipient disturbance is very weak. Such small wind shear conditions typically occur only during the monsoon transitional periods of late April through June, and late September through early December (Gray 1968). Although weak vertical shear is desirable directly over the developing disturbance, it has been shown that a strong positive vertical shear in the outflow regions (>6° from the center) away from the convective centers to the north and a strong negative vertical shear to the south is also desirable (McBride and Zehr 1981; Merrill 1988a,b; McBride 1981). This requirement for increased vertical anticyclonic shear over the developing systems was also found to be true for the tropical cyclones studied in this analysis.

4. General characteristics of N.I.O. tropical cyclones during the FGGE year

During the 1979 FGGE year, the JTWC (1979) observed seven tropical cyclones that formed in the north Indian Ocean. This was higher than the averaged number of 4.5 which JTWC observed during the period of 1975–85. Only one 1979 cyclone system attained typhoon intensity \( V_{\text{max}} > 33 \text{ m s}^{-1} \) and four others reached tropical storm intensity \( V_{\text{max}} > 17 \text{ m s}^{-1} \). Table 1 gives a summary of the 1979 N.I.O. tropical cyclone systems. (Note that TC 24-79 maintained an intensity of 17 m s\(^{-1}\) for only 12 h before it reached land.) Figure 1 shows a summary of the storm tracks with maximum wind intensities as indicated.

As is the case for most tropical cyclones that form in the N.I.O., discussion from JTWC (1979) and satellite photographs indicated that the FGGE year cyclones all originated from cloud cluster disturbances embedded within the monsoon trough. The initial zonal and meridional winds for these seven disturbances are composited along north–south and east–west vertical cross sections in Figs. 2 and 3. (These groupings can be considered to represent the rotational and divergent parts of the wind respectively.) These composites were made from the first reported 1200 UTC time period after their initial best track position by JTWC. In these figures, the surface southwest flow to the south and the northeast flow to the north is in evidence—as would be expected in a monsoon situation. However, of special interest is the very strong preexisting surface-to-400 mb cyclonic circulation about these initial disturbances (Fig. 2). Apparently those processes which lead to the development of such a vorticity field are very important. Some of these processes—such as cross-equatorial surges (Love 1985a,b) and wind surges in the trade winds (Lee 1986) for the western North Pacific, as well as other possible environmental forcings—will be examined more closely in the case studies that follow.

Figure 2 indicates that the incipient cyclone disturbance appears to be lying under a relatively weak vertical shear at least up to 400 mb. Above the 400 mb level of the developing systems, weak southwesterlies prevail (Fig. 3); however, this type of flow seems to be favorable for the development of outflow channels (Chen and Gray 1985) and is considered an advantage for later-stage cyclone intensification. Figure 2a also suggests that McBride’s (1981) requirement for vertical anticyclonic shear at 6° radius from the cyclone’s center is met for the composite storm, as upper-level easterlies overlay westerlies to the south of the center and upper-level westerlies overlay easterlies to the north.

In Fig. 3 the divergent part of the wind can be seen. To the south and west of the center, low-level inflow is very shallow and appears to have originated from cross-equatorial monsoonal flow. This will be seen more easily in the case studies. In the upper levels, net radial flow is found primarily in the meridional (north–south) direction which can perhaps be interpreted as outflow channels towards the pole and the equator. The prevailing upper-level equatorial outflow branch appears to correspond to a cross-equatorial return flow. The transient properties of these mean in-and-out flowing transverse circulations are examined in section 5 to try to determine the role they play in the development of the Indian Ocean tropical cyclones.

<table>
<thead>
<tr>
<th>Cyclone designation</th>
<th>Period of warning</th>
<th>Calendar days of warning</th>
<th>Max. sus wind ( \text{m s}^{-1} )</th>
<th>Est. min SLP (mb)</th>
<th>Number of warnings</th>
<th>Distance traveled (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TC 17-79</td>
<td>6–12 May</td>
<td>7</td>
<td>44</td>
<td>967</td>
<td>26</td>
<td>2346</td>
</tr>
<tr>
<td>TC 18-79</td>
<td>18–20 Jun</td>
<td>3</td>
<td>26</td>
<td>985</td>
<td>12</td>
<td>1076</td>
</tr>
<tr>
<td>TC 22-79</td>
<td>21–23 Sep</td>
<td>3</td>
<td>13</td>
<td>1000</td>
<td>10</td>
<td>1285</td>
</tr>
<tr>
<td>TC 23-79</td>
<td>21–25 Sep</td>
<td>5</td>
<td>28</td>
<td>980</td>
<td>14</td>
<td>2052</td>
</tr>
<tr>
<td>TC 24-79</td>
<td>20 Oct–1 Nov</td>
<td>4</td>
<td>18</td>
<td>995</td>
<td>13</td>
<td>1333</td>
</tr>
<tr>
<td>TC 25-79</td>
<td>16–17 Nov</td>
<td>2</td>
<td>21</td>
<td>994</td>
<td>8</td>
<td>1013</td>
</tr>
<tr>
<td>TC 26-79</td>
<td>23–25 Nov</td>
<td>3</td>
<td>15</td>
<td>995</td>
<td>10</td>
<td>1983</td>
</tr>
<tr>
<td>1979 Totals</td>
<td></td>
<td>27</td>
<td></td>
<td></td>
<td></td>
<td>93</td>
</tr>
</tbody>
</table>

* Overlapping days included only once in sum. (From JTWC 1979)
5. Case studies of three N.I.O. tropical cyclones during FGGE

As is shown in Table 1, the majority of the 1979 N.I.O. tropical cyclones were relatively short lived and weak. This makes it a little more difficult to obtain enough data to ascertain the physical processes that affected these cyclones. However, the FGGE III-b dataset allows us to take a unique look at several of these tropical cyclones because there exists a higher space and time resolution than is usually available. This will be evident after individual case analyses are given for three of the TC systems: TC 18-79 over the Arabian Sea, and TC 17-79 and TC 24-79 over the Bay of Bengal.

It will be shown that each of these three cyclones developed under slightly different synoptic situations, with two showing effects from cross-equatorial influences (TC 17-79 and TC 18-79) and one from influences of the northeast monsoon (TC 24-79). In spite of these differences, it will also be shown that the development of each of these cyclones had many similar characteristics.

a. TC 17-79

TC 17-79 was the strongest tropical cyclone \( V_{\text{max}} = 44 \text{ m s}^{-1} \) in the N.I.O. in 1979 (see Fig. 4), and at the time it was the most destructive cyclone to strike India since TC 22-77 (Nov 1977). It followed a track similar to TC 22-77’s, and did great damage to the Madras area. It caused about 700 deaths.

The tropical disturbance that was soon to develop into TC 17-79 was first identified on satellite imagery by JTWC at 0800 UTC on 5 May 1979. By 1200 UTC on 6 May, observations from ships participating in FGGE clearly defined a cyclonic circulation centered near 7.0°N, 88.0°E with reported wind speeds of 10–13 m s\(^{-1}\). At 0000 UTC 9 May, satellite imagery indicated that—after a 2.5 day erratic and looping track—TC 17-79 had attained typhoon intensity. (During this period another tropical cyclone (TC 16-79, Kevin) was located in the south Indian Ocean about 1400–1500 km to the southwest of TC 17-79.) Following a northwest track, TC 17-79 weakened a little in the next 24 h and then reintensified to its maximum intensity of 44 m s\(^{-1}\) with an estimated pressure of 967 mb on 1200 UTC 11 May. TC 17-79 then rap-
low-level outer circulation resumes its build up on the eighth and attains its peak magnitude at 0000 UTC 10 May, two days before TC 17-79 reaches its maximum intensity.

The third curve in Fig. 5 shows the mean upper-tropospheric radial outflow \( \bar{V}_r \) between 150 and 250 mb at 6° radius. Note how this upper-level outflow increases significantly just before the system is officially reported by JTWC. Another major increase occurs between 1200 UTC 7 May and 1200 UTC 8 May when the system is undergoing its maximum intensification rate. There is a noticeable break in the increase of \( V_{\text{max}} \) between 0000 UTC 9 May and 0000 UTC 10 May, possibly associated with the initial weakening of the upper-level outflow. However, the continued increase in \( V_{\text{max}} \) after this period would suggest that the upper-level outflow—at least averaged over a 6° radius (similar to the low-level outer tangential circulation)—and the intensity are not directly correlated. It is hypothesized that perhaps both \( \bar{V}_r \) and \( \bar{V}_t \) at 6° radius are more closely related to total convection within the larger 6° radius area and that maximum intensity

![Diagram showing wind flow](image)

**Fig. 2.** Composited zonal \((u)\) and meridional \((v)\) wind flow in m s\(^{-1}\) about a (a) north–south and a (b) east–west cross section respectively, for all seven north Indian Ocean tropical cyclones in 1979 at their first reported 1200 UTC time period in a fixed geographic coordinate system. These winds can also be interpreted as the tangential (or rotational) component of the wind.

Idly lost its intensity and dissipated when it moved inland over the Indian subcontinent north of Madras.

1) **Time Series of Wind Parameters**

In the first two curves of Fig. 5, the time series of best track maximum sustained surface wind intensity, \( V_{\text{max}} \) and the low-level tangential outer circulation \((700-1000 \text{ mb } \bar{V}_t, \text{ in m s}^{-1}, \text{ at 6}° \text{ radius})\) are shown. (A 3-point, 12-h interval, running mean was taken to smooth out diurnal and other short time-scale variations on all \( V_r \) and \( V_t \) time series shown.) It is interesting to note that the low-level outer 6° radius tangential circulation \((\bar{V}_t)\), appears to strengthen prior to JTWC's initial report at 0800 UTC 5 May. However, from 5 to 7 May, while \( \bar{V}_t \) increases from 8 m s\(^{-1}\) to 17 m s\(^{-1}\), \( \bar{V}_t \) remains virtually the same. Finally, the

![Diagram showing wind flow](image)

**Fig. 3.** Composited meridional \((v)\) and zonal \((u)\) wind in m s\(^{-1}\) about a (a) north–south and (b) east–west cross section, respectively for all seven N.I.O. tropical cyclones of 1979 at their first reported 1200 UTC time period in a fixed geographic coordinate system. These winds can also be interpreted as radial or divergent winds.
would be better correlated with these quantities if they were present closer in to the cyclone’s central region (≈1–2° radius).

2) EARLY STAGE

Between 0000 UTC 3 May and 0000 UTC 5 May, satellite imagery showed a broad cloud region associated with the monsoon trough located between the equator and 10°N and from 60°E to 90°E with loosely organized cloud clusters spread over the entire region. As is seen in Fig. 5, a significant change in the monsoon flow during this stage is suggested by the strengthening of the low-level outer circulation, $V_l$, of the pre-TC 17-79 disturbance. The ECMWF analyses during this time show a westerly wind maximum (or surge) along the equator that appears to be coupling the development of TC 17-79 to the north with TC 16-79 (Kevin) to the south (Fig. 6). Figure 6a for 1200 UTC 4 May shows the westerly wind maximum and the position of TC 16-79, which had just reached tropical storm intensity, at 6°S, 87°E (DeAngelis 1979). During the next several days the westerly winds near the equator and just south of TC 17-79 increase substantially as the Southern Hemisphere cyclone continues to inten-
Fig. 6. The ECMWF analyzed 850 mb flow at (a) 1200 UTC 4 May, (b) 1200 UTC 5 May, and (c) 1200 UTC 7 May. Large dots denote the approximate locations of TC 17-79 and TC 16-79 (Kevis). Maximum sustained winds ($V_{\text{max}}$) for TC 17-79 are approximately 8, 10, and 21 m s$^{-1}$, respectively, and for TC 16-79 are 17, 26, and 30 m s$^{-1}$, respectively. Isotachs (dashed) are given in m s$^{-1}$. Heavy dashed curves show 10 m s$^{-1}$ isotachs.

Fig. 7. Plan view of low-level circulation (700–1000 mb $V_t$) of TC 17-79 disturbance at (a) 1200 UTC 3 May, (b) 1200 UTC 4 May, and (c) 1200 UTC 5 May for a center approximated at 6.4°N, 90.6°E. The system's maximum winds were less than 15 m s$^{-1}$ for all of these time periods. No data are shown within 3° of the system's center. Arrows are indications of the primary wind direction about the center. Values in m s$^{-1}$. 

sify to 26 m s$^{-1}$ and 31 m s$^{-2}$ on the fifth and seventh, respectively. From the FGGE analyses prior to this time, the cross-equatorial flow along the East African coast did not seem to play a significant role in producing this strong low-level westerly flow between the two cyclones. It is possible though that this type of flow developed from a pressure gradient increase between the subtropical and equatorial regions that was not identified in our analyses. The development of the opposite hemisphere cyclone may have further enhanced this flow.

Figure 7 shows the evolution of the low-level tangential wind for the layer 700–1000 mb out to the 14° radius for the wind fields at three time periods (1200 UTC 3 May, 1200 UTC 4 May, and 1200 UTC 5 May) at the approximate position 6.4°N, 90.6°E. This is the location of TC 17-79 at 1200 UTC 5 May. The heavy curves are the 2 m s$^{-1}$ tangential isolat. At 1200 UTC 3 May, a maximum $V_t$ of 12 m s$^{-1}$ is located at 4°–6° radius south and southwest from the center. North of the center, tangential winds are only 2–3 m s$^{-1}$. The 2 m s$^{-1}$ isolat does not penetrate through the west side ($V_t$ is negative here) to form a closed cyclonic pattern around the center. By 1200 UTC 4 May, however, a closed 2 m s$^{-1}$ isolat is found around the center, and $V_t$ to the north has increased to 5 m s$^{-1}$. The maximum $V_t$ to the south and southwest of the center is maintained at 12 m s$^{-1}$. Negative $V_t$ is still present at 12° radius to the south and 10° to the north and east.
of the center. By 1200 UTC 5 May, positive $V_r$ has spread over most of the region around the cyclone. The maximum mean $V_r$ around the cyclone has increased from 12 to 14 m s$^{-1}$ during this period. It appears then that an important ingredient in the increase of $V_r$ in this system is the change of the preexisting cyclonic shear situation (helped in part by its proximity to the westerly surge and to TC 16-79) 48 h before development to the more cyclonic curvature situation at the time of development.

At upper levels (not shown), an anticyclonic center is located around 15°N, 90°E, north of the pre-cyclone cloud cluster region where TC 17-79 will form. The flow is mostly northeasterly to easterly near the vicinity of the cluster region. No significant change in upper-level flow occurs during the 3-day period of genesis except for a slow deepening of an upper-level trough in the Arabian Sea.

3) DEVELOPING STAGE

At 1200 UTC 5 May, satellite imagery indicates that a well-organized cloud pattern is found centered at 6°N, 91°E. The maximum wind at this time was estimated by JTWC at 10 m s$^{-1}$. Radial-height cross sections of azimuthally averaged tangential wind ($\hat{V}_r$) at 1200 UTC 5 May and 1200 UTC 9 May are shown in diagrams a and b of Fig. 8. Cyclonic circulation extends up to 300–400 mb with maximum anticyclonic wind near 175 mb. This circulation pattern is very similar to those of developing tropical cyclone wind patterns in the northwestern Pacific as discussed by McBride (1981). Other analyses about these times indicated that the cyclonic tangential circulation from the surface to 400 mb showed a steady increase with time while the upper-level anticyclone circulation showed little change until the maximum intensity was reached.

A significant feature in the upper levels appears to be the establishment of an upper-tropospheric outflow to the north. This can be seen by both the initial increase of the 150–250 mb radial wind, $V_r$, in Fig. 5, and the approach of an upper-level trough in the Arabian Sea (Fig. 9) in which an upper-level outflow channel is seen to exist to the north of the cyclone center. Figure 10 further demonstrates this development in the plan views of the 150–250 mb radial winds in a moving coordinate relative to the center of TC 17-79 for 1200 UTC 5 May and 1200 UTC 7 May. Strong outflow forms by 7 May to the north of the center, while a broader outflow region has also formed to the southeast of the cyclone center. From a forecaster's prospective, these maximum outflow regions may be thought of as outflow channels, since they appear to be related to a synoptic-scale feature.

Although the upper-level outflow starts to weaken after 1200 UTC 9 May, the $V_{max}$ still continues to increase from 1200 UTC 9 May to 1200 UTC 11 May. This upper-level outflow weakening appears to be related to the closing off of the poleward outflow channel with the passage of the upper-level trough system.

**Fig. 8.** Radius–height vertical cross sections of azimuthally averaged tangential wind $\hat{V}_r$ in m s$^{-1}$ for TC 17-79 at (a) 1200 UTC 5 May, $V_{max} = 10$ m s$^{-1}$; and (b) 1200 UTC 9 May, $V_{max} = 31$ m s$^{-1}$.

**Fig. 9.** The ECMWF analyzed 200 mb wind field associated with TC 17-79 for 0000 UTC 7 May. The large dot denotes the center of T 17-79. Length of arrows is proportional to wind speed. Trough, streamlines and location of outflow jet have bee indicated by the authors.
Convection, however, seems to have become more centrally concentrated and a well-defined embedded eye was reported by JTWC on 11 May (Fig. 11). These satellite imageries show that the upper-tropospheric outflow remains to the west and southwest of the center throughout this period, although, the hard cirrus edge on the eastern side of the cyclone possibly indicates an influx of upper-level easterlies and thus the reduction of the mean radial wind for the 6° radius area as a whole.

4) DECAYING STAGE

TC 17-79 made landfall at 0600 UTC 12 May with an intensity of 41 m s⁻¹ and rapidly dissipated as its circulation continued to move inland.

b. TC 18-79

The formation of TC 18-79 looks to be quite different from that of TC 17-79. DeAngelis (1980) has speculated that TC 18-79 helped bring about the advance of the southwest monsoon over portions of the Indian subcontinent since it appeared at the same time as the first big monsoonal surge of the year. TC 18-79 was first observed by JTWC on satellite imagery as a tropical depression in the Arabian Sea at 1400 UTC 17 June. Maximum wind speeds at that time were estimated to be 13 m s⁻¹. TC 18-79 followed a westward track throughout its life until it dissipated over the Oman coast. Its maximum sustained winds increased to near 26 m s⁻¹ 36 h after its discovery, and it maintained this magnitude for 24 h until shortly before it crossed the coast at 0200 UTC 20 June.

5) TIME SERIES OF WIND PARAMETERS

Figure 12 shows the time series of intensity \(V_{\text{max}}\) and 6° radius mean values of \(V_r\) and \(V_r\). Once again it appears that the 6° radius outer circulation and radial winds precede the intensity curve by several days. The strengthening of the low-level outer circulation is particularly impressive when compared to TC 17-79 at the same stage of development. The outer cyclonic circulation of this system was not only initially stronger than TC 17-79, but it also extended over a broader region. Figure 13 shows the development of the azimuthally averaged \(V_r\) at 1200 UTC 17 June \(V_{\text{max}} = 13 \text{ m s}^{-1}\) and 1200 UTC 19 June \(V_{\text{max}} = 26 \text{ m s}^{-1}\). The larger strength of the initial tangential wind profile at 17 June appears to be greater than either the early stage profile of TC 17-79 (Fig. 8a) or that of the mean N.I.O. profiles shown in Fig. 2. It is also inter-
Fig. 11. The IR satellite imagery of TC 17-79, center is circled, at 1200 UTC on (a) 9 May and (b) 11 May.

It is interesting to observe that the upper- and lower-level circulation beyond 4° radius did not change much during this 48-hour period, while the maximum intensity of the cyclone doubled in magnitude.

6) Low-level development

The large-scale synoptic situation was quite different for TC 18-79 as compared with TC 17-79. Prior to TC
18-79's formation, a series of frontal systems can be seen (in the satellite imagery and the ECMWF analysis) to be moving eastward in the south Indian Ocean (Fig. 14). A surge type flow similar to that described by Love (1985a,b) appears to propagate equatorward behind the shear lines associated with these fronts. This appears to bring about a strengthening of the low-level wind maximum, first along the Somali coast and then extending eastward across the entire Arabian Sea. Although this low-level wind maximum is usually along the Somali coast during the monsoon season, this initial cross-hemisphere push appears to aid in the formation of TC 18-79 by first increasing the westerly winds on the southern side of the preycyclone disturbance and then generally enhancing its low-level circulation.

This strengthening of the low-level circulation can also be seen in the plan views of the mean 700-1000 mb tangential wind field around the center of TC 18-79 (Fig. 15). Analyses are presented for 1200 UTC 17 June when the center was located at 17°N, 68°E, and for the 24- and 48-h periods prior to this time with respect to the same location. At 1200 UTC 15 June (48 h before the beginning of TC 18-79), a low-level wind speed maximum of 16-17 m s⁻¹ is located 10° south of the precyclone center. Cyclonic circulation is found only on the south side of the center, although a strong cyclonic shear can be seen throughout the area. This is part of the prevailing southwesterly flow from the low-level Somalia jet. The precyclone disturbance center is located just on the poleward (cyclonic shear) side of this low-level wind speed maximum.

Twenty-four hours later, at 1200 UTC 16 June, the maximum wind to the south changes very little; however, the low-level cyclonic flow has now spread to the east and north sides of the developing system. Note how the 2 m s⁻¹ cyclonic isoteach has completely closed around the center, and the low-level anticyclonic region has greatly decreased. By 1200 UTC 17 June, the maximum wind area has increased to approximately 23 m s⁻¹ and moved even closer to the system center, and the cyclonic wind region has virtually spread over almost the entire area. This gradual change of cyclonic shear to cyclonic curvature is similar to that shown for TC 17-79.

7) UPPER-LEVEL DEVELOPMENT

In Fig. 12, it was shown how the 6° mean radial outflow increased greatly prior to the beginning of TC 18-79's formation but did not increase during the period when the maximum winds increased the most between 1200 UTC June 17 and 0000 UTC June 19. A look at the upper-level 200 mb flow perhaps can help
and 0000 UTC 19 June. At 0000 UTC 17 June, the disturbance appears to form very close to the Saudi Arabian–Indian upper-level ridge line. During this time there is only weak easterly flow across the top of the system, but the 20 m s\(^{-1}\) isotach just to the south allows for a fairly strong outflow channel to the west and southwest (and a net radial outflow from the system). The plan view of the upper-level radial wind at 1200 UTC 17 June shows this clearly (Fig. 17a). By 0000 UTC 18 June, when TC 18-79 finally begins to intensify, the outflow region along the equator also appears to strengthen, possibly in response to the favorable positions of the two Southern Hemisphere upper anticyclones near 65° and 80°E (Chen and Gray 1985). At the same time, however, the Northern Hemisphere upper-level anticyclone has now consolidated into a single center further north near the northern portion of the Arabian Sea, resulting in stronger upper-level easterly flow across the system. Williams and Gray (1973), Tuleya and Kurihara (1981), and Lee (1986) have shown that tropical cyclone formation is favored under conditions of upper-tropospheric easterly winds over the disturbance as long as the vertical shear is not too great.

Although TC 18-79 still continues to intensify from 0000 UTC 18 June to 0000 UTC 19 June, TC 18-79 has already begun to move away from the strong cross-equatorial upper-level outflow and into increasing upper-level inflow on the eastern side of the system (Figs. 16c and 19b). This upper-level easterly flow appears to have also increased the vertical shear over the system,

explain this phenomenon. Figure 16 shows the position of TC 18-79 with respect to the 200 mb flow for the time periods 0000 UTC 17 June, 0000 UTC 18 June,
thereby causing the separation of the convection from TC 18-79 and a rapid weakening of the system before it reached the Oman coast. Figure 18 shows the satellite IR picture of TC 18-79 at 1800 UTC June 19, when TC 18-79 starts to weaken. The clear region and sharp edge of the cloud pattern on the east side helps support the hypotheses that upper-level inflow exists to the east of the storm system. Of course, TC 18-79's rapid weakening can also be attributed in part to the advection of dry desert air into its central core as it moved closer to the Arabian Peninsula.

c. TC 24-79

Unlike the two previously discussed tropical cyclones, the origin of TC 24-79 in October 1979 appears to have been more influenced from the poleward side. Its development occurred shortly after the onset of the northeast monsoon over the Bay of Bengal. Although TC 24-79 was a fairly small and weak system \( V_{\text{max}} = 17 \text{ m s}^{-1} \), it will be shown that many of the parameters signifying the initiation of the other two systems were present in this one as well.

Prior to the formation of TC 24-79, satellite imagery indicated that loosely organized cloud clusters were situated throughout most of the north Indian Ocean between the equator and 15°N. JTWC first identified the pre-TC 24-79 cloud cluster at 0000 UTC 27 October. This cloud cluster then moved northwestward (Fig. 19) and by 0000 UTC 29 October the disturbance had moved close to the southwest side (cyclonic shear side) of a strong southeasterly trade wind flow (Fig. 20). Once its convection became more organized, warnings were issued on TC 24-79 starting at 1400 UTC 29 October, although maximum wind speed was still only estimated at 10 m s\(^{-1}\)—about the same as the strong peripheral trade wind flow. Following the low-level prevailing easterly flow, TC 24-79 tracked westward throughout most of its life and gradually increased its maximum intensity of 17 m s\(^{-1}\) just prior to striking the Indian coast near Madras.

8) Time series of wind parameters

Figure 21 shows the time series of \( V_{\text{max}} \) and 6° radius mean values of \( \langle V_r \rangle \) and \( \langle V_t \rangle \). Note as in the previous two equatorially influenced cases, the 6° radius outer circulation and radial winds increased prior to the formation of TC 24-79. However unlike those cases, once the intensity began to increase, these mean outer radius values dropped considerably. This is possibly due to the very small expanse of the circulation field (as seen on satellite images), which decreased with time below

---

18-79. Length of arrows is proportional to wind speeds. Isotachs are in m s\(^{-1}\). Wind flow lines and anticyclonic positions have been indicated by the authors. The intensities of TC 18-79 is 13, 16, and 26 m s\(^{-1}\) at these three time periods, respectively.
the resolution of the FGGE III-b data analysis. In fact, one can see from the vertical cross section of tangential winds at 1200 UTC 31 October when $V_{\text{max}} = 17 \text{ m s}^{-1}$ (Fig. 22), that the outer cyclonic circulation for this system was much weaker and shallower than the other two systems at greater than 4$^\circ$ radius.

Figure 23 shows the plan views of the low-level tangential wind circulations—1200 UTC 27 and 28 October. Initially, with the cyclone’s 5 m s$^{-1}$ movement to the northwest, the pattern in a motion coordinate system appears to show relative cyclonic flow only on the west side. However, similar to the previous two case studies, by 1200 UTC 28 October the cyclonic flow completely envelopes the circulation center. However, in this case, the relatively rapid movement of the cyclone center does not appear to allow the cyclonic circulation to get too large about the system.

Plan views of the upper-level radial wind profiles are shown in Fig. 24 for 1200 UTC 28 and 31 October. Although for both time periods radial outflow (divergence) can be seen towards the northeast, it is not until the latter time period that the flow out towards the northeast appears to be significantly greater than the flow in from the northwest. By this time, however, when TC 24-79 had reached its greatest intensity the cyclone was already within 24 h of making landfall.

Figure 25 depicts the synoptic pattern just prior to this time, showing how the wind maximum and trough over Southeast Asia has enhanced the outflow in this direction. Unlike the case for TC 17-79, the approaching trough to the west over Saudi Arabia does not appear to be the dominant feature for this particular pattern.

TC 24-79 was never a very strong system. However, it seems plausible that the mechanisms which allowed for the continued slow maintenance of the cyclone throughout its life time were related to the favorable superposition of the enhanced low-level circulation field with that of the weak net radial outflow towards the northeast in the upper levels that persisted throughout this period.

6. Discussion of relevant N.I.O. tropical cyclone features

Sections 4 and 5 analyzed the composited large-scale circulation patterns for all seven tropical cyclones that formed in the north Indian Ocean during the 1979 FGGE-year period and looked specifically at three distinctive case studies. Although there may be some inadequacies in the overall resolution of the FGGE III-b data and the ECMWF initialization techniques, these
data are still the best information available for any cyclone season in this relatively data-poor region. We believe the ECMWF analysis showed most of the important characteristics of the large-scale winds about these tropical cyclone systems, particularly in the rotational component of the wind fields and in the large-scale upper-level divergence patterns about each of these cyclones. We will now try to generalize some of the more important physical processes related to these tropical cyclones in terms of their influence on the genesis, intensification, and structure. It is recognized, however, that this discussion, which is based only on 1979 cyclone information, may not always strictly apply to tropical cyclones occurring in this region for other years.

a. Characteristics of the large-scale circulation patterns during tropical cyclone formation and development

Like tropical cyclones in the western North Pacific, most FGGE year N.I.O. tropical cyclones formed

---

**Fig. 18.** The IR satellite imagery of TC 18-79 at 1800 UTC June 19. Center is circled.

**Fig. 19.** Best track of TC 24-79 from JTWC (1979).

**Fig. 20.** The ECMWF analyzed 850 mb flow at 0000 UTC 29 October. Large dot denotes approximate location of TC 24-79. Isotachs (dashed) are given in m s$^{-1}$. The heavy dashed curves show 10 m s$^{-1}$ isotachs.
Fig. 21. Time series for TC 24-79 of its intensity ($V_{\text{max}}$) in $\text{m s}^{-1}$, low-level (700-1000 mb) $6^\circ$ radius outer circulation ($\bar{V}_r$) in $\text{m s}^{-1}$, and upper-level (150-250 mb) outflow ($\bar{V}_o$) at $6^\circ$ radius in $\text{m s}^{-1}$.

within the monsoon trough region. The average wind fields for all the seven N.I.O. cases in 1979 revealed a very deep monsoon-generated cyclonic circulation around the center of the tropical cyclone formation region (Fig. 2). An important feature from our case study analyses is that there was always a buildup of both the low-level cyclonic circulation and the upper-level outward radial flow prior to the formation of the tropical cyclone system. This feature was found to exist for most of the other N.I.O. cyclones that formed in the FSGGE year as well (Fig. 26).\(^1\) [This feature is common to many tropical cyclones of the northwestern Pacific, as has been observed by Lee (1986), and for Atlantic cyclones (Gentry et al. 1980)]. The analysis also shows that in many cases this build up cross-equatorial monsoonal surges or other features which act to strengthen the westerly wind on the equatorward side of the pre-cyclone disturbances. Love (1985b) has observed similar equatorward westerly wind increases about the west Pacific and Australian region tropical disturbances. These increases appear to be associated with middle-latitude cold surge penetrations into the tropics in the opposite hemisphere.

In the latter part of the autumn season (mid-October–December), however, the required low-level cyclonic circulation increase for tropical cyclone formation may occur more on the poleward than the equatorward side of the pre-cyclone N.I.O. systems, as was shown for TC 24-79. It is thus possible for the main low-level cyclonic circulation increase of N.I.O. systems to occur on either the equatorward or the poleward sides. [During November of the FSGGE year, two
cyclones formed virtually at the same time; one from a low-level poleward influence (TC 24-79) and one from an equatorward influence (TC 25-79)]. The poleward trade wind circulation increase may perhaps come as a result of an east Asian winter season northeast surge or from other processes that act to enhance the trade wind flow.

Another special feature of the N.I.O. basin was the existence of dual cyclones on either side of the equator (Fig. 27). The strengthening of the equatorial circulation about a tropical cyclone in one hemisphere can be related to a similar increase in the equatorial low-level circulation of the other hemisphere. These wind field increases may be caused by an increase in the meridional pressure gradient force or by the simultaneous increase in winds due to the development of both cyclones. Lee (1986) also showed the interactions between tropical cyclones in the western North Pacific. Keen (1982) and others have observed the occurrence of cross-equatorial tropical cyclone pairs in both the Indian Ocean and in the Pacific.

A strong low-level positive vorticity field is very important to tropical cyclone formation in the N.I.O., as it is in most monsoon-trough genesis regions (as previously discussed by Gray 1968, 1979). However, in this analysis, the initial enhancement of low-level circulation about the pre-cyclone disturbance was typically on only one side of the disturbance (i.e., equatorward side or poleward side). Early cyclone formation and later growth cause a gradual wrapping around of the tangential wind field to the other sides of the cyclone. Using time series of the individual storm profiles we have shown how much variation there can be in changes of the maximum intensity, $V_{\text{max}}$, and the outer circulation; $\bar{V}_r$ (700–1000 mb), and divergence fields, $\bar{V}_o$ (150–250 mb) at $6^\circ$ radius. Although we have already demonstrated how both of these parameters appeared to increase before cyclone intensification starts, once intensification begins, outer wind features do not

\[ 1 \text{ The time series for TC 22-79 and TC 26-79 also showed similar characteristics but because of their very short life span and overall weak intensity they are not shown here.} \]

Fig. 22. Cross section of tangential wind for TC 24-79 at 1200 UT October 31 ($V_{\text{max}} = 17 \text{ m s}^{-1}$).
Fig. 23. Plan view of low-level circulation (700-1000 mb $V_t$) in m s$^{-1}$ relative to the center of TC 24-79 at (a) 1200 UTC 27 October and (b) 1200 UTC 28 October. Arrows are indications of primary wind flow about the center.

Fig. 24. Plan view of upper-level radial wind (150-250 mb $V_r$) for TC 24-79 at (a) 1200 UTC 28 October and (b) 1200 UTC 3 October in moving coordinates in m s$^{-1}$. Arrows are indications of primary wind flow about the center.
always behave in unison with the changes in the cyclone’s maximum wind values. In fact, in some cases these outer values decreased as the central intensity increased. There can be many reasons for these results. In one obvious situation, the inner circulation intensifies and concentrates in association with increases of deep convection near the center. This concentration and build up of circulation could not be readily monitored inside 6° radius with the FGGE III-b data. It is also likely that the changes in \( V_{\text{max}} \), \( \bar{V}_t \) and \( \bar{V}_o \), can behave independently of each other. This has recently been shown to be the case by Weatherford and Gray (1988) when comparing maximum intensities of Pacific tropical cyclones with aircraft measured values of \( \bar{V}_t \) averaged over a 100 to 250 km radius from the cyclone’s center at 700 mb.

1) **Upper-Level Flow Characteristics**

McBride (1981), McBride and Zehr (1981) and others have emphasized the importance of upper-level anticyclonic vorticity (besides the low-level positive vorticity) for tropical cyclone genesis in the western North Pacific and Atlantic. We did not observe a significant systematic change in the strength of the upper-level anticyclonic vorticity in the early stage genesis of our N.I.O. systems, although there was an increase in net upper-level radial outflow about 1–2 days before intensification began. Sieranka et al. (1986) found a similar feature in their analyses.

Upper-level anticyclonic flow features and outflow channels, however, appeared to play a very important role in the later intensification stages of N.I.O. cyclones. Since the increase of maximum winds (\( V_{\text{max}} \)) in these systems was often not well related to the net upper-

![Figure 25](image)

**Fig. 25.** The ECMWF analyzed 200 mb wind field associated with TC 24-79 for 0000 UTC 31 October (\( V_{\text{max}} = 15 \, \text{m s}^{-1} \)). The large dot denote the approximate center of TC 24-79. Troughs and streamlines have been analyzed by the authors (isotachs are in m s\(^{-1}\)).

![Figure 26a](image)

**Fig. 26.** Time series of (a) TC 23-79 and (b) TC 25-79 of intensity (\( V_{\text{max}} \)) in m s\(^{-1}\), low-level (700–1000) 6° radius outer circulation (\( \bar{V}_t \)) in m s\(^{-1}\), and upper-level (150–250 mb) outflow (\( \bar{V}_o \)) a 6° radius in m s\(^{-1}\).
what happened in the case of TC 22-79 (figure not shown; refer to Lee and Gray 1984). Thus, the favorable positioning of the cyclone center with that of the environmental flow may be what is required to help create the narrow, vigorous outflow channels necessary for intensification (Merrill 1988a,b; Holliday and Thompson 1979; Chen and Gray 1985).

7. Conclusions

Although the FGGE III-b analyses have some drawbacks, they are still a very valuable and unique dataset, especially if one makes primary use of the uninitialized rotational part of the wind field on large time scales. This study shows that it is possible to use the FGGE analyses to study the large-scale circulation patterns associated with tropical cyclone development, if some precautions are taken. Results have indicated that an increase of an asymmetrical low-level circulation occurs before the formation of a tropical cyclone. This increase is generally a result of large-scale forcing, which can come from either the equatorward or poleward side, and is manifested initially as horizontal wind shear. This initial shear vorticity is gradually changed into curvature vorticity and becomes more symmetrical as the storm intensifies. These results agree very well with those by Lee (1986), Love (1985a,b), and Lee and Gray (1984).

A fundamental question is the cause of such surrounding asymmetrical wind buildup. In some cases these strong asymmetrical wind changes appear to be advected into the region where the disturbance will develop in a surge-type fashion. In other cases the asymmetrical wind distributions appear to develop in situ.

The observations of this paper support the supposition that early-stage tropical cyclone development is usually not just a result of the favorable arrangement of internal disturbance meso-scale cloud cluster convective elements and meso-scale flow characteristics but rather is dependent upon special large-scale surrounding environmental flow processes which must occur before developing is to proceed. From the tropical disturbance point of view, such large-scale flow changes might be referred to as external forcing. This argument, however, does not rule out the importance of the internal processes during formation after a favorable large-scale circulation has been set up.

The cyclone’s later stage intensification, on the other hand, appears to be influenced by the upper-level flow characteristic. Intensification generally occurs when favorable outflow channels exist (Chen and Gray 1985). In general, the FGGE year North Indian Ocean tropical cyclones appear very similar to those of the other tropical cyclones in terms of their structure, formation and intensification.

Acknowledgments. This research has been supported by the Naval Environmental Prediction Research Facility (NEPRF) (Grant N00228-83-3122) and by the National Science Foundation/National Oceanic and Atmospheric Administration Grant ATM-8419116. We have utilized the computing facilities of the National Center for Atmospheric Research (NCAR) for ECMWF data analysis from the NSF Grant ATM-8214041. The National Center for Atmospheric Research is supported by the National Science Foundation.

We would like to thank Judy Sorbie, Patti Nimmo and Barbara Brumit for very competent support in the manuscript preparation and the two reviews for their many helpful suggestions.

REFERENCES


