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TROPICAL CYCLONE EYE RE-FORMATION AFTER A 30-HOUR MOVEMENT OVER THE MALAGASY REPUBLIC[1]

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ABSTRACT

An analysis of the life cycle of a tropical cyclone in the Southern Hemisphere is presented. The recurving cyclone of hurricane intensity moved over the Malagasy Republic, and its well-developed eye disappeared. After moving back over warm oceanic water in which the temperature was 28°–29°C, a large cloud-free vortex center was observed by satellite within 30 hr. This center or eye became increasingly well-formed until the storm became extratropical. Some possible conclusions are discussed.

1. INTRODUCTION

A quasi-steady-state tropical cyclone of hurricane intensity born in the Indian Ocean moved west-southwestward through the Ocean Islands, making landfall just south of Mahanoro, Malagasy Republic (19.8°S, 48.8°E). Recurvature to the south took the center of the storm over the rough east-central interior for approximately 30 hr, during which interval the eye (well-formed before landfall as seen by satellite photographs) disappeared. The storm completed recurvature; and within 30 hr after moving back over sea water in which the temperature was 28°–29°C, the storm formed a large cloudless center.

Satellite photographs during the next 48 hr showed the clouds (surrounding the cloud-free center) exhibiting more of the characteristics the storm had before it moved onshore. However, the cyclone never did quite attain its earlier appearance before it became extratropical. Available upper air data suggest the cyclone was maintained aloft in the mid-troposphere while over land and redeveloped its lower structure over a warm-surface oceanic heat source and under anticyclonic conditions in the upper troposphere.

2. DEVELOPMENT AND MOVEMENT OF THE CYCLONE

The tropical cyclone was first observed by satellite photographs in the Indian Ocean near 16°S, 81°E, at 0000 GMT on Feb. 8, 1970. It was so indicated on the tropical strip surface maps (20°N–20°S, 0°–180°E-W) now being analyzed routinely for 0000 and 1200 GMT by the Southern Hemisphere and Tropical Analysis Section of the Surface Analysis Branch of the Analysis and Forecast Division (A&FD), National Meteorological Center (NMC).

The cyclone formed over the warm Indian Ocean in easterlies poleward of the intertropical convergence zone (ITCZ) located near and parallel to 9°S. During the period of formation and deepening, the cyclone remained essentially stationary; but by 1200 GMT on February 9, satellite data showed that a westward movement had begun. By 1200 GMT on February 10, the cyclone was located near 17.5°S, 76°E. Satellite photographs indicated that it had reached hurricane intensity. A satellite weather bulletin for 1022 GMT on February 10 described the storm—stage X, diameter of 2.5°, category 4, well-defined eye. This diameter and category gave an estimated maximum wind speed (MWS) of 85–90 kt (Hubert and Timchalk 1969).

A generally west-southwest movement persisted until recurvature on February 23–24. No less than five other tropical cyclones of varying intensity were in evidence in the tropical Indian and Pacific (Coral Sea) Oceans south of the Equator at the birth and during the life of the cyclone under study. The high water mark of tropical cyclone activity was reached contemporaneously with this storm. A satellite photograph (fig. 1) taken above the Indian Ocean at 0929 GMT on February 17 shows the unnamed cyclone near 16°S, 67.5°E, and cyclone

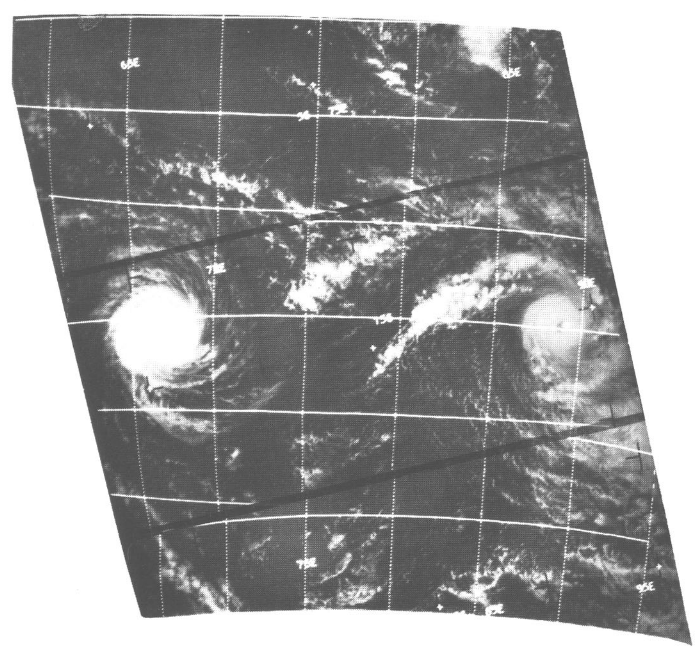

FIGURE 1.—ESSA 9 photograph of the unnamed cyclone (to the left) and cyclone Judy (to the right) at 0929 GMT on Feb. 17, 1970.

[1] After re-formation, the eye is defined in this paper as a cloud-free vortex center.

Judy near 15°S, 88°E. The ITCZ was near 9°S (to the north of the two cyclones). The satellite classification system indicated that the cyclone had maximum winds of 95–100 kt and that Judy had maximum winds of 95 kt (Hubert and Timchalk 1969).

The cyclone (near 18°S, 56.5°E, at 1200 GMT on February 20) was moving through the Ocean Islands in a west-southwest direction at 11 kt. Peripheral ship data (fig. 2) indicated that the storm was quite small, with the area of hurricane-force winds probably not more than 50 to 70 n.mi. in diameter. An ESSA 9 photograph (fig. 3) taken at 1128 GMT on February 21 showed the cyclone (centered near 19°S, 52.5°E) still moving west-southwest at 11 kt. Only a slight increase in size and intensity had occurred in 72 hr, indicating that a quasi-steady state had been attained. The satellite weather bulletin for 1128 GMT on February 21 described the intense cyclone—stage X, diameter 4, category 4. These criteria indicated a maximum wind speed of 105 kt. The eye (fig. 3), with a diameter of approximately 30 n.mi., was clearly discernible.

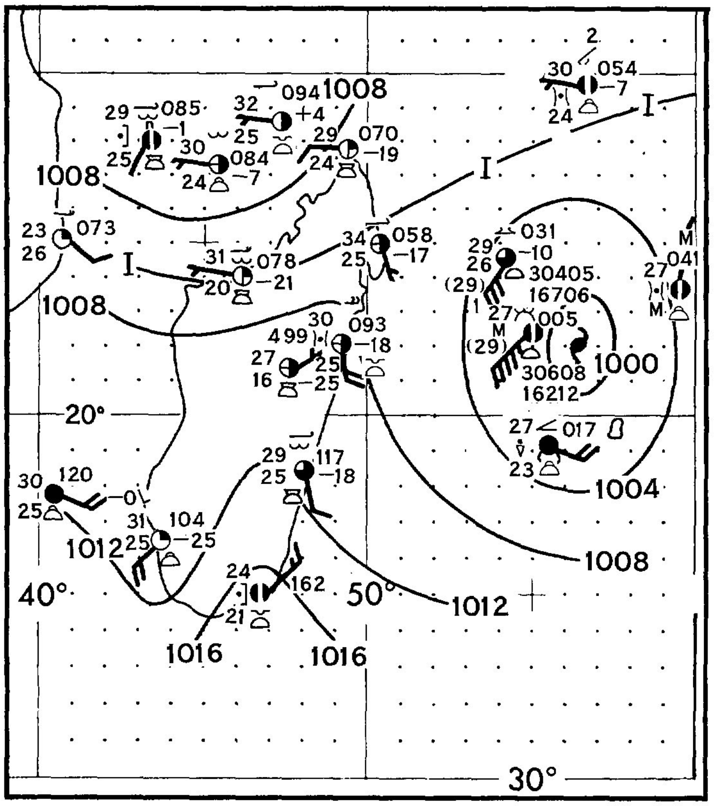

FIGURE 2.—Surface chart for 1200 GMT on Feb. 20, 1970; pressure (mb), temperature (°C), wind (kt), and ITCZ (I–I).

3. LANDFALL, RECURVATURE, AND DISAPPEARANCE OF THE EYE

From 1200 GMT on February 21 until landfall between 0000 and 1200 GMT on February 23, the cyclone exhibited a steady deceleration in its forward movement. The eye of the storm (fig. 4) was still clearly visible at 1012 GMT on the 22d when the center was near 20°S, 50°E, or approximately 75 n.mi. east of Mahanoro. The weather station there was reporting winds (fig. 5) of only 25 kt with the center of the storm in close proximity, indicating again the smallness of the area of hurricane winds. An estimate of maximum winds would be 80–85 kt, a slight decrease in 24 hr, possibly due to the interference of the rough Malagasy landmass with the western edge of the storm.

The satellite photograph (fig. 6) at 1108 GMT on February 23 no longer showed an eye. An apparent center of cyclonic circulation and the densest cloud mass was near 20°S, 48°E, or 30 n.mi. west of Mahanoro. The cyclone had moved onshore and had weakened. No surface or satellite information was available for 0000 GMT on Feb-

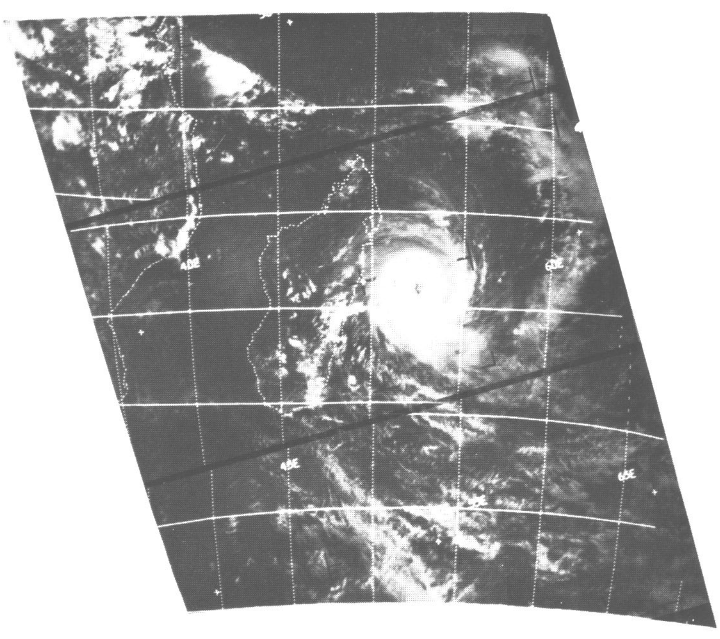

FIGURE 3.—ESSA 9 view of the unnamed cyclone near the Malagasy Republic at 1128 GMT on Feb. 21, 1970; MWS, 105 kt (Hubert and Timchalk 1969).

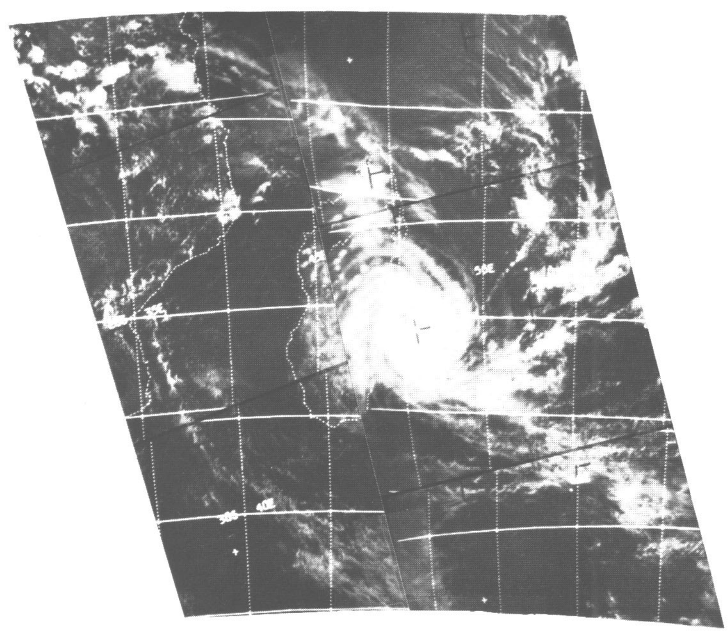

FIGURE 4.—ESSA 9 photograph of the unnamed cyclone near the Malagasy Republic at 1012 GMT on Feb. 22, 1970; MWS, 80–85 kt (Hubert and Timchalk 1969).

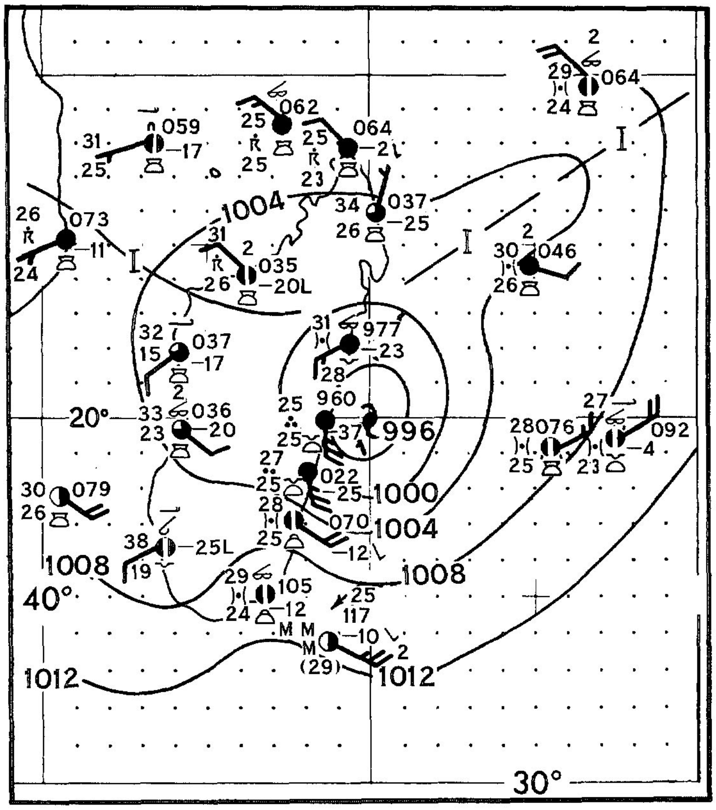

FIGURE 5.—Surface chart for 1200 GMT on Feb. 22, 1970.

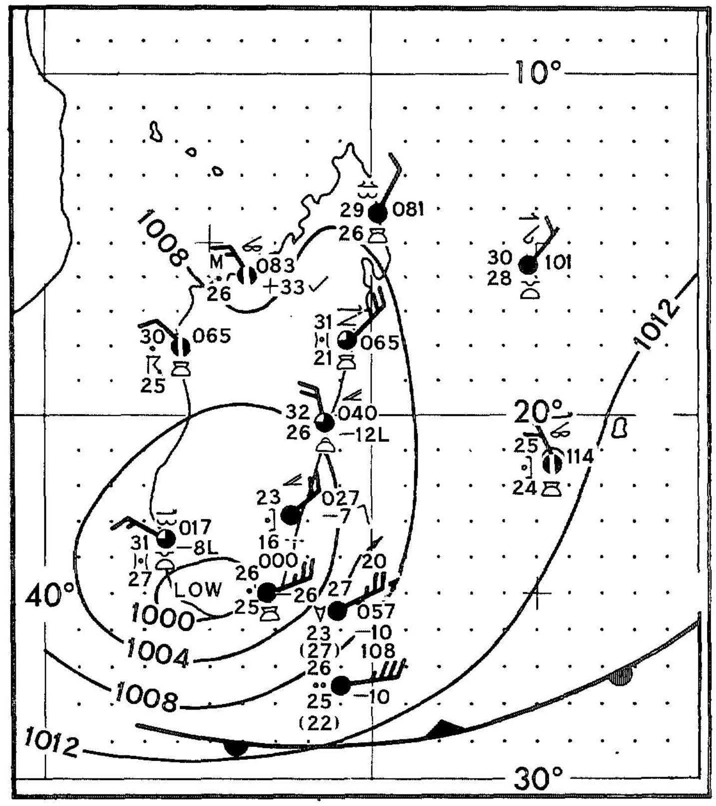

FIGURE 7.—Surface chart for 1200 GMT on Feb. 24, 1970.

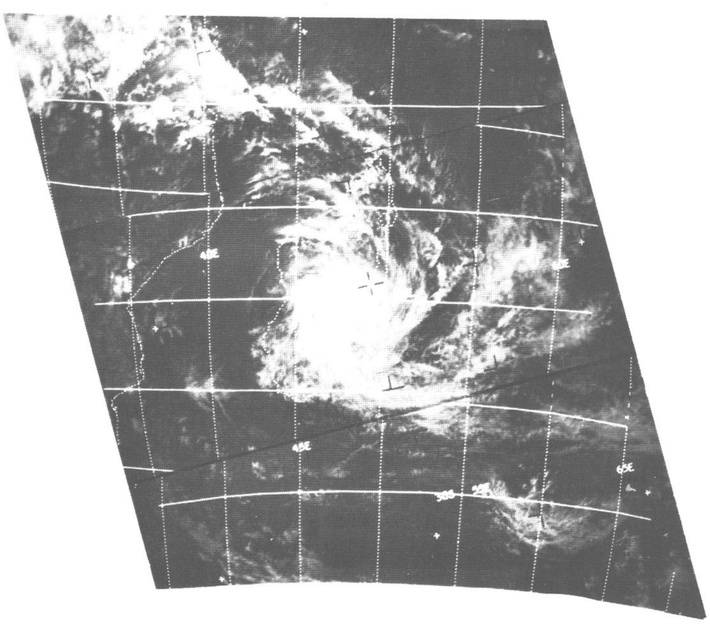

FIGURE 6.—ESSA 9 view of the unnamed cyclone over the Malagasy Republic at 1108 GMT on Feb. 23, 1970.

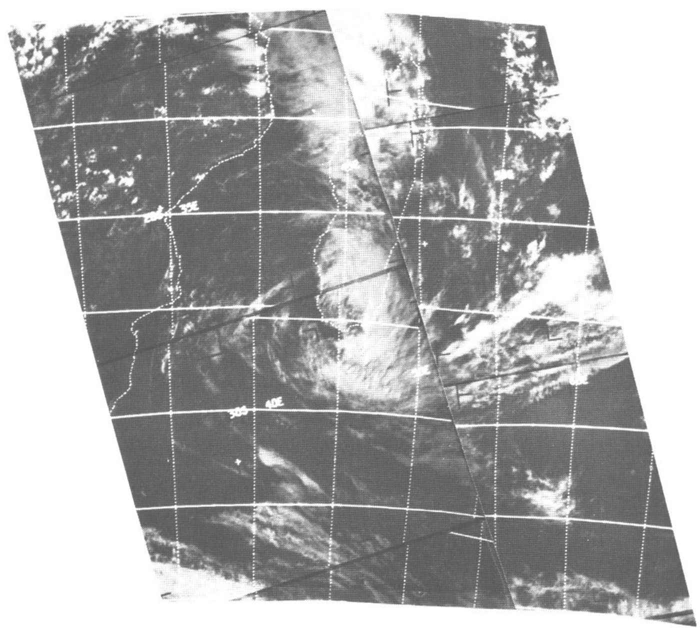

FIGURE 8.—ESSA 9 photograph of the unnamed cyclone over the Malagasy Republic at1207 GMT on Feb. 24, 1970. No eye is visible; and the cloud band, extending southeastward from the center of the cyclonic circulation, may be frontal in nature but could be associated with a high-level jet.

ruary 24. By 1200 GMT on the 24th, surface and satellite data (figs. 7 and 8) located the center near 25°S, 45°E, or approximately 50 n.mi. northwest of Faux-Cap (25.5°S, 45.6°E). Recurvature to the south had begun after 1200 GMT on the 23d, as depicted by the track (fig. 9). The storm, after traversing the rough east-central interior of the island (Madagascar) was beginning to emerge from the landmass. Cyclonic cloud circulation was apparent, but no eye could be detected. Surface data (fig. 7) showed a weakened but

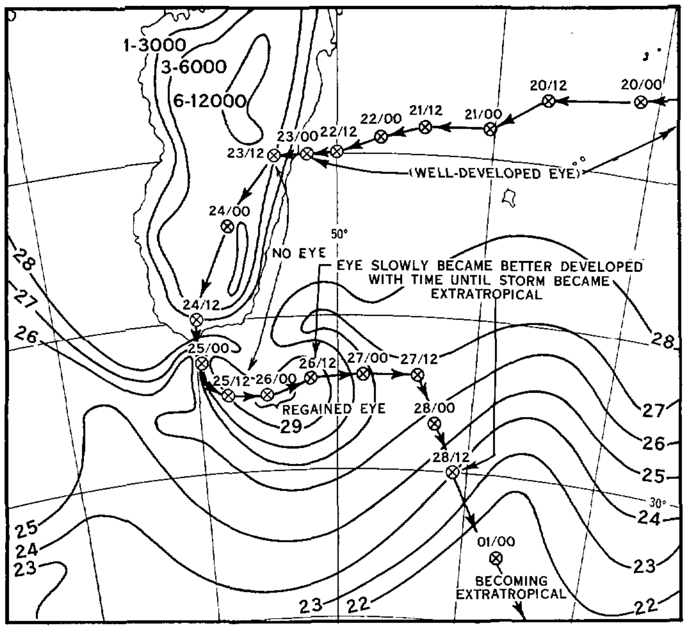

FIGURE 9.—Topographic map (ft) of the Malagasy Republic, including 12-hr positions of the unnamed cyclone and sea water temperature (°C) from ship data for February 1970.

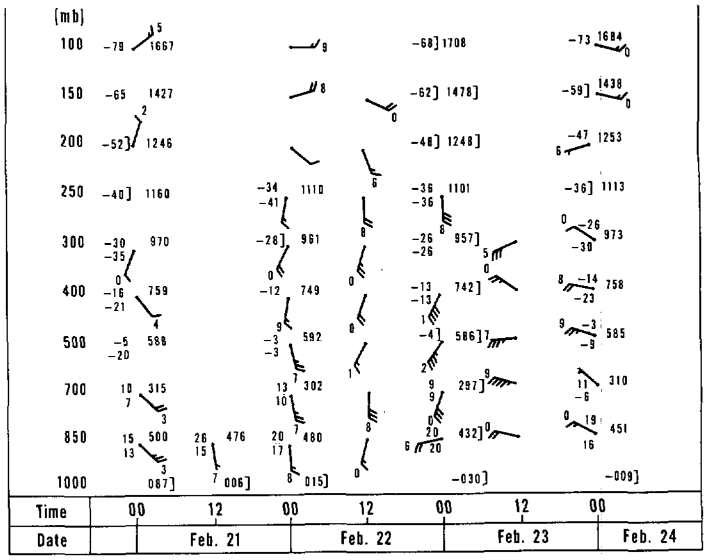

FIGURE 10.—Vertical time section at Tananarive, Malagasy Republic; height [dekameters (dam)], temperature (°C), and wind (kt).

definite cyclonic surface circulation. Over the ocean southeast of the center, squalls and 25- to 35-kt winds were occurring. It is possible that the course of the storm was closer to the coast than figure 9 indicates, but the breakdown of the organization of the central cloud mass (fig. 8) indicated that the storm core was effectively removed from its *surface* energy source.

4. UPPER AIR OBSERVATIONS NEAR THE CYCLONE BEFORE, DURING, AND AFTER LANDFALL

The only consistently available upper air observations over the Malagasy Republic near the cyclone track were taken at Tananarive (18.8°S, 47.5°E, at an elevation of 4,147 ft). Figure 10 shows the vertical time section of the observations available before, during, and after the passage of the cyclone. Unfortunately, radiosonde observations were unavailable at the time the storm was nearest to the station; but useful information was obtained from the observed upper winds.

A general warming trend in the soundings occurred between 0000 GMT on February 21 and 22. Thereafter, the soundings remained relatively unchanged except for cooling at 700 mb at 0000 GMT on the 23d, probably due to precipitation associated with the storm. Tropopause heights were difficult to ascertain from the data available, but they appeared to be near 100 mb. Apparent outflow aloft was evident as early as 0000 GMT on the 22d and continued to appear at 1200 GMT on the same day. The level of change aloft from a cyclonic circulation to anticyclonic was near or above 200 mb.

The upper winds observed at 0000 GMT on February 23, when the cyclone was approximately 120 n.mi. from the station, revealed that the strongest cyclonic circulation aloft was between 700 and 300 mb. At 1200 GMT on the 23d when the storm was at its nearest location to the station (approx. 90 n.mi.), the strongest cyclonic circulation aloft was between 700 and 500 mb.

5. SOME POSSIBLE CONCLUSIONS FROM UPPER AIR DATA AND OTHER CONSIDERATIONS

From the winds aloft observed at 0000 and 1200 GMT on February 23, it appears that the strongest height gradients aloft at the 90-n.mi. radius in the lower troposphere were near 600 mb or 12,000–14,000 ft. This was approximately 6 hr *after* the storm had moved inland and was at its closest proximity to Tananarive.

Since height gradients are known to depend upon thermal gradients and since cooling in the core of the cyclone causes a decrease in height gradients (Miller 1963), it appears that the cyclone did not cool as much in the 700- to 500-mb layer as below 700 mb in the inflow layer.

It is postulated that the height gradients of the central core of the cyclone in the layer between 700 and 500 mb were maintained dynamically during the land traverse. This cannot be proven because of insufficient data. Subsequent events would indicate that large upward vertical motions were maintained near the storm center at some upper level.

When assuming that this was the case, several factors were apparent. One was the tropospheric environment in which the cyclone existed. This was pure maritime tropical air with 850- to 500-mb thicknesses of at least 438 dekameters (dam) or 1000- to 500-mb thicknesses of 579 dam. Another was the state of the summer hemisphere oceanic atmosphere—one of maximum instability. The

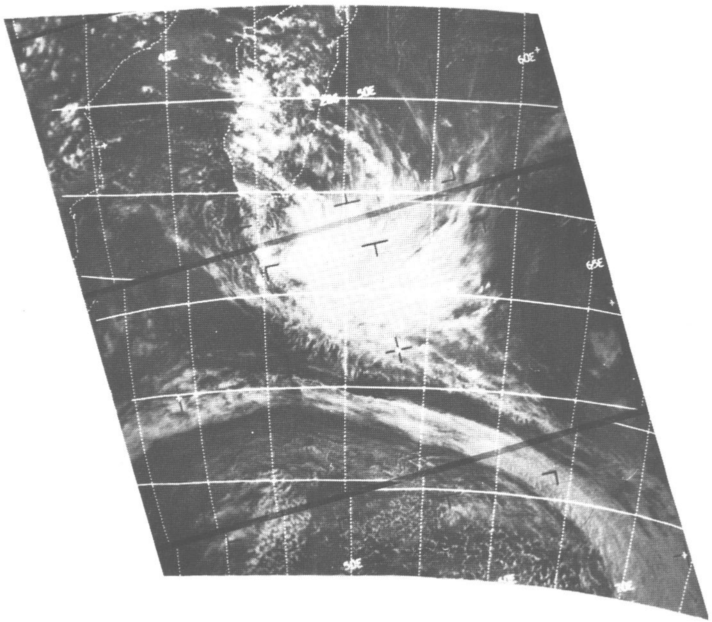

FIGURE 11.—ESSA 9 photograph of the unnamed cyclone as it appeared near the Malagasy Republic at 1110 GMT on Feb. 25, 1970. Note the enlargement of the cloud (banding east and southeast of the center) and a well-defined frontal band extending nearly to 35°S.

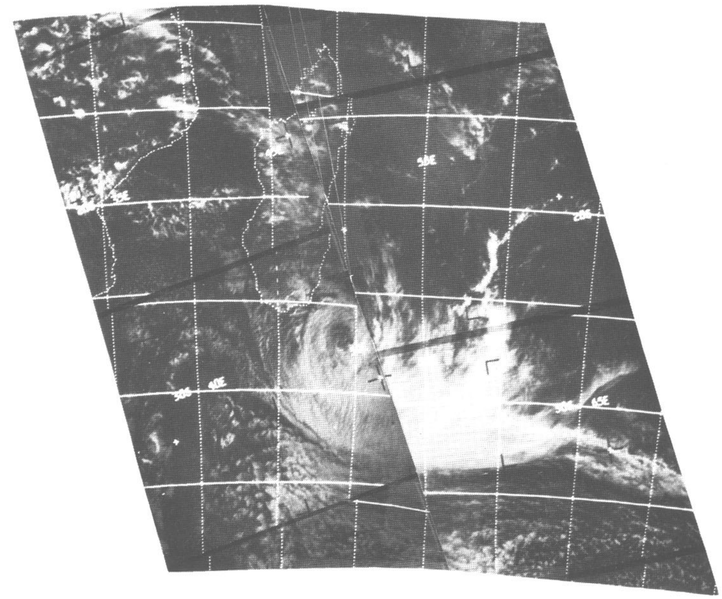

FIGURE 12.—ESSA 9 view of the unnamed cyclone near the Malagasy Republic at 1209 GMT on Feb. 26, 1970.

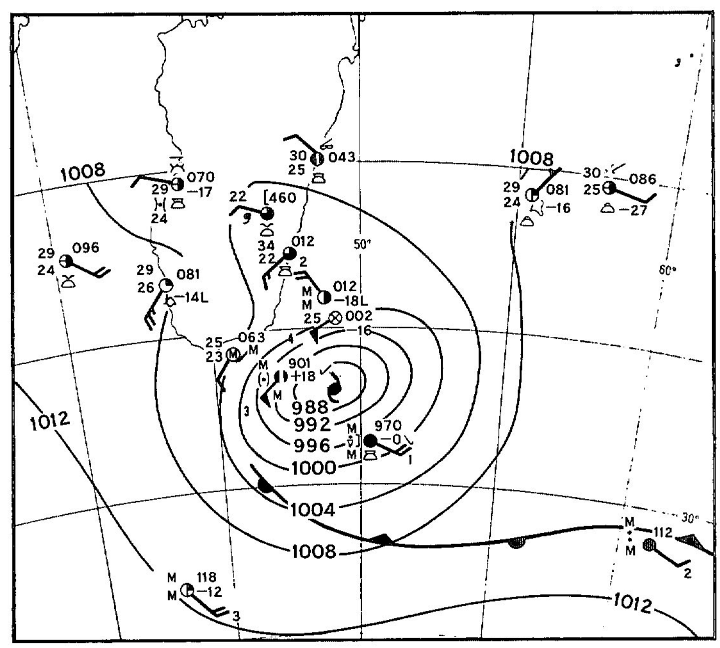

FIGURE 13.—Surface chart for 1200 GMT on Feb. 26, 1970.

large number of contemporaneous tropical storms of varying degrees of intensity gave evidence of this. Finally, a NMC computer-produced 250-mb analysis (not shown), the only upper air chart available to the author, indicated anticyclonic conditions over the cyclone in the upper troposphere.

As the storm moved back over the warm oceanic surface energy source (fig. 9), it is postulated that the maximum upward vertical motions retained in the 700- to 500-mb layer near the core interacted with the surface heat source. A consequent redevelopment of the inflow layer (Miller 1963) and of surface gradients was effected (figs. 11–13), and a large cloud-free cyclonic center was re-formed.

Some cooling of the upper core very likely took place while the cyclone was over land. This cooling may have led to a spreading out as well as a reduction in height gradients. Such expansion may have been responsible for the large size of the re-formed center.

A similar event was possible with the redevelopment of the eye of hurricane Cleo in August–September 1964. Cleo spent almost 3 days over the interiors of North Carolina and South Carolina (losing much of its surface organization) before moving back over an oceanic heat source and redeveloping an eye (U.S. Weather Bureau 1964).

6. RE-FORMATION OF THE EYE

The remnants of the cyclone (fig. 9) moved over water (in which the surface temperature was 28°–29°C) sometime between 1200 GMT on February 24 and 0000 GMT on February 25. By 1207 GMT on the 24th, the center of the storm (fig. 8) was near 25°S, 45°E, with weak but definite cyclonic organization of the clouds. The storm (fig. 11) was centered near 27.5°S, 46°E, at 1110 GMT on the 25th. The area of organized cloud banding east and southeast of the center had greatly enlarged and intensified in 24 hr. According to the NMC computer-produced 250-mb analysis (not shown), conditions at that level were anticyclonic over the area of eye re-formation.

Satellite photographs taken at 1209 GMT on February 26 disclosed that the cyclone (fig. 12) had re-formed a large cloud-free center over 60 n.mi. in diameter near 27°S,

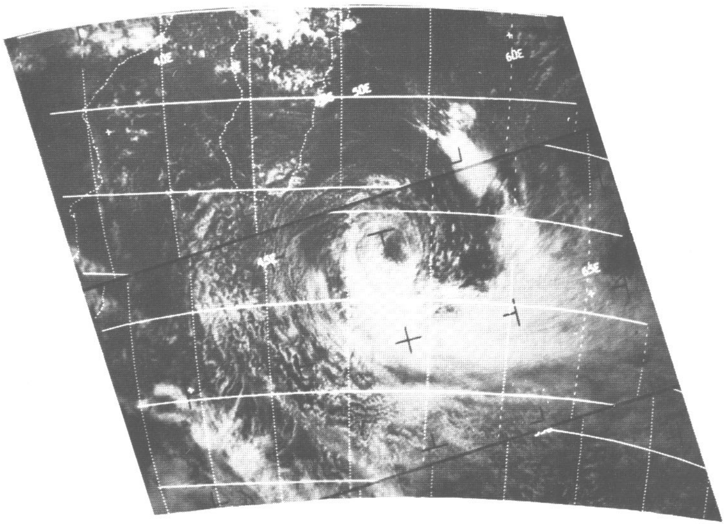

FIGURE 14.—ESSA 9 photograph of the unnamed cyclone near the Malagasy Republic at 1112 GMT on Feb. 27, 1970.

49°E. The clouds surrounding the center presented a more compact organization than those observed 24 hr earlier; however, the bright, compact presentation of the storm before moving over land was lacking.

Some available ship data (fig. 13) at 1200 GMT on February 26 showed sustained winds of 50 kt in the western and northern quadrants of the storm. A surface and inflow layer pressure gradient (sufficient for tropical storm to hurricane intensity) had been regenerated. A front moving in from the south had joined the main cloud area south to southeast of the center, but no cold air had entered the tropical cyclone circulation.

7. FINAL STAGES OF THE CYCLONE

After 1200 GMT on February 26, no surface data were available near the cyclone; satellite data were relied on exclusively. A satellite photograph (fig. 14) taken at 1112 GMT on the 27th showed a circular cloud mass surrounding the large cloudless center near 27°S, 53°E. Only slight changes were noted from the picture taken 24 hr previously. The frontal band continued to be evident south and southeast of the cyclone. Some possible presence of cooler, drier air appeared from the cumuliform cloud banding around the western, northern, and eastern periphery of the storm. Also, the dry tongue east of 55°E may have indicated this, with a possible front forming along 60°E (east of the dry tongue).

Satellite data for 1016 GMT on February 28 showed continued movement of dry air around the cyclone (fig. 15) with its cloud-free center near 30°S, 54°E. The diameter of the eye was considerably smaller, less than 30 n.mi. The cyclone, appearing more intense than 24 to 48 hr earlier, was beginning to approach the appearance of the storm before it moved over land. The dry tongue east of the center along 60°E had continued to sweep cyclonically

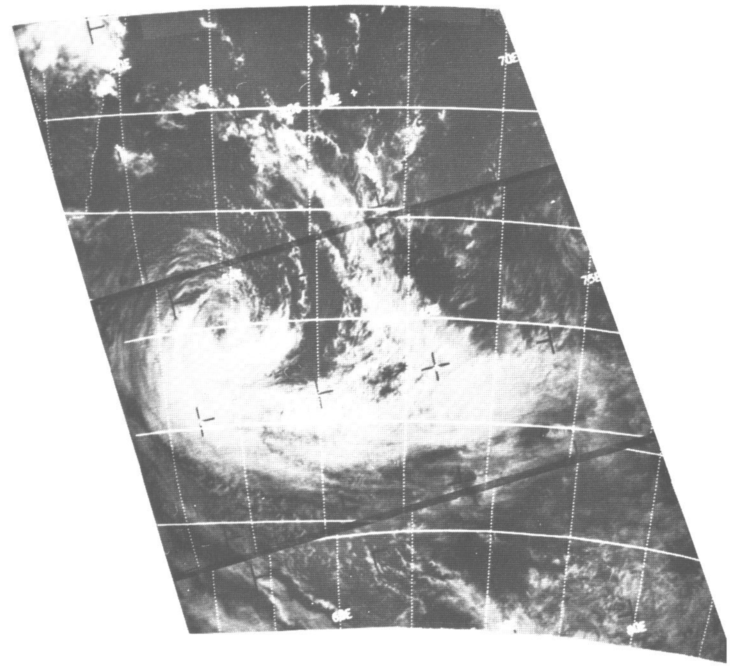

FIGURE 15.—ESSA 9 view of the unnamed cyclone over the Indian Ocean at 1016 GMT on Feb. 28, 1970.

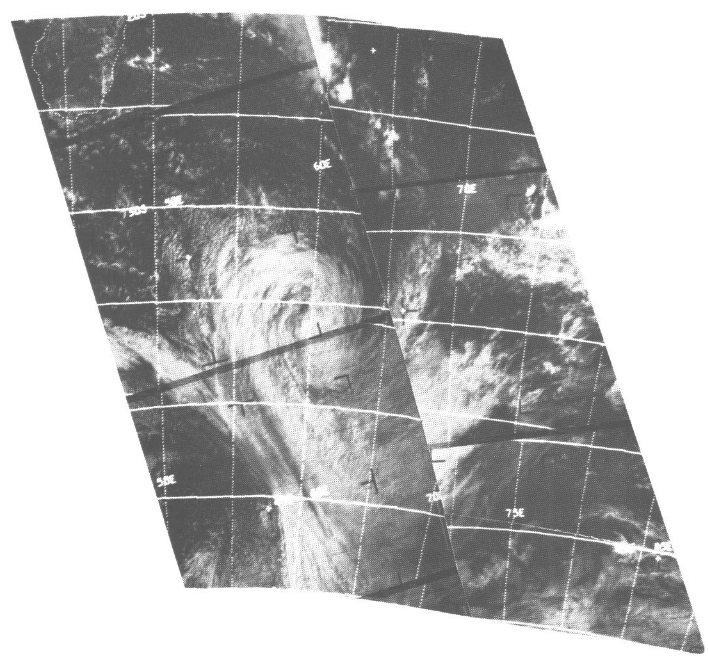

FIGURE 16.—ESSA 9 photograph of the unnamed cyclone over the Indian Ocean at 1114 GMT on Mar. 1, 1970.

around the eastern edge of the cyclone while the cloud band or possible front east of the dry tongue had intensified.

Photographs taken by satellite at 1114 GMT on March 1 gave evidence that the cyclone (fig. 16), centered near 37°S, 60°E, was becoming extratropical. The cloud-free center was no longer visible. The dry tongue east of the storm was still apparent, as was the front between 65° and 70°E. Although the eye was no longer apparent, the

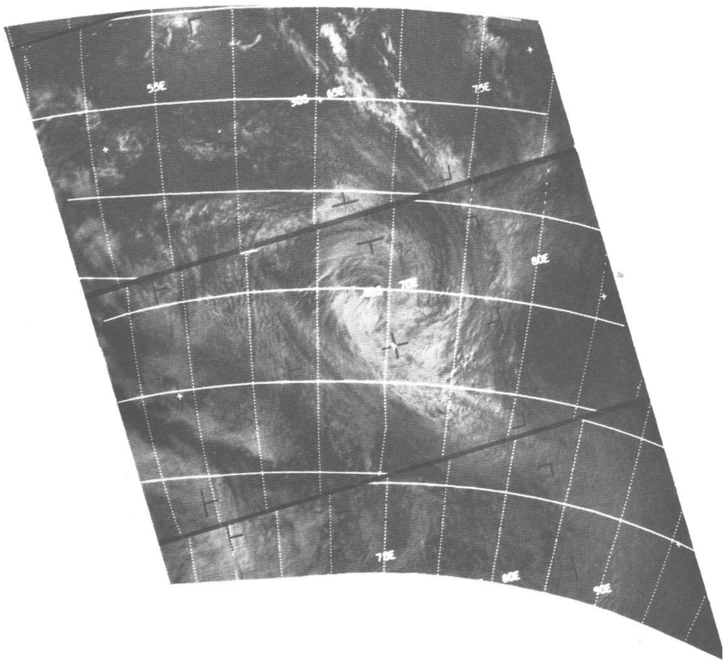

FIGURE 17.—ESSA 9 view of the unnamed cyclone over the Indian Ocean at 1019 GMT on Mar. 2, 1970.

cloud circulation continued to be intense. The storm had accelerated southeastward, with a movement of 7° latitude in 24 hr, indicating that the storm was strongly imbedded in the westerlies. Figure 17 at 1019 GMT on March 2 is a classical picture of an extratropical cyclone. The storm, centered near 40°S, 70°E, was moving southeastward at an accelerated rate.

8. SUMMARY AND CONCLUSIONS

From the foregoing data, we have seen a quasi-steady-state tropical cyclone of hurricane intensity leave its oceanic energy source, move over a rough landmass, weaken, and lose its eye. After approximately 30 hr over land, it moved back over the ocean. Within 30 hr after moving over sea water in which the average temperature was 28°–29°C, a large cloud-free vortex with a compact cloud organization was re-formed. Upper air data suggests the possibility of the cyclone having been maintained dynamically aloft while over land. With the surface energy source again becoming available, the lower tropospheric upward vertical motions apparently interacted with the surface heat source with a consequent rejuvenation of surface gradients and an eye. Upper tropospheric conditions over the area of eye re-formation apparently were favorable (anticyclonic) for redevelopment.

FACTORS INHERENT IN THIS EVENT AND IN SIMILAR EVENTS

1. Occurrences of this nature are *most* apt to happen when the summer hemisphere oceanic atmosphere is at its maximum instability [i.e., when sensible and latent heat available are at a maximum, as is the case in late summer (February through March in the Southern Hemisphere; August through September in the Northern Hemisphere)]. As noted earlier, this cyclone formed and existed while five other tropical cyclones of varying degrees of intensity were in existence—an indication of the instability of the oceanic atmosphere. This is not to exclude early summer or fall events—merely to point out a time of apparent maximum probability of occurrence.
2. The tropical cyclone remains enveloped in a maritime tropical air mass (with 850- to 500-mb thicknesses of at least 438 dam or 1000- to 500-mb thicknesses of 579 dam) while traversing the landmass and during eye re-formation.
3. The storm is a well formed steady-state cyclone of at least moderate hurricane intensity before moving over land.
4. While the storm is traversing the landmass, maximum cyclonic vorticity and upward vertical motions are maintained aloft (probably near 600 mb) by some dynamic mechanism.
5. The shorter the time period the cyclone is over land (removed from its surface energy source), the greater the chance of eye re-formation.
6. Finally, of necessity, the storm must move back over water at or above the threshold temperature for the formation of tropical cyclones (27°C, Palmén 1948). The higher the sea temperature, the greater the chance is of eye re-formation. Favorable conditions in the upper troposphere (neutral or anticyclonic) also enhance eye re-formation.

ACKNOWLEDGMENTS

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