A Warm-Core Disturbance in the Western Atlantic During BOMEX

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ABSTRACT

A synoptic analysis of the only tropical depression in the BOMEX data set shows it to be a kink in the Intertropical Convergence Zone. The depression has a warm core through the troposphere to at least 250 mb, and strongest circulation in and just above the boundary layer. At 250 mb, an anticyclonic wind field lies above the depression. Divergence, vorticity, and relative humidity fields, as well as cloud patterns, corroborate a dynamical picture of the depression wherein air rising in a warm core is associated with convergence and cyclonic vorticity resulting from a kink in the ITCZ. The picture is compatible with the CISK mechanism.

1. Introduction

During July 1969, the fourth phase of the Barbados Oceanographic and Meteorological Experiment (BOMEX) collected data with the particular aim of studying tropical convection. Of the disturbances which passed through the data network, only the one reported here grew sufficiently intense to be regarded as a tropical depression (Frank, 1970). This paper presents a case study of that depression, which passed through the BOMEX data network during the period from 24 to 26 July 1969.4

Warm-core tropical depressions of less than tropical storm intensity have been noted in the Pacific Ocean by Palmer (1951) and in the western Atlantic by Malkus (1962). Riehl (1954) describes the passage of a warm-core disturbance across the Antilles. Elsberry (1966) presented data from a depression observed in the western Atlantic in September 1963 that possessed a warm core and a wind field having its greatest perturbation in the lowest layers. As with ours, this disturbance dissipated without attaining tropical storm intensity.

This case study uses frequent and closely spaced surface, rawinsonde, and aircraft observations to establish a consistent picture of one tropical disturbance in sufficient detail to permit calculations of vorticity and divergence. The results of the case study confirm the schematic synoptic model proposed for such disturbances by Malkus (1962).

2. The BOMEX data

Fig. 1 shows the positions on 25 and 26 July of the rawinsonde stations. Details of the data processing, ship and aircraft observations and satellite pictures can be found in the thesis by Leary (1972). Time compositing was selected as the best method of combining the available data so as to minimize limitations of both quality and quantity.

Charts were prepared for the 25th and 26th of July, each with a nominal time of 1200 GMT (0800 AST). Data taken as far as 12 h from the nominal time were plotted on the composites, with positions corrected for the movement of the storm. A preliminary examination of aircraft and rawinsonde wind data yielded a preliminary model of the depression upon which to base the composites. This model consists of a wind shift line separating northeasterly winds to the west from southeasterly winds to the east at 950 mb. The line had an orientation from northeast (035°) to southwest (215°). The wind shift line moved perpendicular to its orientation, from southeast (125°) to northwest (305°) at a constant speed of 10 kt. Observations for other than the nominal times were displaced along a line parallel to the motion of the wind shift line, by an amount proportional to the deviation of the time from 1200 GMT and the speed of the storm.

The 25th and 26th of July were chosen because on those days the storm passed through the data network, and appeared most intense on satellite pictures. The
region of interest, shown in Fig. 1, was determined by the position of the storm. The data coverage extended from 5°N to 20°N, and from 45°W to 70°W.

3. Streamline analyses

Figs. 2 and 3 show streamline and isotach analyses for the composite charts described above for 25 July and 26 July, respectively, at 950 mb (including surface data where 950 mb data were not available), 850 mb, and the upper troposphere (300 mb and above). Streamlines were determined with considerable care, by first constructing isogons (lines of constant wind direction) and then following the technique described by Petterssen (1956).

A visual impression of Figs. 2a and 3a is that of a piece of the Intertropical Convergence Zone (ITCZ) with a sharp kink from SW to NE, so the ITCZ is predominantly EW on both sides, but more poleward to the east of the kink. The wind converges from both sides. Where the ITCZ bulges north, these converging winds have components parallel to the ITCZ. On the left of the bulge, where the ITCZ runs SW–NE, the converging winds to the left run toward the southwest,
whereas those to the right go northeast; this wind-shift across the line implies cyclonic vorticity.

We expect the strong convergence into the ITCZ to be driven by, or associated with, strong moist convection. On a rotating planet, we also expect strong convergence to be associated with cyclonic vorticity for disturbances of sufficiently long life. Thus, we expect strong convection over a convergence line to be associated with a kink from SW to NE.

4. Vorticity and divergence calculations

Divergence and vorticity patterns for the disturbance could help in understanding the dynamics of the depression, but the observations were irregularly spaced. If we analyzed to a uniform grid, the wide gaps in underlying areas would require a loss of resolution of the sharp features near the center. Besides, the conversion from direction and speed to vector components is tedious by hand. So, we developed a graphical technique that uses the data to best advantage, while being easy to perform by hand.

The separate analyses for the two days at 950 mb (Figs. 2a and 3a) were superimposed, with the centers of circulation coincident. The same procedure was applied to the 850 mb analyses (Figs. 2b and 3b). The wind data in Figs. 2a and 3a were plotted manually on a single base map in the form of vectors to obtain Fig. 4. The 850 mb wind data in Figs. 2b and 3b were plotted in the same way to obtain Fig. 5. The direction of the
arrows in Figs. 4 and 5 represent the wind direction to the nearest degree. Compositing data for both days is necessary to provide enough data points for meaningful calculations of vorticity and divergence. The agreement of the plotted winds was sufficiently good that the resulting Fig. 4 was used in all subsequent work at 950 mb. The velocity data at 850 mb also superposed well, as seen in Fig. 5. These figures suggest that the depression, for the purposes of these calculations, may be adequately described as steady with respect to the moving core, for the two-day period. We expect that any errors in these calculations due to the compositing procedure will tend to reduce the magnitudes of divergences and vorticities rather than to create spuriously high values.

At each point in Figs. 4 and 5 for which a value of the divergence or vorticity field was to be computed, a circle was constructed, with the point at its center, and a radius chosen to maximize data coverage on the perimeter of the circle. Radii ranged from 0.75 to 2.5° latitude, and were generally about 1° latitude. The radius was bigger in areas of sparse data, and smaller when the observations were plentiful. After a circle was constructed, eight equally spaced points on the circle were marked off. For divergence calculations, the outward wind component normal to the circle, $v_r$, was determined at each of the eight points by interpolation from the nearby data. These were added graphically. The divergence was determined by the following
equation:

\[ \overline{\nabla \cdot \mathbf{v}} = - \frac{1}{A} \int_0^r \rho_i dS = \frac{2\pi}{r} \sum_{i=1}^8 \rho_i r_i \]

where \( S \) is the circumference, \( r \) the radius, and \( A \) the area, of the circle, and the overbar denotes an average over the area of the circle.

For vorticity calculations, the procedure was the same, except that the tangential component \( v_t \) of the
wind relative to the circle was measured. The equation used to compute the vorticity was the following:

\[
\nabla \times \mathbf{v} = \frac{1}{A} \oint_{C} \mathbf{v} \cdot d\mathbf{s} = \frac{2\ell}{r} \approx \sum_{i=1}^{8} \frac{v_{i2}}{r_i}
\]

with the sign convention of positive \( v_i \) for counterclockwise (cyclonic) flow and negative \( v_i \) for clockwise (anticyclonic) flow.

The 950 mb velocity field of Fig. 4 was selected for the divergence calculations because it is representative of the planetary boundary layer, wherein most of the

\[
\text{DIVERGENCE UNITS: 10^{-4} sec^{-1}}
\]

950 mb

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**Fig. 5.** Same as Fig. 4, for 850 mb.

**Fig. 6.** Divergence \(10^{-4} \text{ s}^{-1}\) field calculated from the 950 mb wind observations in Fig. 4. The position of the vortex center is shown by an asterisk.
convergence was taking place. In contrast, the 850 mb velocity field exhibits much weaker convergence (e.g., compare the wind fields in Figs. 3a and 3b). Fig. 6 shows the resultant analyzed divergence field at 950 mb.

The 850 mb velocity field of Fig. 5 was selected for the vorticity calculations because it should be high enough to be less directly affected by friction than the 950 mb velocity field, but low enough to show pronounced vorticity, and to compare with the 950 mb divergences. The results are shown in Fig. 7. The fact that the contoured fields of Figs. 6 and 7 are physically reasonable justifies our faith in the compositing technique and the analysis procedure.

5. Divergence and vorticity fields

The main feature of the divergence field of Fig. 6 is an area of strong convergence, with a diameter of the order of 100 km and magnitudes up to $5 \times 10^{-3}$ s$^{-1}$. By conservation of angular momentum, one expects convergence to collect the earth's rotation into a concentrated vortex. This relative vorticity is indeed clearly seen in Fig. 7. There is a prominent area of cyclonic vorticity centered approximately on the axis of the trough in the 850 mb flow field of Fig. 5. The maximum measured cyclonic vorticity is $6.9 \times 10^{-6}$ s$^{-1}$, nearly twice the local value of the Coriolis parameter. In the rear of the trough (to the southeast) there is a pronounced ridge in the flow, with anticyclonic vorticities up to $3.5 \times 10^{-3}$ s$^{-1}$, nearly cancelling the earth's vorticity. The strongest convergence lies between the cyclonic and anticyclonic centers. This is consistent with a kink in the ITCZ because the cyclonic circulation at the northward bulge brings air up from the SW at the same time that the anticyclonic circulation east of the trough axis brings up air from the southeast. These air currents meet the trades in a particularly strong convergence (e.g., see Fig. 3a).

West of the trough the vorticity field is relatively featureless, associated with widespread, but rather weak divergence.

A strong low-level convergence is associated with rising of (moist) surface air and condensation, implying clouds, high humidities, and warm air over the area of convergence. Direct observations are discussed later. One of the consequences of a warm core, by the hydrostatic relation, is relatively high pressures aloft, which should lead to upper-level anticyclonic flow. About the depression, the upper-level flow is strongly anticyclonic, as Figs. 2c and 3c show. This high-level anticyclonic flow is consistent with a dynamical picture of the depression featuring low-level convergence and cyclonic flow, rising motions and convective precipitation in middle levels, and outflow in the upper troposphere. By conservation of angular momentum, the outflow becomes anticyclonic to compensate for the angular momentum lost to the earth due to friction in the surface layer. This picture of low-level inflow and outflow at high levels is also consistent with the recent results of Yanai et al. (1975), who find a high correlation between cloud base vertical mass flux and the large-scale vertical velocity at or near the detrainment level.

6. Thermal structure and humidity

Figs. 8 and 9 show temperatures from the NOAA RFF flights on 26 July at 1.524 km (5000 ft) and 3.048 km (10,000 ft).
associated with the depression at 1803 GMT on 25 July. These outlines were obtained by carefully sketching the position of the cloud boundaries from ATS III satellite photographs. The cloud pattern was repositioned to a reference time of 1200 GMT on 26 July, for consistency with the other figures.

The cloud pattern delineates nicely the kink in the ITCZ, and fits well the humidity analyses. The two ATS III satellite photographs available on 26 July are similar, but show some shrinkage in cloud cover.

7. Discussion

The depression described in this paper possesses a warm core, is most intense in the lowest layers of the atmosphere, and is overlain by anticyclonic circulation in the upper troposphere.

Frank (1970) associates this depression with a disturbance passing over Dakar in western Africa on 19 July. Perhaps a portion of the ITCZ resembled a beam pressed together at the ends by a passing disturbance or an upper-level divergence which interacted with the ITCZ to produce a kink. This kink could in turn convert the convergence into vorticity and concentrated winds which lead to intense convection. The
close association between boundary-layer convergence and mid-level indicators of rising motion is rather impressive, and is consistent with the CISK theory of frictionally induced convergence in the subcloud layer (Charney, 1964).

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