The Role of Organized Unsatuated Convective Downdrafts in the Structure and Rapid Decay of an Equatorial Disturbance

EDWARD J. ZIPSER

National Center for Atmospheric Research, Boulder, Colo.

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ABSTRACT

The Line Islands Experiment, conducted on and near Palmyra, Fanning and Christmas Islands during February-April 1967, produced extensive data on disturbances of the equatorial trough zone. One disturbance which passed through the heart of the data network is analyzed in detail. This disturbance intensified rapidly just east of Fanning Island during the night of 31 March-1 April, but satellite observations show that it dissipated rapidly during the daylight hours of 1 April. The convergence-divergence patterns associated with the growth and decay of the disturbance are most intense in the lowest 300 m. Data from serial rawinsonde releases on the islands, combined with research aircraft data, are presented which demonstrate that highly unsaturated downdrafts are produced, first on the convective scale and the mesoscale, and finally becoming organized over the entire 600-km extent of the system. Cumulus development is effectively suppressed in the downdraft air, only being restored after 6-12 hr by the greatly enhanced energy flux from sea to atmosphere, and through the boundary layer. In order to produce the observed downdrafts, it is shown that the three-dimensional circulation patterns and thermodynamic processes within regions of intense convection are closely analogous to those in typical mid-latitude squall lines.

1. Introduction

It is now generally recognized that one of the central problems of tropical meteorology is the interaction between synoptic-scale systems and processes on the convective scale. The most significant interactions of this type take place in organized disturbances, in which large convective clouds are concentrated. In their study of the energy budget of the equatorial trough zone, Riehl and Malkus (1958) state that synoptic-scale disturbances account for the bulk of the vertical energy transport, and that individual cumulonimbus towers themselves can accomplish most of the required transport. They also point out that convective downdrafts are another likely agency for contributing to the energy transport through deep layers of the atmosphere, and also enhance the energy transfer from sea to atmosphere by bringing cooler and drier air in contact with the sea surface.

Little has been written on the meteorology of the central equatorial Pacific region, as opposed to its climatology. The nature of the disturbances within the equatorial trough in the central Pacific has remained particularly obscure. Palmer (1952), in describing the equatorial wave model, claims that such waves "are characteristic of the central Pacific, between the longitudes of 160°E and 150°W." While unquestioned documentation of the waves exists in the region of the Marshall Islands, the author is unaware of any similar documentation east of the 180° meridian.

If knowledge of the synoptic-scale circulations east of 180° is fragmentary, knowledge of the nature of their interactions with smaller scale processes is totally lacking. To some extent, this statement is valid over most of the equatorial oceans. Little if any literature exists which specifically incorporates the structure and organization of convective clouds, mesosystems or downdrafts in equatorial disturbances (excluding tropical cyclones). One notable exception is the recent work of Riehl (1967, 1968), which demonstrates significant modification of the low-level thermodynamic properties by convective downdrafts within several disturbances in the Caribbean region. In general, however, the deficiency of this type of study in the literature is not difficult to understand, especially with reference to the Pacific. The synoptic data networks that were set up for the nuclear test programs ceased to exist before the advent of good meteorological satellite coverage. In the Caribbean region, where the synoptic network approaches adequacy, Simpson et al. (1967), although in possession of some satellite and aircraft data, were unable to discuss the role of sub-synoptic scale processes, even though it was apparent that such processes must have been of critical importance in accounting for the rapid time changes in the disturbances they described, and for the great differences that

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they cited between those disturbances and accepted synoptic models. A combination of frequent satellite data and adequate conventional data on all scales seems to be a requirement for studies of convective-synoptic scale interaction.

The Line Islands Experiment, conducted on and near Palmyra, Fanning and Christmas Islands (Fig. 1) during February–April 1967, produced a comprehensive sample of satellite, aircraft and surface-based meteorological data. The frequent pictures taken by the ATS-1 synchronous satellite are an important new component of this data package. A complete catalogue of the data obtained is available (Zipser and Taylor, 1968). The Line Islands Experiment data provide an opportunity for detailed analysis of some equatorial trough zone disturbances, and one specific well-documented example is presented here. This is not necessarily proposed as a synoptic model, or even as a “typical” system for the region, but as a rather extreme example of the extent and importance that downdrafts can assume in an equatorial disturbance.

2. The 1 April 1967 disturbance

The first direct indication of this disturbance in the Line Islands was the onset of heavy rain showers at Fanning Island, at midnight of 31 March. The showery conditions changed to steady rain for several hours before ending at sunrise of 1 April, with a total rainfall of 41 mm. What made the system interesting was the sudden onset of strong winds at 0112 local time (1112 GMT), which persisted for about 5 hr, over an order of magnitude longer than the ordinary squall wind. While not severe by tropical disturbance standards, no stronger low-level winds were observed at any time during the two months of the program. The mean hourly surface wind speed reached 14 m sec\(^{-1}\) at a windward station on Fanning, and the 0321 rawinsonde measured a speed of 24 m sec\(^{-1}\) at a height of 300 m, decreasing with height thereafter. At exactly 0800, Palmyra experienced a sudden onset of strong winds, which also persisted for several hours. In contrast with the situation at Fanning, the winds were not accompanied by precipitation at Palmyra, but by stratus-cumulus clouds at first, then by a complete clearing of low clouds.

A distillation of events on the three Line Islands surface weather stations is presented in Fig. 2. The periods of strong winds just mentioned are evident on the Fanning and Palmyra time sections, and the pronounced wind direction shift which accompanies the winds at Palmyra can be seen. Also at Palmyra, there is a marked pressure rise (corrected for diurnal variations) during the high wind period. At Christmas, just to the south of this weather system, no rapid changes in wind speed are observed.

The lack of data for large regions surrounding the Line Islands prevents an accurate large-scale analysis of the environment of the disturbance, but the generalized wind field over the tropical Pacific at low levels and at 250 mb near midday on 1 April is shown in Fig. 3, with a satellite picture for the same time (Fig. 4). The disturbance affecting the Line Islands is located within the equatorial trough zone, with the convergence zone near its normal location (Sadler, 1959) of 5N. The westerlies over this region at 250 mb were persistent throughout the period of the Line Islands Experiment and are at about their average strength. The presence of convergence zones on both sides of the equatorial dry zone suggested by the cloud distribution is also not unusual.

The weather system in the Line Islands, therefore, appears to be a rather strong disturbance in a normal location in a normal large-scale environment. A logical and straightforward first step in its study would seem to be to use satellite data to produce its track and life history. This exercise produces a startling result; namely, that no such system exists on the late afternoon of 31 March, only 7 hr before its arrival at Fanning. As subsequent documentation verifies, the system undergoes intensification and expansion between 1800–2200 on 31 March, probably passes its peak intensity just before reaching Fanning at 0100, and dissipates during the daylight hours of 1 April. The structure of the system through its life cycle will now be examined.

\(^a\) The Line Islands are in the 150W meridian time zone, 10 hr behind GMT. For convenience, this local time will be used throughout the paper.
Fig. 2. Mean hourly surface wind direction and speed at Palmyra, Fanning, and Christmas Islands. The hourly rainfall in tenths of millimeters is given next to the wind speed. At Palmyra, the hourly deviation from the April mean for that hour \( (p-p) \) is also given.

\[ a. \text{Cloud structure} \]

A series of satellite pictures spanning the life history of the disturbance is shown in Fig. 5. The middle four pictures cover most of the daylight hours of 1 April. At 0820, there is a solid cloud shield of about 300 km by 550 km, with Fanning near its center. Since the rain has already stopped at Fanning, the implication is that active convective clouds and rain are confined to the west and north portions of the cloud mass. At 1005, the shield is still relatively solid, but the rudimentary cloud line on the north flank seen at 0820 has now become well-defined on the west and north flanks. The apparent increase in brightness and sharpness in the 1005 picture is artificial and due to being from a different satellite system. Through the remainder of the day, the cloud shield dissipates, while the cloud line takes on a well-organized curved shape and moves rapidly west and north, expanding to a total length of 900 km. It will be shown that this line marks the leading edge of the downdraft air at low levels. If this is so, it is apparent that this downdraft air had already filled the system by 0820, and it is likely, even at this time (Fig. 5b), that the solid cloud shield is composed mostly of inactive stratiform clouds at middle and upper levels, the debris resulting from previous strong convection. There is still considerable rain falling from these clouds, however. The first available picture on the next day (Fig. 5f) shows the complete disappearance of the original disturbance and new cloud development to the north and west near the final borders of the downdraft air.

The location of the edge of the downdraft air as a function of time is given in Fig. 6. Despite the deficiencies, the system can be back-tracked from Fanning for a few hours with some confidence. It is patent
Fig. 3a. Large-scale streamline pattern over the tropical Pacific Ocean at 250 mb at 14 local time, 1 April 1967. Rawinsonde observations are signified by circles, winds from commercial aircraft by squares.

Fig. 3b. Large-scale streamline pattern over the tropical Pacific Ocean at low levels at 14 local time, 1 April 1967. Rawinsonde observations at 300 m are signified by filled circles, surface winds from ships or islands by open circles. Several observations plotted in sparse data regions are off-time.
obvious that the disturbance in question cannot be identified with the large cloud mass near 10N on the previous day (Fig. 5a). Rather, suspicion is cast on the mesoscale cloud system near 5N, 155W. It is likely that this system moved toward the west-southwest, undergoing nearly explosive intensification and expansion before reaching Fanning, as it already had an extensive downdraft by that time, indicating some considerable lifetime.

b. Boundary layer winds

The wind field in the boundary layer is represented by space-time sections (Fig. 7). The “streamlines” on these charts are valid to the extent that a time-to-space conversion of the observations is valid. In Fig. 7a, during the supposed rapid intensification phase of the disturbance, a broad east-west zone of convergence is implied, concentrated just south of Fanning. Associated with this zone are a number of aggregates of large cumulus and small cumulonimbus clouds (see Fig. 5a), some of which produce mesoscale downdrafts, which are represented schematically in Fig. 7a and which are documented in Section 3a. This wind field is consistent with the hypothesis that the disturbance intensified and expanded by rapid cumulonimbus growth in the area so indicated. Ground-based observations at Fanning confirm this sequence of cloud development. After 2200, the southerly component of the wind all but disappears at Christmas, but the disturbance has probably attained peak intensity by this time.

The situation 12 hr later has changed dramatically (Fig. 7b). The downdraft air extends over a large area and is about to reach Palmyra. At this time, Doppler winds along a research aircraft track supplement the island-based observations. The wind field within the downdraft air is strongly divergent, both in speed and direction.

There are significant differences between the winds near the surface and at 850 mb (Fig. 7b). The strong confluence near the surface that was associated with the rapid intensification of the disturbance cannot be found at 850 mb. Since a study of individual soundings reveals that it is only barely apparent at 950 mb, it is likely that convergence is confined to the sub-cloud layer. As Gray (1968) and others have pointed out, when dealing with most tropical soundings, it is only in the sub-cloud layer that convergence will be effective in producing intense convection. The major downdraft region appears much less divergent at 850 mb than near the surface. This impression is reinforced by the time section of vertical soundings given in Fig. 8. The two soundings made in the downdraft air, at 1100 and 1400, reveal winds backing strongly with height; by 800 mb the wind direction is the same inside as outside the downdraft regime.
Fig. 5. Sequence of satellite pictures spanning the life cycle of the 1 April 1967 disturbance in the Line Islands region. The mesoscale cloud system seen on the previous afternoon (Sa, heavy arrow) is probably the only precursor of the disturbance in existence the previous day. The sequence 5b-5e shows the cloud shield of the disturbance dissipating during 1 April, coincident with the rapid expansion of the curved cloud line which marks the leading edge of the downdraft air. Palmyra, Fanning and Christmas Islands are located by letters on each picture.
c. Winds above the boundary layer

The Palmyra height-time section (Fig. 8) depicts the low-level easterlies giving way to winds with a westerly component at 600 mb. The strongest westerlies are just above 200 mb, where speeds approach 30 m sec\(^{-1}\). The height-time section for Christmas (not reproduced) shows virtually identical conditions, and neither station shows significant time changes in wind velocity, suggesting that this weather disturbance is not associated with any marked wind system in the middle or upper troposphere. Palmyra (except for the lowest 200 mb) is on the northern fringe of the disturbance, and Christmas on the southern. When the height-time section which best represents the interior of the disturbance is examined (Fanning, Fig. 9), the major difference that is found is in the middle troposphere. Whereas westerlies are found in the environment everywhere above 600 mb, a deep zone of easterlies exists at Fanning for some 6–9 hr, affecting the layer from 600–350 mb.

The space-time section for the Line Islands at 500 mb (Fig. 10) assists in visualizing the events in the middle troposphere. A small scale anticyclone is implied north of Fanning, and a cyclonic shear zone of limited extent south of Fanning. While one might postulate that these small-scale systems were traveling westward along the intertropical convergence zone and were related to the development of the disturbance, it seems more reasonable to regard them as a result of the intense convection. Recalling that the most intense convection developed near and east of Fanning during the night, note that the air with high equivalent potential temperature in Fig. 10 can be traced back to this critical region of space and time. The actual situation is quite complex, as the appearance of Fig. 10 changes significantly by going up or down only 50 mb.

3. Structure and origin of the downdraft air

a. Individual convective systems on 31 March

Prior to the major development, a number of mesoscale and smaller cloud systems existed within a zone about 400 km wide extending along a west-southwest axis through the Line Islands region (Fig. 5a), along the convergence zone of Fig. 7a. The active convective clouds reach heights of 6–10 km, and the larger systems have lifetimes of several hours. There is little change in the large-scale wind field or thermodynamic structure on 31 March, so it is believed that these systems were growing and dying in the same environment as that of the system which developed explosively that evening. The active convective towers existed in an environment in which the shear of the zonal wind through their depth exceeded 35 m sec\(^{-1}\). Since each mesosystem moved generally westward at 10–15 m sec\(^{-1}\), the relative
Fig. 7a. Space-time section of low-level winds centered around 0730 local time, 31 March 1967, or during the period of suspected rapid intensification of the disturbance in the area marked "rapid cumulonimbus growth." The symbols are the same as in Fig. 7b.

Fig. 7b. Space-time section of low-level winds centered around 0730 local time, 1 April 1967, or during the period of best documentation of the large-scale downdraft. The open circles represent mean hourly surface winds, the filled circles represent rawinsonde winds at 300 m, and the squares represent aircraft winds at 150 m. The space-time conversion is based upon westward motion of systems at 15 m sec⁻¹, except within the downdraft air, where positions have been modified in accordance with probable air trajectories. Heavy dashed lines mark the edge of the downdraft air, only schematically in the case of the mesoscale downdrafts. Light dashed lines are 850 mb "streamlines."
wind into the systems in the middle troposphere was from the west-southwest at 20 m sec\(^{-1}\). Some typical convective towers on the north and west flanks of one such system were photographed from Fanning just before sunset (Fig. 11). There is obviously ample opportunity for the dry middle tropospheric air to be entrained by these mesosystems, and by implication, the major system as well.

The research aircraft based on Palmyra during the program (NCAR’s Beech Queen Air A-80) made a north-south flight on 31 March through this zone of convective systems (Fig. 12, also Fig. 7a). These modest mesosystems produced downdrafts of considerable extent. From 1518–1529, the side cameras show a dark, active cloud mass to the west, with an anvil shearing over the flight track extending eastward. It is raining from the anvil, but the only rain encountered by the aircraft was between 1525–1528. But significant cooling and drying extends over a 50 km north-south extent, somewhat larger than that dimension of the anvil. Considering the \(v\) component of the wind only, there is strong diffusence and probably divergence in the rain area, noting the direction change from 1523–1529. These winds, diverging from the downdraft area, appear to converge with the 60°–70° winds of the environment at about 1512 and 1530. The high winds and low dew points at 1534 probably indicate an older downdraft, and the beginning of a third downdraft is seen at 1553, where heavy rain showers are encountered under a young and vigorous line of large cumulus.

b. The large-scale downdraft

The clearest evidence of the nature and origin of the low-level air behind the cloud line (Figs. 5, 6) comes from the time cross section of Palmyra rawinsonde observations (Fig. 8). This air arrives at Palmyra at 0800, so the sounding at exactly that time probably does not reflect its appearance significantly. But the next two soundings show the strong southeasterly winds below 800 mb, these winds being associated with remarkable low equivalent potential temperature (\(\theta_e\))

Fig. 9. Height-time cross-section of winds at Fanning.
the 330K isotherm extends below 900 mb. The $\theta_e$ distribution prior to the direct influence of the disturbance is about normal for the tropical atmosphere; a high $\theta_e$ region in the low troposphere, with a minimum of $\theta_e$ in the middle troposphere. There are only two possible origins for the low $\theta_e$ air at 800-950 mb at Palmyra. One is the equatorial dry zone near or south of Christmas, where such air frequently exists above an inversion which may be below 850 mb. In this case, this origin is inadmissible, because the back-tracked trajectory of the air from Palmyra places it over Fanning during the heavy rain period. The other possibility is that the air is of middle tropospheric origin, between 600-400 mb, and that this air descended in unsaturated downdrafts to the low troposphere, where pressure forces (note the pressure rise at Palmyra in Fig. 2 after the

Fig. 11. Rapidly growing small cumulonimbus clouds typical of the north and west flanks of the mesoscale systems of 31 March 1967 (see Figs. 5a, 7a, 12, and text). This composite photograph is from Fanning, looking toward a direction of 150°, with a 120° horizontal field of view, taken at 1800.
cool air arrives) accelerated it out of the rain area. This explanation is accepted as the only reasonable one available.

The cooling in the downdraft air did not take place by evaporation of raindrops into ambient low-level air. All aircraft traverses of precipitation-influenced air at 150 m altitude showed substantial reductions in $\theta_v$, the sole exceptions being small, young cumulus showers. If rain simply cooled the ambient air without replacing it with air from aloft, a temperature decrease and dew-point increase would be the only results, with $\theta_v$ remaining unchanged. The term “downdraft air,” by implying the middle tropospheric origin of the low-level air under discussion, is appropriate on all scales up to the full extent of the system.

The research aircraft flew a leg from Palmyra to Fanning at 150 m altitude in the early morning hours of 1 April, just before the downdraft air reached Palmyra (Fig. 13, also Fig. 7b). The most significant contribution of this flight is in verifying that events inferred to occur from satellite pictures and time changes at fixed points in fact have the large horizontal dimensions in space that were implied. Details on mesoscale structure are also added that are not available from the fixed stations.

The aircraft intercepted the leading edge of the downdraft air 44 km southeast of Palmyra, affording an opportunity for a complete horizontal section through the downdraft system. The leading edge of the downdraft air is very well-marked, appearing as a pseudocold front at 0708. The pseudo-front is marked by a cloud line very similar to a line-squall cloud, but the cumulus in the line do not extend to any great height. It is likely that the curved line in Fig. 5, representing this pseudo-front for the remainder of the day, was also composed of cumulus lines of no great height. The driest air between Palmyra and Fanning has a $\theta_v$ of 337K (at 150 m), signifying middle tropospheric origin (0730–0737). It is significant that this lowest $\theta_v$ region coincides with a region of moderate to heavy steady rain from middle clouds, and also with a region of speed divergence. A second and larger region of steady rain from middle clouds, while not accompanied by particularly low $\theta_v$ values, is associated with a region of strong speed divergence (0757–0813). In view of the directional divergence implied throughout most of the major downdraft system by Fig. 7b, these two regions of rainfall probably represent specific generating regions of unsaturated downdrafts, on the mesoscale rather than the convective scale.

Superimposed upon the mesoscale variations, strong sinking throughout the downdraft air in the low levels is implied by the wind field (Fig. 7b) and by cloud observations. Except for the northwestern portion of the downdraft region, no cumulus clouds at all were observed within the downdraft air from the aircraft, from Fanning or from Palmyra. In fact, much of the downdraft region was devoid of low clouds of any type.

The low-level wind field of Fig. 7b can be used to estimate the magnitude of the horizontal divergence within the downdraft region. Excluding a strip along the northern and western borders of the region, the
horizontal divergence in the lowest 300 m is estimated at 5 or 6 × 10^{-6} \text{ sec}^{-1} by the kinematic method. Estimating the fractional change in area with time by the independent method of the rate of expansion of the cloud arc in Fig. 5 \( [(1/A)dA/dt] \) is \( \frac{1}{6} \text{ hr}^{-1} \), giving a divergence of 3.5 × 10^{-5} \text{ sec}^{-1} applied to the entire area of the downdraft. Using 6 × 10^{-5} \text{ sec}^{-1} as a reasonable divergence for that portion of the downdraft air occupied by the strong sinking (the southeastern two-thirds), this implies sinking of 6 cm sec^{-1} at 900 mb, and the order of 10 cm sec^{-1} at 800 mb, presuming that the divergence decreases to near zero at 800 mb.

c. Thermodynamics of the downdraft production

Discussion of the downdraft production itself is hampered by the lack of a sufficient number of direct
observations. While evidence has been presented to show that both processes occurred, the extent to which sinking took place in convective scale downdrafts, or on a larger scale under raining anvils and middle cloud decks, is not known. Certain boundary conditions are known quite well, however. It is clear that air with $\theta_e \leq 330\text{K}$ reached the lowest kilometer on a large scale. It is also known that this air must have originated above 600 mb, and that conditions in the middle tropospheric environment were quite uniform outside the regions of intense convection; note, for example, the distribution of $\theta_e$ at 500 mb in Fig. 10.

The mid-tropospheric environment entering the convective systems is represented by averaging the temperature and dew point of the seven most relevant soundings to form a composite, which is plotted in Fig. 14. From 600 mb, a constant $\theta_e$ downdraft is depicted. For convenience, this is labelled on the thermodynamic diagram in units of equivalent wet-bulb potential temperature ($\theta_w$). This is not a unique process, for the rate of evaporation is an unknown variable. The particular temperature and dew-point curves used were selected by making an estimate of representative values at 900 mb from the radiosonde observations within the downdraft air. This gives an increase in specific humidity of from 2.7 to 8.8 gm kg$^{-1}$ from 600 to 900 mb, and a relative humidity increase of from 36 to 52%, with $\theta_w$ constant at 18°C.

The existence of this highly unsaturated downdraft can be contrasted with the assumption made by Riehl and Malkus (1958) that the downdrafts in equatorial trough zone disturbances are saturated. If the typical downdraft is unsaturated, their computations of the downdraft contribution to vertical energy flux in the middle troposphere would be modified in the direction of decreasing the upward flux of sensible heat and increasing the upward flux of latent heat, although the total heat flux would remain unchanged. The important change in their results that is implied is in the ratio of sensible to latent heat flux from sea to atmosphere (Bowen ratio) when the downdrafts reach the boundary layer. By allowing the downdrafts to be unsaturated, the Bowen ratio is markedly decreased from the value estimated by Riehl and Malkus, bringing it more closely into agreement with values computed in tropical Atlantic disturbances by Garstang (1967). The downdraft studied here has a humidity structure in the rain area very similar to the highly unsaturated rain areas of some mid-latitude squall lines (Brown, 1963; Newton, 1950). The recent work of Riehl (1968) has demon-

![Thermodynamic Diagram](image)

Fig. 14. Part of a skew $T$-log $p$ thermodynamic diagram illustrating processes in the downdraft production. All solid lines represent temperature; all dashed lines represent dew point. All heavy lines represent idealized processes. The light lines diverging toward higher temperature and dew point from the idealized downdraft curves indicate the degree of modification of the constant $\theta_e$ downdraft by sea-air energy transfer. See text.
Fig. 15a. Schematic streamlines of airflow relative to convective cloud systems in east-west section illustrating the mechanism of downdraft production. The low $\theta_a$ air in the environment can pass under the anvil without necessarily intercepting convective towers, although such air that does intercept towers can be entrained by turbulent mixing into the towers and can also produce more intense and smaller scale downdrafts than the direct large-scale production under the rising anvil. The dotted line is a possible relative path of the Fanning sounding given in Fig. 14. See text.

Fig. 15b. Same as Fig. 15a, except in north-south section. Compare this diagram with those presented by Newton (1950, 1963) for the mid-latitude squall line. Both Fig. 15a and Fig. 15b represent the intensification phase of the disturbance, with a large population of active cumulonimbus towers, either in individual clusters or in organized lines.

Fig. 15c. A north-south section similar to Fig. 15b, but representing the dissipating phase of the disturbance, when maintenance of the downdraft is primarily by rain falling from the extensive cloud shield, although with considerable mesoscale variations in intensity not depicted in this diagram.
strated the existence of unsaturated downdraft air occupying the lowest 200 mb in portions of the rain areas of Caribbean disturbances.

The reconstruction of the cumulonimbus updrafts is much more straightforward. The thermodynamic state of the high $\theta_v$ air entering the updrafts is uniform, with surface temperature of 26.3°C compared with a sea surface temperature of 27.0°C. The mean specific humidity within the subcloud layer, used with the observed surface temperature, gives a condensation level of 960 mb and a $\theta_v$ for undilute updrafts of 24.0°C. The temperature difference between undilute updrafts and downdrafts is 1°C in the low troposphere and 3°C in the middle troposphere. Since completely undilute ascent would give cumulonimbus tops in excess of 13 km, and most observed tops are 8–10 km high, it is probable that entrainment modifies the typical updrafts as indicated in Fig. 14. There is no way to estimate entrainment rates in this case, but the extremely dry air in the middle troposphere would not have to be entrained in large quantities to produce significant decreases in buoyancy.

The sounding taken at 0321 on 1 April, at Fanning, was released during the heavy rain period. Unfortunately, the humidity element failed shortly after release, but the temperature sounding is valid, and very interesting. From the surface to 850 mb, it follows the supposed downdraft temperature closely, modified by a turbulence-induced adiabatic layer and low-level inversion, which is reasonable in view of the 24 m sec$^{-1}$ wind observed at 300 m altitude. Near 700 mb, the balloon appears to be in a warm region, from 600-500 mb in a cold region, and just above 500 mb in another warm region. The inversion at 500 mb could well mark the base of the anvil. A possible path of the balloon relative to the cloud system is depicted in Fig. 15a which may explain the observed temperature variations.

d. Sea-air interaction in the downdraft region

Below about 900 mb, no observations can be found which indicate a constant $\theta_v=18$C downdraft. The closest approach at the surface is the 24.0°C temperature and 19.5°C dew point at Fanning at about 0500, when the heavy rain had tapered off to light rain, giving $\theta_v=20.5$C. The aircraft observed a similar figure at 150 m altitude. While there is undoubtedly some mixing of downdraft air with the higher $\theta_v$ air it replaces, an important mechanism for modifying the downdraft near the surface must be the energy flux from sea to atmosphere.

For the moment, suppose that the downdraft actually reached the sea surface as indicated by the heavy arrows in Fig. 14. The latent and sensible heat flux from sea to atmosphere can be estimated by methods used by Garstang (1967) in a tropical Atlantic environment. At a height of 6 m, with a sea-air temperature difference of 4°C, specific humidity difference of 12.8 gm kg$^{-1}$, and wind speed of 15 m sec$^{-1}$, the bulk Richardson number is $-0.034$ and the drag coefficient is $2.65 \times 10^{-3}$. Using these values in the bulk aerodynamic transfer equations, the eddy flux of sensible heat is 380 cal day$^{-1}$ cm$^{-2}$ and the eddy flux of latent heat is 3000 cal day$^{-1}$ cm$^{-2}$ (5 cm day$^{-1}$ evaporation), or an order of magnitude greater than Garstang's mean eddy flux for disturbed conditions in the tropical Atlantic. Were these transfer rates to occur for even one hour, the modification of the extreme downdraft conditions indicated in Fig. 14 would be completely explained. In actual fact, these extreme transfer rates would not occur over the whole hour. The main point, however, is that were the extreme downdraft conditions to exist in the surface layers, modification would be so rapid that the chances of ever observing these conditions would be very slight. Therefore, their existence can be neither confirmed nor disproved.

Even the modified downdraft has a profound influence on sea-air energy transfer. Although the quality of the observations is not sufficient to justify quantitative estimates, reasonable bounds place the average latent heat flux over the downdraft region at 600–1200 cal cm$^{-2}$ day$^{-1}$, or about 2–4 times the mean, and the sensible heat flux at 60–120 cal cm$^{-2}$ day$^{-1}$, or about 2–4 times Garstang's mean disturbance values and 5–10 times his mean undisturbed values. The role of this large energy flux is to produce greatly enhanced upward flux of heat and moisture through the downdraft air in the boundary layer. The complete absence of convective clouds throughout most of the downdraft area makes it clear that in spite of its large magnitude, the addition of heat and moisture to the air from below was insufficient to restore normal cumulus development for 6–12 hr. This air is therefore completely unable to take part in the deep convection required to maintain tropical disturbances, and in fact kills such convection everywhere that it spreads.

4. Structure of the convective systems producing the downdrafts

The large-scale downdraft emerging from this disturbance was already in existence during the first few hours of its lifetime as a major cloud system. Therefore, it is likely that individual aggregates of cumulonimbus clouds were structured in such a way as to permit rapid and intense downdraft development. In fact, it was demonstrated in Section 3a that similar aggregates had significant downdrafts associated with them just prior to the major development. But the large scale and long duration of the important downdraft system strongly suggest that an additional mechanism was operating which permitted unsaturated, rain-cooled, rapidly sinking air to develop on a scale larger than the cumulonimbus aggregates themselves.

A structure of the system that seems to meet these requirements is given schematically in Fig. 15a. The larger aggregates of convective clouds move westward
at about 15 m sec\(^{-1}\), about as fast as the low-level easterlies above the subcloud layer, but faster than the subcloud layer air. For significant positive buoyancy, the air forming active cumulonimbus towers must come from the subcloud layer, with a relative wind with a westerly component. This is consistent with westward propagation, with new growth on west flanks and dissipation on east flanks, which is very frequently observed on time-lapse cloud pictures, and well-illustrated by Fig. 11, which shows that the clouds on the northwest flank of a mesoscale convective system are growing rapidly. In this case, there is also a propagation component toward the north. This high \(\theta_e\) air, having risen in cumulonimbus towers, remains in the anvil or in associated middle and upper clouds. It appears on the Palmira cross section (Fig. 8) above 500 mb after the arrival of the downdraft at low levels, and it can be seen at both Fanning and Palmira on the 500 mb space-time section (Fig. 10). The associated \(\theta_e\) values of 338–343K, compared with 350K in the inflowing subcloud layer air, indicate that considerable mixing with the middle tropospheric environment has taken place.

The air which takes part in the downdraft circulation comes from the 600–400 mb layer, where \(\theta_e \leq 330\)K and the environment winds relative to the moving system are about 245° at 20 m sec\(^{-1}\). Two things can happen to this air, and in this case, both probably do occur. First, it can flow freely under the heavily raining anvil on a large scale and sink in a direct circulation to the lower troposphere, remaining highly unsaturated. This low \(\theta_e\) air can arrive at a position under the anvil either directly or by passing around individual cumulonimbus towers, but the end product is similar in each case. Second, it can be entrained directly into individual convective towers by turbulent interactions, diluting the buoyancy of the towers but also forming unsaturated downdrafts immediately downshear of the towers on a convective scale or mesoscale. All of these processes add to the volume of the downdraft air in the lower troposphere.

Figs. 15a and 15b illustrate downdraft production during the earlier, active phase of the 1 April disturbance when there was a significant population of intense convective clouds. It also applies to the case of mesoscale cumulonimbus aggregates. By contrast, Fig. 15c illustrates the maintenance of the downdraft by primarily the larger scale production of downdraft air by rain falling from the large residual cloud mass. This picture would be valid for the later stages of the disturbance during the daylight hours of 1 April, when the arc of cumulus clouds marking the leading edge of the downdraft circulation moves out from under the cloud mass on the satellite pictures of Fig. 5. At some intermediate stage, just before daybreak, this cumulus line must have decreased in intensity so that it could no longer contribute to the maintenance of the main cloud shield, and the system as a whole begins the decay phase, which takes longer than the growth phase apparently did.

The circulation and thermodynamic processes proposed here are not different in any fundamental respect from those in mid-latitude squall lines (see, e.g., Newton, 1963). It is logical to ask whether this particular disturbance is unique or whether it is simply a rather extreme example of a large class of weather systems. Studies now in progress, based upon data collected in the Line Islands Experiment and also in the Barbados program of 1968, are showing that large-scale unsaturated downdrafts are features of many tropical disturbances. The model proposed here is also fundamentally similar to the disturbance lines of West Africa described by Hamilton and Archbold (1945). It is strongly indicated that circulations similar to squall lines should be included among the meteorological residents of the equatorial trough zone environment.

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