Mesoscale and Convective-Scale Downdrafts as Distinct Components of Squall-Line Structure

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ABSTRACT

This paper describes the two different kinds of downdraft air frequently observed to the rear of some squall lines at low levels. The primary data source is measurements taken during aircraft penetrations of certain low-latitude squall lines; they are supplemented by satellite data, radar data, surface meteorological data, and soundings ahead of and behind the squall lines. A shallow layer of cool, near-saturated air occupies the lowest few hundred meters and is separated by a marked stable layer from a deep layer of highly unsaturated air. The lowest layer is hypothesized to be the product of convective-scale saturated downdrafts, and the drier air is shown to be the result of mesoscale unsaturated downdrafts as described by Zipser (1969).

Over a warm ocean, there is a large latent and sensible heat flux from the surface into the lowest layer, which rapidly becomes a new mixed layer and incorporates the drier air from above by entrainment. Mesoscale sinking in the post-squall region is shown to slow the deepening of the shallow mixed layer. The surface dew point drops during squall passage, but is observed to recover more slowly than the temperature toward ambient values. Frequently, the dew point reaches its absolute minimum value several hours after squall passage, clearly indicating that enhanced evaporation from the surface can be less than the moisture flux through the top of the mixed layer.

An idealized model describing a class of squall lines is presented and discussed. The thermodynamic transformations that take place in each layer of air are identified hypothetically, and they can account for the observed properties of each airstream both before and after passage through the system. The proposed structure permits the coexistence of convective-scale saturated downdrafts and mesoscale unsaturated downdrafts, the former in the active convective clouds of the squall line, the latter farther to the rear.

1. Introduction

In the tropics and in middle latitudes, cumulonimbus convection frequently becomes organized into mesoscale systems. It is widely acknowledged that our lack of knowledge about the organization of tropical convective clouds into mesosystems forms one of the greatest obstacles to developing a general understanding of convective processes and to parameterizing them in numerical models. Recently, numerous diagnostic studies have deduced the contributions made by populations of convective clouds to the energetics of tropical disturbances. But a major question which must be faced is whether there are important differences between isolated cumulonimbus and those which are organized into mesoscale systems. Since only a tiny fraction of tropical convective rain falls from isolated clouds, the question is crucial. The research reported in this paper is directed toward developing observational knowledge of a class of tropical mesosystems.

Mesoscale systems made up of convective clouds organized in quasilinear fashion are simpler to analyze than most other mesoscale systems. The Glossary of Meteorology (Huschke, 1959) defines any line of cumulonimbus clouds as a squall line. To avoid confusion, this paper defines the term “squall line” to refer to cumulonimbus clouds, organized in linear fashion, associated with a pseudo-cold front (squall front) at the surface, propagating with considerable speed with respect to the ambient low-level air, in the general direction of the squall wind in the cold air behind the squall front. This paper deals with such squall lines, mainly over the tropical oceans. More precisely, its subject is the “squall system,” defined as the aggregate of phenomena associated with such squall lines, including the active cumulonimbus clouds, the anvil clouds and the cool air behind the squall front. Portions of the squall system exist for several hours after the active cumulonimbus of the squall line itself have dissipated.

In sub-Saharan Africa, squall lines not only are common (Hamilton and Archbold, 1945; Tschirhart, 1959) but provide most of the rainfall. Ramage (1971) discusses their importance in that and other monsoon regions. The field experiments to examine tropical cumulonimbus in Venezuela [VIMHEX I and II; see,
e.g., Riehl et al. (1973); Betts, Grover and Moncrieff (1976)] encountered a large number of squalls, and experiments in three different parts of the oceanic tropics have made it increasingly clear that they are not uncommon over the oceans. Houze (1975, 1976, 1977) described their radar structure in the GARP Atlantic Tropical Experiment (GATE; see Kuettner et al., 1974) and reported that four squall lines accounted for 50% of the rainfall at one of the GATE ships during Phase 3. The evidence at hand is ample to justify considering the squall line an important contributor to tropical rainfall and hence to the energetics of the tropics on the scale of the general circulation.

The crucial importance of the downdraft cycle to the energetics of individual cumulonimbus clouds was demonstrated quantitatively by Braham (1952), and Riehl and Malkus (1958) showed the necessity of including cumulonimbus downdrafts in the energy balance of the tropical rainfall belt as a whole. The organization of the downdrafts is one of the keys to understanding the squall line.

In a paper focusing on a single squall system, Zipser (1969) concluded that cool, dry air fills the rain areas of some such systems at low levels, discouraging new convective growth in air left behind by the system. On the other hand, the leading edge of the cold downdraft air, as in a mid-latitude squall, behaves much like a density current, plowing up the potentially buoyant boundary layer air and encouraging new convection. The downdraft air to the rear of this system had very low moist static energy; it was deduced to have come from the mid-troposphere, the only possible source of air with appropriate thermodynamic properties; and must have descended in unsaturated downdrafts under the influence of rain.

The results of Zipser (1969) depended upon inductive reasoning based upon measurements made far from the squall line and mostly very late in its life cycle. Since then, a number of field experiments have yielded much data relevant to understanding tropical convective systems. Betts (1976), Betts et al. (1976) and Miller and Betts (1977) have described in some detail the characteristics of the systems affecting Venezuela. Many of them are undoubtedly squall lines, although those authors sometimes refer to them as "traveling mesoscale convective systems." Their studies were based upon rawinsonde data taken before and after passage of the systems and generally combine data from a number of disturbances to give a composite structure.

This paper begins with a description of a particularly well-defined squall system over the oceanic tropics. The case is chosen for analysis because the author was fortunate to be on a research aircraft that was able to make several transects of the system. Those aspects of the system thought to have considerable generality are noted, based upon some supporting evidence from other cases. Finally, the airflow through the system, only partially determined from the observations, is hypothesized in such a way as to account for the observed structure.

The goal toward which this work is directed is the development of a descriptive model of a class of mesoscale systems. In the absence of definitive data sets, there are problems with both the case study and compositing approaches. At present, there appears to be no way to deduce such models completely objectively; but it will be clearly stated when hypotheses and not facts are being presented.

It is hoped that studies based upon the GATE data, only recently begun, will confirm or revise these concepts of squall-line structure and make them more quantitative. If squall systems prove to have certain common structural features and to evolve in a systematic manner, it may be possible to approach the problem of their parameterization in numerical models by integrating over their life cycle of at least 12 h. Just as one would not consider only the growing stage of a cumulus cloud, one should not consider only a single stage of a squall system. The squall system's circulation is too important to be ignored, but it is still a subsynoptic-scale phenomenon which is difficult to treat explicitly.

2. Case study of a Caribbean squall system

Prior to GATE in 1974, the tropical squall system known to the author to be most effectively observed by a combination of aircraft and surface-based instruments passed Barbados on 18 August 1968. The extensive field program centered on Barbados during the summer of 1968 has been described by Garstang et al. (1970). Some aspects of the 18 August system, which was probably the strongest single disturbance affecting Barbados during that field program, have been discussed by Seguin and Garstang (1976).

a. Large-scale environment

There is little that is remarkable about the large-scale setting of the squall system. There was a weak wave in the easterlies, which had little deep convection associated with it prior to 18 August. Following the squall line's generation, maturity and decay on 18 August, the entire system collapsed, and neither the wave nor organized deep convection was noted thereafter. In common with a large number of events described elsewhere (Simpson et al., 1967; Zipser, 1969; Smith et al., 1975a,b; Zipser, 1975; Gautier and Zipser, 1977) this mesoscale event developed some considerable strength, overshadowing the synoptic-scale system presumably responsible for its genesis, but then dissipated almost as quickly as it formed. The entire process lasted 12–24 h.
b. Life cycle of the squall line

In addition to the aircraft data, use was made of surface data, serial upper-air sounding data, radar and photographic data from both Barbados and the Discoverer; and surface data from the Triton buoy. The squall line cooperated fully with this observing array by forming near the research vessel Discoverer during the morning hours, passing Barbados near 1100 AST (Atlantic Standard Time, 4 h behind GMT, used throughout this section), and remaining (barely) in range for the aircraft to cross it west of Martinique three times between 1600 and 1800 (Fig. 1). On the basis of visual observations, it is believed that the system was entering the dissipation stage at 1800, but no data pertaining to the nighttime hours are available for confirmation.

The sequence of cloud and radar photographs shows that before 0800 on 18 August the convection took the form of small groups of cumulonimbus clouds, each group having dimensions of a few tens of kilometers. Between 0800 and 1000, the squall line organized into an approximately north–south band more than 100 km long, near the ship Discoverer. For the next several hours, the Barbados radar sequence shows a regular propagation of the leading edge of the system toward the west and northwest, by continuous new-cell formation on those flanks. Houze (1976, 1977) has recently described this process for a GATE squall line, showing how the new echoes join the main echo mass shortly after their formation, sometimes retaining their identity, and sometimes becoming indistinguishable from the remainder of the echo mass.

c. Airflow relative to the squall line

The area ahead of the squall line was better sampled than the post-squall region. Behind the squall, there was a single sounding at Barbados at 1400 (200 km to the rear) and information below 800 mb from the aircraft closer to the squall line. Ahead of the squall, the soundings made at 0800 (1200 GMT) at Barbados, Guadeloupe and Antigua appear to be representative of the generally undisturbed trade wind air into which the squall advanced. For most of its history, the squall was located between Barbados and Guadeloupe; hence the best estimate of a representative composite sounding would combine information for both regions. Antigua is only 70 km north of Guadeloupe, so those two soundings were averaged to represent the northern region, and that result was, in turn, averaged with the Barbados sounding to form the composite pre-squall sounding. The aircraft wind data in the intermediate location agree with the composite sounding within 1 m s⁻¹.

To obtain winds relative to the squall line, squall velocity must be subtracted from the ambient winds. The southern portion of the squall line was oriented almost north–south and moved at 17.4 m s⁻¹. The northern portion of the squall line, near the aircraft traverse, was oriented almost east–west and moved at
11.3 m s\(^{-1}\). Fig. 2 shows wind components relative to both portions of the squall line; there are no important differences.

There is little question that the squall moved faster than the pre-squall winds at any level, i.e., the relative wind was directed into the squall from the front. That is similar to the airflow regime observed by Zipser (1969), Betts et al. (1976), Miller and Betts (1977) and Houze (1977), and modeled by Moncrieff and Miller (1976). In a small system of a few tens of kilometers, such as a few of the Venezuela examples and the Moncrieff and Miller (1976) numerical model, the air may go around the system. But this squall front, like many others, was continuous over an arc of several hundred kilometers, and it is far more likely that most air in the rear of the squall had passed through the system. There are several ways for this to happen, which are discussed in Section 5.

d. Cross section through the squall system

The cross section through the squall system is given in Fig. 3. Important new information comes from the aircraft penetrations by the NCAR Queen Air. After passing through most of the system at 150 m, the aircraft turned in the (apparently) horizontally homogeneous light-rain area about 85 km behind the leading edge, climbed to 2150 m (785 mb) through the cloud-free anvil rain area and penetrated the leading edge, then descended and repeated the 150 m pass\(^3\) en route back to Barbados.

The ambient airflow is from front to back at all levels relative to the squall line.\(^4\) The pseudo-cold front at 150 m is nearly a material surface separating different air masses. In a manner proposed by Newton (1963), Zipser (1969), Betts (1976) and many others, the high-energy subcloud layer air ahead of the squall front is lifted bodily and must surely rise to anvil levels and remain there (Newton, 1966). The absence of 23.5°C \(\theta_w\) air on the 785 mb squall penetration shown in Fig. 3 is interpreted as meaning that the aircraft missed the updraft cores, not that they do not exist.

The air found in the lowest kilometer in the post-squall rain area has a range of wet-bulb potential temperature \((\theta_w)\) ranging from 19 to 22°C. This is low enough to attribute to downdrafts, but the very great range requires explanation. Mesoscale descent of air from the middle troposphere in unsaturated downdrafts (Zipser, 1969) can account for the low value. Downdrafts originating from ambient air above cloud base

\(^{3}\) No wind data are shown from the second pass, when there was an intermittent failure of the true air speed measurement and hence the wind determination. The author maintained a log of winds estimated from sea state on both 150 m passes, which shows no significant differences. Also, during those intervals when the true air speed system was operative, the winds were similar on both low-level passes.

\(^{4}\) The motion of individual cumulonimbus clouds is unknown; but were it known, it would still be appropriate to composite with respect to the squall line when we are dealing with a space scale of hundreds of kilometers and a time scale of many hours.
Fig. 3. Cross section through 18 August 1968 squall line near aircraft track indicated in Fig. 1. Flow relative to the squall measured by the aircraft (m s⁻¹) is indicated alongside aircraft track by horizontal arrows. Cirled numbers are $\theta_a$ in °C. Relative winds and $\theta_e$ from the composite pre-squall sounding (Fig. 2b) are shown along the left-hand margin. The dotted lines mark estimated locations of stable layer base ($l_B$) and top ($l_T$). See also Fig. 4 and text.
(Betts, 1976) can account for the high value. Penetrative convective-scale downdrafts presumably occur in the squall-line cumulonimbus themselves, and it is not clear what their $\theta_w$ value would be. To narrow the range of possibilities, it is necessary to examine the thermodynamic properties of the air more closely.

The temperature and dew-point traces from both aircraft transects of the system at 150 m are reproduced in Fig. 4. On both transects, the squall front is well defined, with a 3°C temperature drop in about 10 km. The front clearly separates the ambient subcloud-layer air with $\theta_w > 23.5^\circ$C from cool, near-saturated air with $\theta_w \approx 21-22^\circ$C. This cool air occupied the heavy-rain area behind the squall front. Then, after 40 km on the first pass and 25 km on the second pass, the aircraft encountered relatively warm and dry air ($\theta_w \approx 19-20^\circ$C). For the reasons discussed by Zipser (1969), this air originated from unsaturated downdrafts, in this case from somewhere above 750 mb where air low enough in $\theta_w$ first appears on the pre-squall soundings.

Farther behind the squall line, there is irregular alternation between the 19-20°C $\theta_w$ air and the 21-22°C $\theta_w$ air. Visual observation tends to link some of the highly unsaturated air intrusions with releases of heavier rain from the anvil, about 20 km in horizontal scale. As in the Zipser (1969) case, the normal component of the wind diverges in these very dry regions, suggesting mesoscale sinking. The hypothesis is now put forward that the 150 m flight level is generally below the base of a marked stable layer which dips below 150 m upon occasion, accounting for the very dry portions of the transect.

There are only a few soundings that can be used to support or refute the above suggestion, but one of them is in the right place at the right time. The sounding taken by the Queen Air in continuous rain under the anvil (Fig. 5; location given in Fig. 3) shows a fairly well-mixed layer between 150 and 400 m, with $\theta_w$ near 21.5°C. A very strong stable layer occupies the 400-950 m interval, with the 19°C $\theta_w$ air from 1000 to 2000 m. Relative humidity is below 50% in moderate-to-heavy rain. Further confirmation is provided by the earlier sounding at Barbados, which shows a lower mixed-layer depth and a deeper stable layer. In Section 3 a number of similar soundings from other cases are presented; they suggest that a low-level stable layer may frequently separate air of $\theta_w = 19^\circ$C from air of 21-22°C.

It is important to know whether the warm dry air penetrates all the way to the surface and not just to within 100 m or so. There are no time series available from the region of the squall penetrated by the aircraft, but there are from the Discoverer, from the Triton and from Barbados. Although it is difficult to prove a negative, such a penetration to the surface is highly implausible and certainly did not occur at the three sites just mentioned. If the air at 150 m with temperature of 24°C and dew point of 17°C were to reach the surface, assuming no additional evaporation of rain, the temperature would be higher than 25°C and the dew point 17°C within 2 h of squall passage, before the
end of the rain. Such a dew point is far below any surface measurement known to the author at that or any other time during that field program, and the temperature of 25°C is rather higher than the observations. On the other hand, extrapolating from the $\theta_w = 21.5\,^\circ$C air, hypothesized to be representative of the mixed layer, to the surface yields a temperature in the 23–24°C range and a dew point of 20–21°C, in much better agreement with the surface observations behind the squall line. It appears that this cool, near-saturated air spreads out and occupies the lowest few hundred meters in the post-squall region, while the warm dry air stays above it, occasionally penetrating below 150 m but not to the surface. Later, the incorporation of the dry air into the lower layer by entrainment is discussed at length; what has been ruled out is penetration of the dry air to the surface without mixing.

The soundings in Fig. 5 show that the warm dry air in the post-squall region reaches temperatures up to 4°C (actual) and 3°C (virtual) warmer than those in the ambient pre-squall air in the 850–900 mb layer. Miller and Betts (1977) observed warm air in analogous regions of Venezuela storms, and they suggest that the warming is due to dynamically forced descent. This, in turn, casts some doubt on Zipser’s (1969) suggestion that the downdrafts in this region are driven by evaporative cooling. Riehl and Lückefeldt (1973), also
considering Venezuela storms, retain the idea that evaporative cooling drives the downdrafts, viewing the warming as a kind of overshooting. In this case, the cross section shows that the warm dry air in question has followed a long trajectory within the anvil rain area, so evaporation of rain must have been a factor. Further, as shown below, the sinking in the anvil rain area takes place mainly on the mesoscale, one to two orders of magnitude larger than the convective-scale drafts in the cumulonimbus. The "parcel method," as conventionally applied, is not appropriate for this mesoscale sinking.

The magnitude of the mesoscale vertical velocities can be estimated only crudely from the available data, by assuming that the divergence of the low-level wind is approximated by

$$\nabla \cdot V_m \approx \frac{\partial v_n}{\partial n},$$

where $v_n$ is the wind component normal to the squall line and $n$ is in the direction normal to the squall line. The 10 m s$^{-1}$ wind change at the leading edge is apparently concentrated in a 2 km zone, giving an estimated convergence of $5 \times 10^{-4}$ s$^{-1}$ for that zone and $1 \times 10^{-4}$ averaged over 10 km. The divergence in the rear is spread over a much larger area (Fig. 3). In the anvil rain area the estimated average divergence in the 30–65 km zone is $3 \times 10^{-4}$ s$^{-1}$. The magnitude of the mesoscale sinking in the anvil rain region (between 30 and 65 km) can be estimated by assuming the divergence to be constant in the lowest layers, yielding values of 10 cm s$^{-1}$ at 300 m, 20 cm s$^{-1}$ at 600 m, etc. Similar estimates, usually within factors of 2 or 3, can be made for other cases.\(^4\)

\(4\) For example, a rather similar squall line, observed by the same aircraft on a transect at 150 m on 30 August 1968, was estimated to have convergence of $1.8 \times 10^{-3}$ s$^{-1}$ over 10 km at the squall front and divergence of $4 \times 10^{-5}$ s$^{-1}$ over 30 km in the heavy-rain area to the rear.

The anvil base, estimated to be at about 4–6 km in altitude, with no other significant clouds in sight. It was extremely dark throughout that zone, with frequent lightning. The overall cloud structure is not greatly different from that of Hamilton and Archbold (1945) for West African "disturbance lines." The anvil base was indefinite and is believed to have consisted of melting snow in much of the precipitation region. That speculation is given a certain degree of credence by the observations of Houze (1975, 1976, 1977), who notes that radar bright bands were a characteristic feature observed in the anvil rain area of squall lines in GATE.

There is little doubt that the anvil was extremely thick. The cumulonimbus tops were measured photo-grammetrically from the aircraft's side camera time-lapse films. The highest cloud tops measured were at 15 km+2 km, and it is believed that the general anvil tops were at no less than 13 km in altitude. Accepting the estimate that anvil base was located in the 4–6 km range, which includes the melting level, the best estimate of anvil thickness in the region 30 to 100 km behind the squall is 8 km, with a crude error estimate of +2 km. That tapers gradually to a thin, transparent cirriform cloud at 350 km (Figs. 6a and 6b), which is also the distance, in this case, that the anvil appears to extend on the satellite photograph (Fig. 7a). The visual and photographic evidence is strong that the cloud mass on the satellite photograph contains deep cumulonimbus clouds rooted to the low troposphere only along the leading edge. The rear 80–90% of the cloud area is made up of anvil clouds, virtually all above the freezing level.

Not all anvils are as thick as this one. Sikdar and Suomi (1971) and Ludlam (1966) speak of anvils 1 km thick. But Newton's (1963, 1966) cross sections indicate thicknesses approaching 10 km in some severe squall lines, and Houze (1977) shows a GATE squall system with an anvil very similar to this one in all dimensions. The author has observed many in the 6–10 km range. Such an extremely thick anvil must be of considerable importance for the water budget of the system. Houze (1977) estimates that 40% of the rainfall of the entire squall system came from the anvil. In this case the anvil rain was substantial, persisting for 2–3 h after squall passage at the Discoverer, the Triton and Barbados, and it was observed from aircraft to extend more than 100 km to the rear. The anvil precipitation persists at large distances from active cumulonimbus towers and for some hours after those towers have disappeared.

It is difficult to imagine that the extent and persistence of such anvil systems would be possible if those systems consisted merely of passive detainted cumulonimbus tops. Rather, it may be necessary to have some organized ascent in the upper half of the troposphere to sustain them. In a numerical integration simulating squall-system evolution, Brown (1974) produced exactly such a result: a massive precipitating
anvil with mesoscale ascent, late in the life cycle. The precipitation from the anvil drove a mesoscale sinking region in the lower troposphere, with a strong mid-tropospheric convergence needed for mass balance.

3. Squall-system structure generalized to other cases

Despite the data deficiencies, the description of the 18 August 1968 squall system is complete enough to construct a conceptual model of the airflow through the storm and of the convective-scale and mesoscale processes that are consistent with the observations of overall storm structure. Such a model would necessarily be only qualitative and would include many speculative aspects; yet it would apply to that case only.

That squall system has numerous characteristics which seem capable of being generalized. The cloud structure, relative wind profiles and thermodynamic structure of low-level post-squall air, among other things, are similar to those observed in other squalls. In this section, certain structural aspects that appear to be representative of a class of tropical squall lines will be summarized. There is no pretense that all tropical squall lines are being represented or that the conceptual model which follows is rendered any less qualitative; the motivation is to extend the discussion beyond a single case to a subset of squall lines, since some of the observations from different systems tend to complement one another.

a. Relative winds as a function of height

Betts et al. (1976) have discussed the winds around a large number of Venezuelan squall lines. They find that the flow of the air ahead of a squall line is directed
into the squall from the front at all levels, but with a minimum of extremely little relative flow near 700 mb (representing an actual easterly wind maximum). They observe a markedly different wind profile behind the squall line, with weak inflow from the rear between 900 and 600 mb. They note that that feature varies considerably from case to case.

The 18 August Barbados system just discussed fits that description very closely. The aircraft wind measurements (Fig. 3) show a small region of very weak flow from the rear just behind the squall line near 800 mb, but the region is not sampled at all well, so its extent is not known. A squall line on 30 August 1968 had an extremely similar pre-squall relative wind profile, but no soundings were made behind the system.

Similar relative wind profiles were noted in many squall lines observed during GATE. Houze (1977) has studied one of them (4 September) extensively. Others occurred on 28 June, 13 August, 5 September (over Senegal) and 12 September. Aspliden (personal communication) finds such a profile in a composite study of 85 West African squall lines. Farther afield, the case studied by Zipser (1969) in the central Pacific also had similar relative wind profiles.

Last but not least, certain mid-latitude squall lines have relative airflow approaching the system from the front throughout the low and middle troposphere. Newton (1963) discussed one such line extensively, and the case already cited by Sanders and Paine (1975) is definitely of that type. In both cases there was some relative airflow from the rear near 700–800 mb, but only in the post-squall region.

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* A second has been studied by Sanders and Stokes (Sanders, personal communication).

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**Fig. 7.** Satellite pictures of squall-line cloud systems, all confirmed to have active, deep clouds only near the leading edge, and to have cloud structure pictured in Fig. 6 over more than half their area. (a) 1600 AST 18 August 1968, (b) 1600 AST 30 August 1968, (c) 1500 GMT 5 September 1974, (d) 1430 GMT 12 September 1974. Arrows locate leading edge and direction of motion. The black dot in (a) and (b) locates Barbados. The open circle in (d) locates the Oceangrapher.
Table 1. Representative wet-bulb potential temperature ($\theta_v$) and dew point depression ($T - T_d$), both in degrees C, in three regions of seven squall lines penetrated by aircraft at low levels: ambient subcloud air ahead of squall front (1), the heavy rain area 10–30 km behind the squall front, within the squall line itself (2), and the dry air farther to the rear under the raining anvil (3).

<table>
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<td></td>
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<td></td>
<td>$\theta_v$</td>
<td>$T - T_d$</td>
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<td>6</td>
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<td>22.2</td>
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<td>5°N, 101°W</td>
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* Discussed at length in text.
** Discussed in text. Only squall in table over land, accounts for 6°C dew-point depression ahead of squall.
† Discussed in text. The portion of squall penetrated by aircraft was advancing into rather dry air, probably not fully recovered from previous squall.
†† The LIE case from Zipser (1969), at an extremely late stage in its life cycle.

b. Cloud structure

The main features of the 18 August cloud system were illustrated in the cross section of Fig. 3. The deep cumulonimbus which form the squall line exist just behind the squall front and are continually propagating into the ambient air ahead by new growth, while older towers successively join the main anvil mass. About 20–30 km to the rear, the cumulonimbus bases give way rapidly to the anvil base at 4–6 km in altitude. In the large area where rain falls only from the anvil, very few low clouds exist.

The same features are certainly found in many other squall systems. The 5 September 1974 squall over land was observed by the author from an aircraft, with a sounding made toward the rear of the anvil rain area. A few cloud photographs from that region are shown (Figs. 6c and 6d). There are only a few scud near 100 m in altitude; the anvil base was above the highest altitude flown of 3 km and was estimated to be near 5 km. That is near the freezing level, and it is quite possible that the visible ceiling was partially made up of falling snow near the melting level. The 30 August 1968 squall near Barbados, the 12 September GATE squall, the 4 September GATE squall (Houze, 1977) and the squall reported in Zipser (1969) had greatly similar cloud distribution. So did the mid-latitude squall lines described by Newton (1963) and Sanders and Paine (1975). The satellite pictures of Fig. 7 are all confirmed, through direct observation of the cloud structure under the anvil, to have active cloud only along the leading edge of each cloud system. In each case, the anvil is again estimated to be 6–10 km thick.

c. Thermodynamic structure along low-level cross sections

The temperature and dew-point traces through the 18 August system (Fig. 4) were discussed in the previous section. The main features noted there can be found in several other squall systems where aircraft penetrated them at low levels (Table 1).

In each case, a well-defined squall front separates ambient subcloud-layer air with $\theta_v$ generally greater than 23.5°C from cool, near-saturated air in the heavy-rain area, which is typically 10–30 km behind the squall front. In the most active squall lines, $\theta_v$ decreases sharply by up to 3°C. The cool air in the heavy-rain area, to be called the “saturated downdraft air,” has a lower specific humidity (and lower dew point) than the ambient subcloud air at the same level. Therefore, despite its near-saturation, it is cooler and drier than ambient subcloud air in an absolute sense. Also, in each case the aircraft encountered some air under the raining anvil that had very low $\theta_v$, great dew-point depression (low relative humidity), and sometimes but not always, a higher temperature than any other air found at that level. This will be called the “unsaturated downdraft air.” There is a wide variation in the percentage of the sampled anvil rain area which was occupied by the unsaturated downdraft air. This percentage tended to be greater with altitude and with the age of the system and to be greater in the 100–200 km distance range behind the squall front.

d. Vertical soundings in the post-squall area—the diamond and the onion

It is surprisingly rare to find soundings that can be confirmed to be in the region behind a tropical squall line. A number of them are displayed in Fig. 8, on the same diagram to illustrate some important features in common with the 18 August soundings. Note especially that on all soundings a marked stable layer separates cool, near-saturated air near the surface from very warm and dry air just above. The maximum separation of temperature and dew point approaches 15°C, usually near 900 mb, although it tends to be higher in
Venezuela soundings, and it is as low as 960 mb in the GATE squall. The relative humidity in the rain can be as low as 40–50%, a clear demonstration that the air can descend while remaining highly unsaturated. Of course, when the sounding approaches the base of the anvil, the temperature and dew point curves come together again, completing the “diamond” or “onion” shape. In the aggregate, the family of curves suggests that cloud base is near or slightly above 600 mb, which is at 4 km.

\[ e. \text{The lowest kilometer of the post-squall region—small mixed-layer depth} \]

The aircraft sounding made behind the Senegal squall, in the anvil rain area, is particularly instructive. The saturated downdraft air near the surface has

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6 H. Richl (personal communication) notes that the diamond-onion-shaped soundings are characteristic of the steady rain areas to the rear of convective systems in Venezuela, “late rains” as he calls them.
\( \theta_w = 22^\circ \text{C} \) and the unsaturated air above the inversion has \( \theta_w = 19-20^\circ \text{C} \). There is no mixed layer even though the aircraft descended to within 50 m of the tree tops. Wind data are available and they give the same relative flow profile as in the analogous region of Fig. 3. That is, the air near the surface has nearly calm winds and is overrun by the warm, dry air above, moving much closer to the squall-line velocity. But the relative motion is outward in both layers, indicating, as in Fig. 3, that the air has come not from outside the squall system, but from inside. Wherever data are available, they rule out horizontal advection of some exotic “air mass” as the explanation for the observed structure of the lowest kilometer in the post-squall area.

The other sounding over land (Fig. 8c) also shows no mixed layer. At the time of these soundings, there had been no opportunity for the air to be heated from the underlying surface, which would create a new mixed layer. The soundings over water have mixed-layer depths from 50 to 500 m. The processes within the squall line can be presumed to have produced this strong stabilization. Garstang and Betts (1974), Echternacht and Garstang (1976) and Seguin and Garstang (1976) report that stabilization of the lowest several hundred meters is characteristic of disturbed regions in general and Garstang (1967) found that the fluxes of moisture and especially of heat from sea to air are usually enhanced in such regions. They point out that over the ocean mixed-layer depths are usually low in disturbed regions, ranging from 40 m to about 400 m.\(^7\) These soundings tend to confirm their results for the important special case of this type of squall system.

The squall line of 12 September 1974 passed directly over the GATE ship array and will be the subject of future studies. Fig. 9 gives the position of the squall front with time and two surface streamline charts; it is included because it will help place the acoustic sounder analog record (Fig. 10) in time and space perspective. Mandics and Hall (1976) have discussed the data collected by the NOAA Wave Propagation Laboratory’s acoustic sounder aboard the Oceanographer in GATE, and more recently, Gaynor and Mandics (1977) have described the relationship of the acoustic sounder records to specific events, including that squall system [note also Wylie (1976) and Houze (1977)]. After the end of the rain, a pattern known to be characteristic of strong low-level stability and humidity gradients dominates the record for many hours. The mixed-layer depth indicated by the record is from 200 to 400 m, except from 1700 to 1900 GMT when it is within 200 m of the surface much of the time (compare with Fig. 8c).

\(^7\) Garstang and his co-workers at the University of Virginia (personal communication) have confirmed and greatly extended these results, using tethered balloon data and other GATE boundary layer data. They find that 200 m is a frequent mixed-layer depth in extremely disturbed convective states, including post-squall conditions.
Fig. 10. Acoustic sounder facsimile records from the Oceanographer for the 12 September 1974 squall, and from a similar squall the previous evening (after Mandics and Hall, 1976).
f. Magnitude of mesoscale sinking in the post-squall region

It was noted earlier that low-level divergence in the anvil rain areas of two Barbados squalls was $\frac{1}{2} \times 10^{-3}$ s$^{-1}$ over distances of 30–35 km. The 12 September situation can be analyzed in two dimensions, and the results are similar. Figs. 9b and 9c show the surface wind fields at 1200 and 1600 GMT. At the latter time, the mesoscale divergent region is well documented (time series were used to aid the analysis) and the surface wind divergence is $\frac{1}{2} \times 10^{-3}$ s$^{-1}$, averaged over a circle 150 km in diameter. That implies an average sinking rate of 10 cm s$^{-1}$ at 500 m in altitude over the circle.

g. Surface layer properties and delayed dew-point minima

When the surface observations for the GATE ships were displayed in time series form, several features believed to be of importance in the structure of this type of squall line were noted. Examples of time series are given in Fig. 11 for several GATE ships on 11–12 September 1974 and for a few other dates. The temperature and dew point drop as expected with the passage of the squall front. But several hours later, when the temperature is recovering toward a more normal value, the dew point decreases a second time. More often than not, the lowest absolute value occurs 3–5 h after squall passage. That also happened during a number of squalls in the Line Islands Experiment (see Zipser and Taylor, 1968), including the major event described in Zipser (1969), when the lowest dew point measured at any surface station during the entire experiment (21.3°C at Fanning) was recorded 5 h after squall passage.

\* Courtesy of a well-ventilated concrete bunker left over from World War II. A few meters away an identical instrument inside a standard Stevenson screen registered 95% instead of 70% relative humidity. The screen was covered with water drops in the calm, cool post-storm environment.
h. **Mesohighs and mesolows**

Another property of some tropical squalls emerged from the time series of surface data in Fig. 11. That is the pressure variations that accompany the passage of the system. It is necessary to consider departures from the normal semi-diurnal pressure wave for these pressure changes to become obvious.

Fujita (1963) and Williams (1963) are among many who have noted mesoscale high pressure regions immediately following squall-line passage and the occasional presence of a mesoscale low-pressure area some distance behind squall lines. Williams connected the mesolow to the previously noted warm dry air at low levels, so the "onion" soundings apparently occur behind some mid-latitude squall lines. Although unspectacular by some mid-latitude standards, the tropical squalls frequently have mesohighs in the rain area behind the squall, where a large depth of cold saturated air, combined with large liquid water contents (Sanders and Emanuel, 1977), can explain a rise in pressure of several millibars hydrometrically. The nonhydrostatic pressure terms are significant for severe storms (Newton and Newton, 1959), but for the more moderate systems under discussion those may be less important. Where they exist, the mesolows do appear to be strongest about 3-5 h behind the squall, near the trailing edge of the anvil rain, or at about the same place as the surface dew-point minimum. This location, as demonstrated earlier, is often where the greatest low-level warming occurs. To entirely account for a 2 mb mesolow, the mean virtual temperature would have to be about 2°C warmer than the environment in the 1000-700 mb layer, not at all impossible (it is even exceeded in Fig. 8c) but rather more than is often observed.

An independent verification of the mesoscale pressure gradient from the mesohigh to the mesolow is provided by one of the aircraft penetrations of the 12 September 1974 squall system. The pressure altitude and radar altitude diverge by 20 geopotential meters (~2 mb) in the same sense indicated by the surface time series, i.e., there is a 2 mb pressure drop from within the squall line to 150 km to the rear. The approximate locations of the mesohigh and mesolow for that case are indicated in Figs. 9b and 9c. There is considerable variation in the magnitude of the mesolow from case to case, however, and even between different observations in the 12 September situation.

4. **The role of mesoscale sinking in the maintenance of the shallow mixed layer**

In the squall line itself, it is not clear how one would define the atmospheric boundary layer. Echternacht and Garstang (1976) report tethered balloon observations in strongly disturbed conditions that show mixed-layer depths of 40 m and in some cases a total absence of any mixed layer at all. They attribute the stable profiles to large convective fluxes through deep layers, especially noting the role of evaporatively driven downdrafts (see also Betts, 1976). They also argue that mixed-layer models designed for fair weather conditions "cannot be used in disturbed conditions."

The type of squall system discussed here, however, has deep cumulonimbus with bases in the boundary layer only within about 30 km of the squall front. Beneath the base of the anvil, there are no convective clouds of any significance. The air near the surface 30-50 km to the rear has a relative motion outward from the squall which is maintained for many hours and several hundred kilometers. When that air leaves the deep convection region, large heat flux is indicated by bulk aerodynamic methods, which creates an initially shallow convective boundary layer that satisfies the assumptions of the fair weather layer models used by Lilly (1968), Tennekes (1973), Deardorff (1974) and Mahrt and Lenschow (1976). There may be some rain falling initially from the anvil, but there is a big difference between evaporation into ambient mixed-layer air and penetration of that mixed layer by evaporatively driven convective downdrafts. As noted previously, there is little or no penetration of the dry air into the mixed layer at all, except by the entrainment process well described by the models. A schematic diagram showing the evolution of profiles of virtual potential temperature behind the squall line is given in Fig. 12.

It is useful to ask whether the shallow mixed layer observed in these specific post-squall conditions is at least crudely consistent with the observed mesoscale sinking. Following Deardorff (1974), a simplification of the "jump model" predicts the rate of rise of $z_i$, the mixed-layer top, to be

$$\frac{dz_i}{dt} = 1.2 \left( \frac{\theta}{\theta_v} \right) \left( \frac{\partial \theta_i}{\partial z} \right)$$

where $w_i$ is the "large-scale" vertical velocity at $z=z_i$, $(\theta/\theta_v)$, is the surface virtual temperature flux, and $\partial \theta_i/\partial z$ is to be evaluated just above the jump at $z_i$.

The model will be applied in the 50-150 km zone, which the mixed layer air traverses for several hours.
and where the mixed-layer depth may be in the 100–400 m range. Conditions typical of post-squall environments are used: a sea surface temperature of 27°C, a surface temperature of 24°C, a surface dew point of 21°C, a surface wind speed of 7 m s⁻¹, yielding an evaporation rate of 0.7 cm day⁻¹ by the bulk aerodynamic method, and a Bowen ratio of 0.16. The surface virtual temperature flux is about 50% greater than the heat flux, or about 4 cm s⁻¹ °C. A drag coefficient of 1.3×10⁻³ is assumed. The value of \( \frac{\partial \theta_v}{\partial t} \) is taken to be 1°C (100 m)⁻¹.

Under these conditions, the rate by which a mixed layer initially 100 m deep will rise, if \( w_i \) is zero, is 4.8 cm s⁻¹; from 200 m it is 2.4 cm s⁻¹, and from 400 m it is 1.2 cm s⁻¹. In several individual cases, such rapid rise rates are certainly unrealistic. Fig. 10 shows two examples in which \( z_i \) decreases to less than 200 m some 6 h after squall passage. To maintain \( z_i \) at 200 m requires a sinking rate of 2.4 cm s⁻¹. That implies a divergence of 1.2×10⁻⁴ s⁻¹ in the lowest 200 m. Typical values of divergence in the post-squall region are the same order of magnitude over 50–100 km. Therefore, the mesoscale sinking in the post-squall environment appears capable of explaining the maintenance of the low mixed-layer heights that are observed.

One of the assumptions in the jump model development which is considered to be rather good (Deardorff, 1974) is that

\[
(wq)_i = -0.2(w\theta)_i
\]

which allows the convergence of heat flux in the mixed layer to be computed; for the 200 m \( z_i \) it gives a heating rate of nearly 0.5°C h⁻¹ for the mixed layer which is certainly not unreasonable.

The jump model can be used to estimate the moisture flux through the top of the mixed layer when the moisture flux is negligible shortly above \( z_i \) (Lilly, 1968; Deardorff, 1974), an assumption which needs verification but which is reasonable in that stable, cloudless environment. The estimate is given by

\[
(w'q)_i = -\frac{d(\theta_u - w_i)}{dt} \Delta q_i
\]

where \( \Delta q_i \) is the specific humidity jump just above \( z_i \). From the soundings in Fig. 8, 3 g kg⁻¹ is taken as a representative value for \( \Delta q_i \), which leads to a moisture flux through the inversion of 7 mm day⁻¹, coincidentally equal to the estimated evaporation rate. Nominally this result implied no moisture flux divergence in the 200 m mixed layer which is assumed to be at a constant depth for this computation. Practically, because the uncertainty in \( \Delta q \) is about a factor of 2, it implies that the change in specific humidity in the post-squall region should be small and could be in either direction.

The surface time series in Fig. 11, in fact, indicate that the recovery of temperature toward ambient values is much more rapid than that of the dew point, which tends to remain low for many hours. The delayed dew-point minima, which tend to be near 100–150 km behind the squall front, can hardly be explained at all unless \( (w'q)_i > (w'q)_s \) for some fraction of the post-squall region. That is most likely in regions of light surface winds where evaporation would be low, and strong mesoscale subsidence where the mixed layer top descends and \( \Delta q_i \) would tend to be greatest.

5. Synthesis of observed characteristics of a class of squall lines: two distinct downdraft processes hypothesized

Previous sections have provided evidence that there is a class of squall lines which share important structural features. This type of squall line is common in many parts of the tropics. It also exists in middle latitudes, but it is not clear how frequently. The observed characteristics of this type of squall line and its associated squall system are summarized below and incorporated into a schematic of the system in Fig. 13.

1) Relative winds are directed into the squall line from the front at all levels, with a minimum relative flow often noted about 700–600 mb. Well behind the squall, the relative flow is strongly outward from the squall near the surface, still outward—but much less so—just above the mixed layer, and from either direction in the 600–900 mb layer, with indications that the flow from the rear may increase with time.

2) New cumulonimbus cloud growth takes place above the squall front along the leading edge, with older towers joining the anvil mass trailing behind. The anvil is 6–10 km thick, and rain falls from the anvil base for 100 km or more to the rear in a region having no significant clouds below the anvil base, which is near 4–5 km.

3) At 150 m in altitude, the region from 10 to 30 km behind the squall front, where almost all active cumulonimbus clouds are located, has very cool, near-saturated air. The remainder of the system to the rear has air varying widely in \( \theta_v \) and in relative humidity.

4) Soundings taken in the rear portion of the squall system show cool, near-saturated air of intermediate \( \theta_v \) near the surface; a deep layer of relatively warm air with low relative humidity and low \( \theta_v \), just above that; and near-saturated conditions again near anvil base.

5) The stable layer which separates the two lowest layers (4, above) has its base, which marks the top of the mixed layer, from 40 to 500 m, with 150 to 400 m rather common.

6) The winds in the surface layer and the mixed
Fig. 13. Schematic cross section through a class of squall system. All flow is relative to the squall line which is moving from right to left. Circled numbers are typical values of $\theta_v$ in °C. See text for detailed discussion.
layer behind the squall line are divergent in the range of 1 to \(5 \times 10^{-4}\) s\(^{-1}\) over distances of 30–100 km. On the same scale, the mesoscale sinking just above the mixed layer is in the 5–25 cm s\(^{-1}\) range at 500 m.

7) The dew point at the surface drops with squall-front passage, but often drops still further in the anvil rain area, reaching an absolute minimum about 100–200 km behind the squall line.

8) A mesoscale high-pressure region at the surface tends to accompany the squall line itself, followed by a mesoscale low-pressure region about 100–200 km behind the squall line, but with considerable variations in individual cases.

A major element of the squall-line structure which is not directly observed but which demands some explanation is the origin of the two layers of air with rather different properties found behind the squall in the lowest kilometer. The range of \(\theta_a\) is far too large for a common origin, so two distinct origins must be sought.

There is widespread agreement that the ambient subcloud-layer air of high \(\theta_a\) is forced to rise at the squall front, is "stripped away"—to use Betts' (1976) description—and ascends to form the active cumulonimbus towers of the squall line. Newton (1966) has given convincing arguments that such air remains in the upper troposphere.

There is also widespread agreement that the air found to the rear of the squall line descends in downdrafts. The main questions are where did it originate and what sort of downdraft processes took place. As noted, the answers must differ depending upon which air mass behind the squall line is considered.

First, it is useful to dispose of the possibility that any unusual characteristics noted behind the squall can be explained by horizontal advection of the anomalous air into that region from outside the squall area. The relative flow in the lowest kilometer is directed outward from the squall line in the schematic and, as discussed earlier, in almost all individual cases. Processes acting within the squall system itself must be primarily or wholly responsible for the observed conditions.

Consider the air that arrives in the lowest kilometer of the post-squall region with \(\theta_a\) of 19–20°C. In the ambient tropical atmosphere, air with this \(\theta_a\) is generally found no lower than 800 mb, and in the pre-squall soundings for the cases discussed here it was generally first encountered between 750 and 700 mb, occupying a layer roughly 200 mb thick. If the relative flow is from the front at 700 mb, much of the air must pass between active cumulonimbus towers to arrive in the heavy-rain area behind the squall and eventually in the anvil rain area. This is not as difficult a feat in nature as it appears to be on a two-dimensional sketch, because the cumulonimbus towers are not continuous either in distance along the squall line or in time. Houze (1977) has carefully observed the discrete nature of squall-line propagation, showing how "line elements" form ahead of existing precipitation and eventually join the anvil mass. Not only is it easy for the air to go around cloud towers, but with discrete propagation, air that approaches the squall line from the front suddenly finds itself behind a new line element and in the rain area of the previous element, encountering little or no active cloud in the process. If the relative flow is from the rear, the air enters the anvil rain area directly. There is evidence that air in some squall lines enters from both front and rear, converging near the heavy-rain area.

There is no reason to change the arguments given by Zipser (1969) in support of the hypothesis that this air with low \(\theta_a\) sinks in unsaturated downdrafts. Miller and Betts (1977) argue that this sinking is dynamically forced, but evaporation of rain into this air is still believed to be the most important factor allowing some of it to sink several kilometers to within a few hundred meters of the surface. Brown's (1974) results show this to be physically and dynamically plausible. The mean sinking rate was estimated in the last section as 5–25 cm s\(^{-1}\) at 500 m in altitude. If evaporation drives the process, air encountering heavy rain bursts would sink preferentially more rapidly than air encountering only light rain, and would tend to have the greatest vertical displacement. Several rain bursts (Fig. 4) coincided with penetrations of the dry air to below 150 m in the 18 August case study. Assuming 20 cm s\(^{-1}\) for the mean sinking rate, a parcel would take 3 h to sink 2 km, a reasonable time.

Zipser (1969) made no statement about whether the unsaturated downdraft air reached the surface. It should be clear that it does not reach the surface except in a highly diluted state by entrainment through the stable layer into the mixed layer, since the necessary conditions at the surface were not even closely approached for any squall studied. Furthermore, the observations show that the lowest 200–400 m behind the squall line has completely different characteristics: it is cool, near-saturated and with \(\theta_a\) of 21–22°C, or intermediate between the ambient subcloud layer air and the unsaturated downdraft air just discussed. A different explanation is required.

Whatever the origin of this air, it descends into the lowest few hundred meters from 10–30 km behind the squall front, within the active squall line. The relative trajectories rule out any other source region. Aircraft penetrations invariably find the coldest air in this zone. It is proposed that this zone is dominated by saturated downdrafts and that the strongest and coldest of the

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10 Melting snow may also be of some considerable importance. It is apparently in abundance (Section 2) and rainfall rates are often several millimeters per hour at the surface and possibly 10 mm h\(^{-1}\) at the melting level. Braham (1952) believed that considerable negative buoyancy in the downdraft came from melting snow, but its magnitude is hard to quantify. G. Morgan (personal communication) recently made a similar suggestion, also pointing out that strict \(\theta_a\) conservation should not be assumed if the air spends much time in the melting layer.
saturated downdrafts are most favored to reach the surface, yielding a stable stratification in the air spreading out from this region.

There is no single definite source for this saturated downdraft air, but two are proposed for consideration. One is the ambient cloud-layer air which generally has a vertical gradient of $\theta_w$ with the necessary 21–22°C $\theta_w$ air typically found between 900 and 800 mb. The second is the convective-scale downdrafts high up in the cumulonimbus clouds, which could be formed from many different combinations of air origianlly in the subcloud layer, cloud layer or dry air, in ratios yielding a final $\theta_w$ of 21–22°C.

Kamburova and Ludlam (1966) demonstrated the extreme difficulty of sustaining any significant convective-scale downdraft through a deep layer without a continuous supply of cloud droplets. Even in heavy rain, the millimeter-size drops cannot evaporate quickly enough to maintain saturation, so the descent lapse rate is nearer the dry than the wet adiabatic and the negative buoyancy quickly disappears. It has already been noted that the unsaturated downdrafts in the anvil rain area descend at rates less than 1 m s$^{-1}$, more slowly than the vigorous downdrafts Kamburova and Ludlam are discussing. Significantly, there is no cloud at all in the slow mesoscale unsaturated downdraft area. It is not doubted that water loading in heavy-rain areas can initiate downdrafts, but Kamburova and Ludlam’s results strongly suggest that the continuous availability of cloud water, which evaporates rapidly enough to permit convective-scale downdrafts to reach speeds of several m s$^{-1}$ and to penetrate from the mid-troposphere to the surface, maintains near-saturated conditions.$^{11}$

Riehl and Malkus (1958) assumed the existence of vigorous saturated downdrafts in tropical cumulonimbus clouds in order to balance the energy budget of the equatorial zone as a whole. That is no assurance, however, that such downdrafts are present in this type of squall line. All that can be said with certainty is that they are possible, they could explain the saturated downdraft air, and they are physically most likely to exist in the 10–30 km zone where a source of such air is required, i.e., in the deep cumulonimbus of the squall lines.

The ambient cloud-layer air$^{12}$ has been proposed by Betts (1976) to be the primary source region for air later found in the post-squall region of Venezuela storms, although the compositing approach in that study made it difficult to distinguish between the two kinds of air in the ambient downdraft air. The numerical model results of Moncrieff and Miller (1976) also suggest that source. That air has a significant relative wind into the squall line, so it is an entirely likely source. In any case, its fate calls for some hypothesis.

The ambient cloud-layer air must be lifted along the squall front, as it lies directly above the lifted subcloud air with no place to go but up. As proposed by Betts (1976), there is a “crossover” of the cloud-layer and subcloud-layer airstream in the two-dimensional plane which is quite complex in the real cloud. It is convenient to define a “crossover zone” as that volume of the squall-line clouds within which the subcloud airstream, initially at the bottom, emerges above the airstream which started in the ambient cloud layer.

It is difficult to come to any conclusions about what happens in the crossover zone, except to point out certain unlikely extreme events. The first unlikely possibility is that there is no crossover. When air at $\theta_w=21^\circ$C starts from ambient conditions at 850 mb and is lifted into the squall-line cumulonimbus, it becomes several degrees cooler than the environment after 100 mb of lifting. It is difficult to imagine that it would not find an opportunity to sink relative to the subcloud air, which of course becomes warmer than its environment and forms the buoyant core of the cumulonimbus. Therefore, some kind of crossover is highly likely. A second, unlikely possibility is that the ambient cloud layer and subcloud air become completely mixed together in the clouds, losing their separate identities. The ambient subcloud-layer air is the only air which can form the buoyant cores of the cumulonimbus clouds so that they reach observed cloud top heights, and if complete mixing took place, such clouds could not exist. A third unlikely possibility is that the two airstreams pass each other with no mixing, as if a large number of stream tubes formed and the top and bottom sets of tubes interchanged position without becoming tangled.

If the above are ruled out, the only solution that remains is that the ambient cloud-layer and subcloud-layer air are lifted and pass each other within the cumulonimbus clouds of the squall line, but not without considerable mixing. It this view is accepted, it is still possible to visualize mostly undilute cumulonimbus cores, provided that a spectrum of mixing is envisioned; those subcloud parcels managing to traverse the crossover zone entraining only a little cloud-layer air are

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$^{11}$ No consideration has been given to the role of drop breakup in heavy rain. If that process could supply a sufficiently large number of sufficiently small droplets, the conclusions herein would be modified accordingly. Young (1975) finds that models which include collisional drop breakup fit observed drop spectra better than those which include only spontaneous disintegration of large drops. If his suggestion is correct, the small droplets required to maintain the saturated downdraft would not demand that the air descend in preexisting clouds, but only a sufficiently large rainfall rate.

$^{12}$ Betts’ cloud layer starts at 850 mb, a typical cloud base in Venezuela. For the oceanic environment, the cloud layer starts at about 950 mb, but for this argument, the 21–22°C $\theta_w$ is usually found from 900 to 800 mb.
favored to become buoyant cores. A similar natural selection can apply to the cloud-layer air; those parcels which start out with the lowest \( \theta_w \) and entrain the smallest amount of high \( \theta_w \) air as they pass through the crossover zone are most favored to sink to the surface, assisted by evaporation of rain and especially of cloud droplets. These hypothesized saturated downdrafts would have to originate within the squall-line cumulonimbus clouds, so their scale would be comparable to that of the convective updrafts, or smaller than the individual cumulonimbus cloud.

6. Summary

The low \( \theta_w \) air found behind the squall line above the mixed layer must originate wherever air of sufficiently low \( \theta_w \) is found in the surroundings, typically above 750 mb. It may approach the squall line from the front, from the rear, or from both directions at once. The descent required is 200 mb or greater, and it occurs mainly in mesoscale unsaturated downdrafts. The cool, near-saturated air found in the lowest few hundred meters forming the post-squall mixed layer is deduced to descend rapidly to the surface in saturated convective-scale downdrafts within the squall-line cumulonimbus. These downdrafts may originate in two ways: first, from ambient cloud-layer air, typically from 900 to 800 mb, lifted into the cumulonimbus and sinking after becoming negatively buoyant, without a great deal of mixing with air from other layers; and second, from higher up within the cumulonimbus, where downdrafts normally originate from water loading and entrainment of low \( \theta_w \) air.

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