A Comparison of Two-Dimensional and Quasi-Three-Dimensional Simulations of a Tropical Squall Line

MELVILLE E. NICHOLLS AND MICHAEL J. WEISSBLUTH
Department of Atmospheric Science, Colorado State University, Fort Collins, Colorado

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ABSTRACT

Results of a simulation of a tropical squall line which allows three dimensionality on the scale of convective elements, shows many similarities with those of a two-dimensional simulation. Differences are 1) The quasi-three-dimensional model produces less front-to-rear acceleration of updraft air and rear-to-front acceleration of downdraft air; 2) The horizontally averaged vertical mass flux and momentum flux profiles show sharper low-level peaks in two-dimensions; 3) The ratio of the maximum to minimum vertical velocities is larger in the quasi-three-dimensional simulation; 4) There is more of a cellular structure in the vertical plane perpendicular to the line in two-dimensions; and 5) The ratio of ice to liquid water is greater in the quasi-three-dimensional simulation.

An unexpected result is that very little of the air feeding the rear low-level downdraft originates from ahead of the system, even in the quasi-three-dimensional simulation. Strong vertical mixing of the inflow air occurs so that the equivalent potential temperature of the mid-level air increases and it ascends rather than feeds the cold pool. The strong vertical mixing is associated with overturning cells, which have little impact on the updraft branch of the circulation tilt. Results indicate that at the upper regions of the main downdraft, the pressure force is playing a role in accelerating air downwards. The major mechanism responsible for the downdraft appears to be diabatic cooling.

1. Introduction

A squall line is a system of thunderstorms arranged in a narrow band, which often propagates at a high speed (10–20 m s⁻¹) relative to the surface. Tropical squall lines typically form in an environment characterized by a low-level jet, in contrast to their midlatitude counterparts which tend to form in stronger, more deeply sheared environments (Barnes and Sieckman 1984; Bluestein and Jain 1985). They are observed to propagate at a speed comparable with or greater than that of the low-level jet maxima (Moncrieff and Miller 1976; Bolton 1984). Moncrieff and Miller (1976) emphasize the importance of the density current (fed by cool convective downdrafts) in maintaining the organized structure of the squall line and suggest that the propagation speeds of the density current and the deep convective cells be comparable for the convective system to be maintained. The observation that tropical squall lines tend to propagate relative to the wind at all levels with subsidence air being transported aloft in deep convective cells led Moncrieff and Miller (1976) to conclude that to be topologically possible the flow in the interior of the cumulonimbus must be of a three-dimensional nature. In particular, midlevel air can flow around convective cores and perhaps enter downdraft circulations. They derive a formula for the propagation speed which is based on this flow structure. However, Houze (1977) found that convective cells are transient, having a distinct life cycle of growth and decay; moreover, they translate rearward through the system as they mature. Hence, it is not obvious how large an influence the three-dimensional nature of convective elements has on squall line characteristics.

Two-dimensional models of squall lines in an environment having a low-level jet have actually met with reasonable success (Thorpe et al. 1982; Dudhia et al. 1987; Yoshizaki 1986; Nicholls 1987, hereafter referred to as N87). Nicholls (1987) showed that many of the observed features of a tropical squall line that occurred during the Global Atmospheric Research Programs Atlantic Tropical Experiment (GATE) are simulated by a two-dimensional model. However, there appeared to be some disagreement with observations. The relatively coarse resolution of the observational network precluded drawing definite conclusions as to the limitations of the model being two-dimensional. Furthermore, differences may be due to other reasons such as inadequacies in the microphysics parameterizations, neglecting radiation, or the simplistic homogeneous basic state used. In this study, the limitations of a two-dimensional model are investigated by comparing results with a quasi-three-dimensional simulation. The quasi-three-dimensional model involves the simulation

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of a section perpendicular to a squall line, with periodic boundary conditions along the lateral walls and open boundary conditions at the ends. This approach has also been used by Rotunno et al. (1988) and Redelsperger et al. (1986). The idea is that the section should be wide enough so that the simulation is three-dimensional on the scale of the cumulonimbus. The model is not three-dimensional on the scale of the whole system. Moreover, the results of the quasi-three-dimensional model are of interest for their own sake, since the convective should be more realistically simulated than in two dimensions.

Schlesinger (1984) investigated the difference between two- and three-dimensional simulations of thunderstorms in a sheared environment. Updraft velocities were considerably less in two dimensions. Furthermore, the dry compensating downdraft was much stronger relative to the updraft in two dimensions than in three. The updraft tilt was also greater in two dimensions. These results are for individual thunderstorms and do not necessarily carry over to a group of cumulonimbus organized in a long-lived line system. For instance, the updraft tilt in Schlesinger’s two-dimensional simulation was downshear rather than upshear as occurs in a tropical squall line (relative to the winds beneath the low-level jet). Simulations initiated by a warm thermal as in Schlesinger’s study require the development of a pronounced cold pool before the updraft tilts upshear (Rotunno et al. 1988). Rotunno et al. find that two- and three-dimensional simulations compare well for shallow weak-to-moderate shears oriented perpendicular to the line, but note significant differences for stronger deeper shears (e.g., supercellular structures may develop along the line). The tropical squall line environment used in this study is moderately sheared at low levels and hence differences between two and three dimensions may not be great. In this study we attempt to more precisely determine the nature and magnitude of these differences for a tropical environment. This enables a better assessment of whether some of the apparent discrepancies between a two-dimensional simulation of a tropical squall line and observations is a result of the neglect of the third dimension.

According to N87, the apparent discrepancies between a two-dimensional simulation of the 12 September squall line that occurred during GATE and observations, are 1) The tilt of the line is too shallow, \( \approx 10^\circ \) from the horizontal, compared to 20°–35° found in an observational study of GATE convective lines by LeMone et al. (1984a); 2) the maximum updraft velocities of 7–8 m s\(^{-1}\) are weaker than might be expected. At 1.6 km above the surface, updrafts which averaged 8.6 m s\(^{-1}\) for 1 km, were recorded near the southeast end of the line (LeMone et al. 1984a). However, the most intense convection occurred on the other end of the line for which no data are available; 3) boundary layer cooling and drying in the squall line wake are slightly more than observed by Fitzjarrald and Garstang (1981) and Johnson and Nicholls (1983), for the 12 September squall line; 4) in the simulation a warm band of air extends continuously across the whole system at midlevels, separating a cool pocket of air in the stratiform region from the cold pool. In the observations the cool pocket of air is analyzed as extending downwards just behind the region of strong convection, linking with the cold pool (Gamache and Houze 1985); 5) warming associated with dry compensating subsidence ahead of the squall line is very pronounced in the simulation and appears greater than observed by Gamache and Houze (1985); 6) the momentum flux is mainly confined to below 6 km in the simulation. However, an observational study of momentum fluxes by GATE convective lines (LeMone et al. 1984b) suggests the maxima occurs at 6 to 7 km above the surface; and 7) water contents seem fairly low in the simulation. No data are available on the concentrations of the various constituents of the water phase in this squall line. A radar study by Hauser and Amayenc (1986) of the water contents in a squall line that occurred over West Africa suggest cloud water and ice mixing ratios as much as twice as large as those simulated for the 12 September squall line, although there are probably differences between continental and oceanic cases.

In the simulation there are significant perturbations associated with embedded convection in the stratiform region and traveling gravity waves. It is possible these effects are exaggerated in two dimensions. In three dimensions new cells may be expected to form at the intersections of downdraft outflows from older cells. This process is not simulated by a two-dimensional model. Hence, the multicellular nature of the two-dimensional simulation may be quite different. It is of interest to discover whether the downdraft air in the three-dimensional simulation is fed by air flowing around convective cores rather than almost entirely from the rear as appears to be the case in the two-dimensional simulation. Another difference with observations is that the mesoscale downdraft beneath the stratiform region is weaker at low levels in the two-dimensional simulation. It is suggested by N87, that this is because the cold pool can spread out easier in three dimensions than in two, leading to increased low-level subsidence. For this process the quasi-three-dimensional model is essentially two dimensional and hence cannot be expected to give better agreement with observations.

The main objective of this study is to ascertain how important the three-dimensional nature of convective elements is in determining squall line characteristics. This knowledge is important, since for many purposes two-dimensional simulations may be realistic enough to be used as a valuable research tool. For instance, they may be used for examining the effect of different wind and thermodynamic profiles on squall line characteristics, or determining the importance of radiation.
In what manner and to what degree differences exist determine the confidence one can have in two-dimensional results. Also, since the quasi-three-dimensional model should fairly realistically simulate the convective region of the tropical squall line, it provides an opportunity to investigate the dynamical interactions between cumulonimbus occurring in a system. In section 2 the cloud model is described, in section 3 the initial conditions, and in section 4 the results. The results section begins by describing the two-dimensional and quasi-three-dimensional simulations. Next a comparison of these simulations is made. Finally, results of tracer and trajectory analyses are presented. The forcing influences for trajectories are only shown for the quasi-three-dimensional simulation. Forcing influences for two-dimensional trajectories appear similar and no attempt has been made to quantify the differences that may exist.

2. Description of the cloud model

The reader is referred to N87 for a more detailed description of the model used in this study. The cloud model used is the Colorado State University Regional Atmospheric Modeling System (RAMS). The model contains a full set of nonhydrostatic compressible dynamic equations, a thermodynamic equation, and a set of microphysics equations for water- and ice-phase cloud and precipitation. The horizontal grid spacing is 1 km and the vertical resolution is variable, corresponding to pressure increments of approximately 35 mb up to a height of 9 km, above which a constant spacing of 1 km is used. There are 34 vertical levels. The length of the domain is 108 km and the height 22 km for both the two-dimensional and quasi-three-dimensional models. The width of the quasi-three-dimensional domain is 30 km. The upper and lower boundaries are rigid walls. A weak dissipative layer 7 km deep is included at the top of the domain to reduce reflection from the upper boundary. The lateral boundaries incorporate a mesoscale compensation region (MCR—see Tripoli and Cotton 1982). The MCR is included to provide a large-scale mass balance adjustment due to circulation trends generated within the interior model domain. Lateral boundaries of the fine-mesh domain additionally incorporate the Klmp-Lilly (1978) radiation boundary condition to allow propagation of gravity waves through the fine mesh/ MCR walls. At the lower boundary, frictional effects and surface fluxes are neglected. Radiation is not included in the model.

3. Initial conditions

In simulating the 12 September squall line (N87), it was necessary to use a rather fine grid resolution of 0.5 km; a 1 km resolution produced a very slow developing and weak system. A 0.5 km resolution for a three-dimensional model is computationally expensive and furthermore, severely limits the domain size that can be used. A series of two-dimensional experiments has been conducted by Nicholls et al. (1988). The objective of this study was to discover the effects of different wind and thermodynamic environments on squall line characteristics. One of the conclusions was that differences in squall line structure for various environments tend to be more of degree than of kind. For instance, increasing the buoyant energy of the sounding by 16% increased the intensity of the squall line, but the basic structure was unaltered. In this study we change the sounding of the 12 September squall line in order to produce a more intense system so that the convection can be adequately resolved by a 1 km grid. These changes are not unrealistically large and we do not believe they significantly influence the conclusions of this study. The buoyant energy is increased by approximately 10% by decreasing the temperature between 1–10 km by an average of 0.7°C. Furthermore, the results of a number of numerical studies (Thorpe et al. 1982; Dudhia et al. 1987; Rotunno et al. 1988 and Nicholls et al. 1988) indicate that weak shear aloft is favorable for squall lines. The 12 September squall line wind profile has a narrow jet with strong shear above it. We broaden the jet and reduce this shear. Finally, the results of Nicholls et al. (1988) suggest that increased midlevel moisture aids the system, so this change is also made.

The initial wind profile adopted in this study is shown in Fig. 1. The wind profile shows a low-level jet with a maximum speed of nearly 12 m s⁻¹ at 650 mb and a weaker upper-level jet. The thermodynamic profile shown in Fig. 2 has a convective available potential energy (CAPE) of approximately 1900 J kg⁻¹. The alterations made to the sounding are not thought to be excessive. The typical wind structure for Nigerian squall lines observed by Bolton (1984), has a broader jet and weaker shear aloft than the sounding used here. The squall line simulated by Dudhia et al. (1987), which occurred over West Africa had a moister midlevel environment than the sounding shown in Fig. 2. A value of CAPE of 1900 J kg⁻¹ is less than that found in the composite analysis of midlatitude squall lines by Blue- stein and Jain (1985), although more than that determined by Barnes and Siekman (1984) for tropical squall lines during GATE. Our intention has been to use a plausible environment for a tropical oceanic squall line. It is certainly biased towards those systems forming in an environment with large CAPE.

The difference in intensity between two-dimensional simulations using a grid resolution of 0.5 km and 1 km is small. The two-dimensional simulation is initialized by perturbing an initially horizontally homogeneous environment with a warm moist bubble (approximately 6 km in horizontal width and 2 km in the vertical and centered at about 2 km above the surface) and applying a cooling rate (10 km in width and 3 km
in height) 2 km to the east of the bubble. The bubble is 0.3°C warmer and 0.5 g kg\(^{-1}\) more moist at its center than the environment and the cooling rate is 0.005°C sec\(^{-1}\), applied for 15 minutes with a linear decrease to zero at 20 min. The surface cooling produced is about \(-4°C\), which is less than that subsequently produced by rain and convective downdrafts (\(\sim -5°C\)). This form of initialization quite quickly produces a circulation resembling that of a squall line moving towards the west. It is meant to crudely represent the interaction between a gust front from an earlier decayed system and a small scale inhomogeneity, which favors convection. The quasi-three-dimensional model is initialized in much the same way, except two warm moist bubbles of slightly different magnitudes are placed ahead of the applied cooling rate. This initialization is chosen so that three-dimensional, convective-scale circulations will quickly develop. The microphysical parameters used in the model are the same as those used by N87.

4. Results

a. Description of the two-dimensional simulation

The simulations are run for a period of 3 h. By this time the leading edge of the squall line is close to the left-hand boundary and the anvil is exiting out of the

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**Fig. 1.** The initial wind profile.

**Fig. 2.** Initial temperature and dewpoint. The dashed line shows a moist adiabat.
right-hand side of the domain. Most of the fields are displayed at 2.5 h, at which time it is felt that the influence of the lateral boundaries are not large. For this reason our study only concerns the early stages of the development of squall lines, which often have lifetimes in excess of 6 h. The system evolves with time. Initially the updraft is only slightly tilted from the vertical. As the cold pool becomes colder and deeper the updraft becomes much more tilted and weakens.

Figures 3a, b, c, and d show fields of velocity vectors and perturbation pressure, vertical velocity, perturbation temperature, and liquid and ice water content, respectively, at 2.5 h. (Perturbation fields are with respect to the initial base state which is horizontally homogeneous.) The circulation consists of a strongly tilted updraft carrying moist low-level air from ahead of the system rearwards; this is undercut by a rear-to-front circulation of drier air, descending to feed the gust front, and shallow return flow near the surface. A mesolow is centered just behind the gust front at about 2 km above the surface. Significant horizontal accelerations are induced by this mesolow. The vertical velocity field shows an updraft which is significantly tilted from the vertical and has a multicellular appearance. A fairly deep cold pool is overlain by a layer of warmer air.

Water contents are particularly large just behind the gust front. Cells move rearwards through the system as they mature, eventually merging into an upper-level trailing stratiform region.

b. Description of the quasi-three-dimensional simulation

The initial cells are very intense. Horizontal cross sections of vertical velocity at 0.8 h are shown in Figs. 4a and b, for z = 3 and 8.5 km, respectively. At z = 3 km it can be seen that downdrafts have developed to the rear of the initial thermals. The updraft velocities tend to be stronger on the sides of the downdrafts rather than directly in front. The vertical velocity field at 8.5 km shows the cells are strong at upper levels. Figure 5 shows the horizontal cross section of temperature at z = 0.1 km. The initial applied cooling rate has produced a cold pool which propagates along the x-axis. The two cells have produced strong downdrafts which feed circular cold pools. Figures 6a and b shows horizontal cross sections of vertical velocity at 1.1 h, for z = 3 and 8.5 km, respectively. Two new cells formed at the intersections of the outflows from the two initial cells. At z = 3 km the vertical velocity shows a band of up-

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**Fig. 3.** Results for the two-dimensional model, at 2.5 h: (a) Velocity vectors and perturbation pressure. The cloud outline which includes rain water is contoured. The contour interval is 40 pascals and the label scale is 10. (b) Vertical velocity. The contour interval is 120 cm s⁻¹. (c) Perturbation temperature. The contour interval is 0.6°C. (d) Total liquid and ice content. The contour interval is 0.8 g kg⁻¹, and the label scale is 100.
ward motion aligned in the $y$-direction. The anvils from the initial cells have merged at upper levels to form a stratiform region, continuous in the $y$-direction. During the next hour, cells tend to be smaller and less well defined than these earlier cells. As in the two-dimensional simulation, the updraft becomes more tilted as the cold pool develops.

Horizontal cross sections of vertical velocity and perturbation horizontal velocity at 2.5 h, for $z = 8.5$ km, are shown in Figs. 7a and b. There are two large cells which are in the process of merging. The horizontal perturbation velocity fields indicate there is strong front-to-rear flow associated with these cells. Figures 8a and 8b show the horizontal cross sections of perturbation temperature and rain mixing ratio at $z = 0.1$ km, respectively. A temperature jump of $-5^\circ$C occurs across the gust front. The rain mixing ratio is largest beneath the cells. Figures 9a, b, c and d portray $x/z$ cross sections at $y = 8$ km, of velocity vectors and perturbation pressure, vertical velocity, perturbation temperature, and liquid and ice mixing ratio, respectively, at 2.5 h. This vertical cross section is through one of the cells and shows an intense updraft. Note that there is considerable smaller-scale cellular structure within this updraft. As in the two-dimensional simulation, the strong front-to-rear flowing updraft is undercut by a rear-to-front flowing downdraft, which feeds a cold pool. The liquid and ice water contents show quite a cellular structure in the strong updraft region, and there is more stratiform at upper levels to the rear. Figure 10 shows the velocity vectors and perturbation pressure at $y = -2$ km, which is between the two cells. Although this cross section is between cells, there is still significant upward motion, and the structure of the circulation is similar to that within cells, albeit weaker. Figures 11a, b, c and d, show $y/z$ cross sections of vertical velocity, the $y$-component of velocity, the perturbation $x$-component of velocity, and the liquid

**Fig. 4.** Horizontal cross sections of vertical velocity at 0.8 h: (a) $z = 3$ km and (b) $z = 8.5$ km. The contour interval is 200 cm s$^{-1}$.

**Fig. 5.** Horizontal cross section of temperature at 0.8 h. Here $z = 0.1$ km and the contour interval is 0.5°C.

**Fig. 6.** Horizontal cross sections of vertical velocity, at 1.1 h. Here (a) $z = 3$ km and (b) $z = 8.5$ km. The contour interval is 200 cm s$^{-1}$.

**Fig. 7.** Horizontal cross sections at 2.5 h, for $z = 8.5$ km: (a) Vertical velocity. The contour interval is 200 cm s$^{-1}$. (b) Perturbation horizontal velocity. The contour interval is 200 cm s$^{-1}$.
and ice mixing ratio, respectively, at 2.5 h, for $x = 10$ km. The $v$ field shows that there tends to be horizontal convergence beneath the center of the cells and diver-

gence above in this plane. Upward motion is nearly continuous in the $y$-direction, at midlevels and is fairly well correlated with the front-to-rear flow. Weak downward motion occurs between cells at upper levels. There is a minimum in the liquid and ice mixing ratio between the cells, below 8 km.

![Fig. 9. The $x/z$ cross sections for $y = 8$ km, at 2.5 h: (a) Velocity vectors and perturbation pressure. The contour interval is 40 pascals and the label scale is 10. (b) Vertical velocity. The contour interval is 120 cm s$^{-1}$. (c) Perturbation temperature. The contour interval is 0.6$^\circ$C. (d) Total liquid and ice content. The contour interval is 0.8 g kg$^{-1}$ and the label scale is 100.](image-url)
c. Comparison of two-dimensional and quasi-three-dimensional simulations

Figures 12a and 12b show the maximum and minimum vertical velocities, respectively, for the two simulations. The maximum updraft velocity in the quasi-three-dimensional simulation increases to large values initially and then decreases considerably. The two-dimensional simulation shows a more gradual increase in updraft strength, which peaks at about 50 min and then a slow decrease. The maximum updraft strength in the quasi-three-dimensional simulation remains greater than in two dimensions. The maximum downdraft strengths peak slightly after the maximum updraft strengths. Although the maximum downdraft strength in the quasi-three-dimensional simulation is much larger than in two-dimensions early, by 2 h, it has declined to approximately the same value. The time-averaged ratio of the maximum updraft strength to the maximum downdraft strength is 2.5 for the quasi-three-dimensional simulation and 2.0 for the two-dimensional case. This is consistent with the results of Schlesinger (1984), who compared two-dimensional and three-dimensional simulations of individual thunderstorms. Much more explosive growth of the initial thermals occurs in the quasi-three-dimensional simulation since convergence into the updraft is not restricted to two dimensions.

Figures 13a, b and c show the time evolution of the total liquid water, total ice content and accumulated precipitation in the domain, respectively. It should be noted that advection of ice particles is occurring through the right-hand side of the domain at 2.5 h (see Figs. 3d and 9d) which is not taken into account in these domain averages. The total liquid water content (which is mainly rainwater) is significantly larger in the two-dimensional simulation during most of the 3 h period. On the other hand, the total ice contents are similar. Assuming these results are not sensitive to the form of the initial forcing (which in this case produced
processes become more important. The accumulated precipitation is significantly less in the quasi-three-dimensional simulation, which is consistent with the reduced rainwater contents.

The $Y$-averaged fields were constructed for the quasi-three-dimensional simulation and compared with these for two dimensions. The $y$-averaged fields of the quasi-three-dimensional simulation are much smoother than those of the two-dimensional simulation, but show many similarities. A sample of 2 of the $y$-averaged fields, velocity vectors, and perturbation pressure, at 2.5 h, is shown in Fig. 14 (compare with Fig. 3a). There is a stronger front-to-rear acceleration of the updraft air and rear-to-front acceleration of the downdraft air in two dimensions. This is associated with a more pronounced mesolow in two dimensions. The updraft in two dimensions has a more abrupt jump at the gust front followed by a slower ascent. The broad structure of the $y$-averaged liquid and ice water contents (not shown) is similar to that of the two-dimensional simulation, with the maxima occurring in approximately

intense initial cells in the quasi-three-dimensional simulation), they suggest that in three dimensions there is a tendency for the ratio of ice to liquid water to be greater than it is in two dimensions. This may be a reflection of the larger updraft velocities in three dimensions, which would be expected to transport relatively more condensate to higher levels where ice

![Image](http://journals.ametsoc.org/mwr/article-pdf/116/12/2437/4170112/1520-0493(1988)116_2437_acotda_2_0_co_2.pdf)

**Fig. 12.** Magnitude of (a) maximum updraft velocities, and (b) maximum downdraft velocities, as a function of time.

![Image](http://journals.ametsoc.org/mwr/article-pdf/116/12/2437/4170112/1520-0493(1988)116_2437_acotda_2_0_co_2.pdf)

**Fig. 13.** Time evolution of (a) total liquid water, (b) total ice water, and (c) accumulated precipitation. Given as the total mass within a 1 m thick section (108 km × 22 km × 1 m).
the same places. However, in two-dimensions there is a new vigorous cell forming at the gust front, which only has a weak counterpart in three dimensions.

Figures 15a–c show the vertical profiles of horizontally averaged vertical mass flux, horizontal velocity and momentum flux, respectively, at 2.5 h. The vertical mass flux is stronger at low levels in the two-dimensional case. The horizontal velocity profile clearly shows a stronger front-to-rear flow at midlevels and a stronger rear-to-front flow at lower levels. Interestingly, in a shallow layer next to the surface, the averaged horizontal velocity is less in the quasi-three-dimensional simulation. The momentum fluxes are stronger at low levels in two dimensions and the profile has a sharper maximum. The height at which the maxima occur are about the same in both simulations.

The surface changes in temperature and mixing ratio behind the gust front are similar in both cases. The surface temperature and mixing ratio perturbations are 5.2°C and 5.0 g kg⁻¹, respectively, in two-dimensions, compared with 4.9°C and 4.8 g kg⁻¹ for the quasi-three-dimensional simulation.

In the x/z plane, vertical velocity fields (see Figs. 3b and 9b) generally show less of a cellular appearance in the quasi-three-dimensional simulation. Furthermore, a closer inspection of the fields (using a finer contour interval than shown in these figures) reveals that emanating internal gravity waves are more prominent in the two-dimensional simulation.

d. Tracer and trajectory analysis

In order to determine the origin of the air in the updraft and downdraft circulations, tracers are introduced into various layers. The tracers are introduced at 1.5 h and the model is then run for 1 h. Tracers are more accurate for determining the origin of air than trajectories since the effects of subgrid scale diffusion are included and they do not involve interpolation between time intervals. Figures 16a–e show the results for five tracers introduced into the two-dimensional simulation. It is evident that hardly any air feeds the rear low-level downdraft from the front of the system during this stage of squall line evolution. (Air does feed the cold pool from ahead of the system very early on, which will be discussed later.) Most of the air transported to high levels comes from below 2 km. Considerable mixing of the inflow air occurs. Only some of the air closest to the surface (z < 0.75 km) reaches cloud top, even though this air is the most unstable. Air in the 2.0–4.5 km layer is entrained into the updraft and ascends. Due to the weak winds relative to the squall line motion in this layer, the rate of entrainment is not large. The origin of the coldest air in the downdraft outflow is the 2.0–4.5 km layer to the rear of the system. The 1–2 km layer descends further to the rear of the system.

Tracers are introduced into the 0–2 km and 2.0–4.5 km layers in the quasi-three-dimensional simulation. Figures 17a and 17b show x/z cross sections for the two tracers at y = 8 km. As in two-dimensions, very little of the air feeding the cold pool originates from ahead of the system. Again there is considerable vertical mixing of the inflow air. Figure 18 shows a y/z cross-section of the tracer introduced ahead of the line, below 2 km, at 2.5 h. The air in-between cells ascends over the gust front. The tracer reaches the lowest levels within cells.

Figure 19 shows three trajectories for the quasi-three-dimensional model, between 1.5 to 2.5 h. Most of the motion for these trajectories occurs in this plane (y ~ 8 km). Figure 20 displays the evolution of vertical velocity, height, equivalent potential temperature, and the vertical acceleration terms along trajectory A. The pressure force is responsible for upward acceleration of the inflow at the gust front. Air is negatively buoyant initially, and becomes positively buoyant above 2 km. At this stage the pressure force opposes the upward motion, as does the water loading. This trajectory does not reach high levels. Considerable mixing reduces the equivalent potential temperature along this trajectory. Trajectory B (Fig. 21) ascends from 2 km to upper levels. At this height the inflow does not experience any forced uplift due to the gust front. The equivalent potential temperature increases along this trajectory due to mixing with air from below. This mixing appears important for enabling inflow air at 2 km to rise to upper levels. The pressure force opposes the buoyancy of the positive temperature anomaly. In this case the water loading term is less than along trajectory A. Trajectories through the center of the updraft cores originate ~1 km above the surface and show little overall change in θₑ (not shown). However, this does not necessarily mean mixing is entirely absent, since there could be cancellation between air mixed upwards having higher θₑ and air mixed downwards having lower θₑ. Trajectory C (Fig. 22) descends from 2.8 to 0.5 km. The smoothness of the θₑ curve and its near constant
FIG. 15. Horizontally averaged vertical profiles, at 2.5 h: (a) vertical mass flux, (b) horizontal velocity, and (c) momentum flux.
value, indicates there is no significant mixing with air having different equivalent potential temperature. The pressure force is mainly balanced by the warming term during the first part of the descent. As the air reaches lower levels, the direction of the buoyancy and pressure forces change, remaining opposed to one another. The physical mechanism responsible for causing the air to descend is difficult to ascertain from consideration of the forcing terms. For instance, evaporational cooling could be the major factor driving a parcel of air downwards, but the temperature anomaly within the parcel could conceivably be positive. This is because as air cools it descends so that the temperature anomaly relative to the environment at that level does not change by much. The added effect of water loading, for example, could cause the temperature anomaly to be positive during part of its descent. The importance of cooling due to evaporation and melting is suggested by the fact that air descending adiabatically from 2.8 to 0.5 km would end up with a temperature anomaly
FIG. 17. As in Fig. 15, except the label is 100, for the x/z cross sections of tracers introduced into the quasi-three-dimensional model, at y = 8 km: (a) 0.0–2.0 km, and (b) 2.0–4.5 km.

some 13°C warmer than observed. During the early part of the descent of trajectory C, the temperature perturbation is positive. This positive temperature anomaly is mainly balanced by the pressure force, with the loading term being significantly less (although this is not true along all downdraft trajectories). The downward pressure force may be responsible for the initial descent along trajectory C. We suggest two possible reasons why a downward pressure force could cause air to descend in the upper region of the downdraft. First, the downdraft is in close proximity to the warm updraft. The pressure distribution associated with this warm updraft is likely to lead to a downward force at its edges. Second, as described by Knupp (1985), a downdraft produced by cooling forms a low pressure anomaly in its upper regions, which drives horizontal convergence and also descent above.

Vertical mixing of inflow air in the convective region of squall lines has been hypothesized by Zipser (1977). Results presented here indicate that such mixing does indeed occur and is considerable for this particular case. Most of the air feeding the cold pool originates from the rear of the system, and simple thermodynamic considerations suggest that melting and evaporation of hydrometeors is the major factor responsible for the low-level rear downdraft. It appears that the vertical pressure force (which itself may be partly related to low-level cooling) and waterloading is causing the downdraft air to be warmer than the ambient temperature during the initial part of the descent.

The forcing influences on the two-dimensional trajectories are qualitatively similar to those for the quasi-three-dimensional simulation. In contrast to two dimensions, in three dimensions some of the air originating from low levels passes through the center of the deeper stronger updraft cores reaching the upper levels in a relatively undilute state.

5. Conclusions

In this paper we have attempted to determine the differences between a simulation of a tropical squall
in-between cells resembles the circulation within cells, albeit weaker. Considerable vertical mixing of the inflow air occurs in the updraft in both simulations. Only a small amount of the most unstable air, closest to the surface, ascends to cloud top. Results suggest that at the upper regions of the main downdraft, the pressure force is playing a role in accelerating air downwards. The major mechanism responsible for the downdraft appears to be diabatic cooling.

There are less differences between the simulations than were originally anticipated. The average tilt of the updraft from the vertical is only slightly less in the quasi-three-dimensional simulation. The boundary layer modification is only marginally reduced. Strong subsidence warming is observed ahead of the squall line and warm air extends continuously across the system at midlevels, in both simulations.

Fig. 20. Evolution of $w$ (solid), height (dash), $\theta_e$ (dot) and the vertical acceleration terms along trajectory A.

line which allows three dimensionality on the scale of convective cells and one which is two dimensional. Differences are 1) there is greater front-to-rear acceleration of updraft air and rear-to-front acceleration of downdraft air, in two dimensions; 2) the horizontally averaged vertical mass flux and momentum flux profiles show sharper low-level peaks in two dimensions; 3) the ratio of the maximum to minimum vertical velocities is larger in the quasi-three-dimensional simulation; 4) there is more of a cellular structure in the vertical plane perpendicular to the line in two dimensions; 5) the ratio of ice to liquid water is greater in the quasi-three-dimensional simulation. An unexpected result is that very little of the rear downdraft air which reaches low levels originates from ahead of the squall line in the quasi-three-dimensional model. In the quasi-three-dimensional simulation, the circulation

Fig. 21. Evolution of $w$ (solid), height (dash), $\theta_e$ (dot) and the vertical acceleration terms along trajectory B.
The simulations have a multicellular structure. However, there is less of a cellular appearance in the $x/z$-plane for the quasi-three-dimensional simulation. There appears to be a tendency for the updraft branch of the circulation, which is fairly vertically oriented in the beginning, to become more cellular as it tilts. The tracer and trajectory analyses illustrate the considerable vertical mixing of the inflow air associated with cells.

Rotunno et al. (1988) modeled squall lines in two and three dimensions using different wind and thermodynamic structures than used in this study. For the case of strong low-level shear and no shear aloft, they obtain an oscillating mode where cells periodically grow and decay. Cells tilt downshear as they develop so that precipitation falls into the inflow air. The subsequent collapse of the cell creates a surge in the cold pool, which then initiates a new cell. The downdraft beneath the decaying cell can bring midlevel air from ahead of the squall line, down to the surface. Eventually, the cold pool strengthens, causing the updraft to tilt upshear, and its strength steadily—albeit slowly—declines. The simulations in this study show no oscillating phase and are akin to the later period of the simulation by Rotunno et al. Initializing the simulation as they did, using a warm bubble only, we were still unable to obtain an oscillating phase. This may be because the jet wind profile leads to the rapid development of an upshear tilt, and the formation of a pronounced cold pool. It could also be due to differences in buoyant energy and model parameters. In our simulations the cellular behavior that occurs as the updraft develops an upshear tilt may not be primarily due to the same mechanism as described above. In order to ascertain whether cellular behavior occurs in the absence of cold pool surges, we ran a simulation initialized by a warm bubble only, with the rain parameterization turned off. In order to attain moderate updraft strengths in the absence of low-level forcing by a cold pool, it was necessary to increase the buoyant energy slightly. The initial updraft tilted downshear and divided in two, clearly demonstrating cellular behavior in the absence of cold pool surges. Subsequently, there was the production of deep gravity waves which interacted with the convection and modulated the cellular behavior. The mechanisms leading to the formation of cells are complex and require further investigation.

In our simulations, an up–down branch (Thorpe et al. 1982) feeding the rear downdraft from the fore exists very early, but once the cold pool cools below about $-4^\circ$C, it is inhibited. (It is only when the lowest level air is lifted higher by the developing cold pool that its potential for releasing latent heat can be realized.) If the environmental air in the lowest 1 km is made more stable, it is possible to obtain a more persistent up–downdraft. In this case the squall line is significantly weaker and less boundary layer modification occurs. A persistent up–down branch is found in other simulations (e.g., Dudhia et al. 1987) and also is a feature observed in a midlatitude squall line analysed by Ogura and Liou (1980). The low-level rear downdraft is not fed significantly by air passing around cells at midlevels. Considerable vertical mixing with air from below increases its equivalent potential temperature and it has a tendency to ascend.

It is possible that the conclusions of this study could be significantly modified for squall lines forming in a different environment. Vertical mixing of the inflow air may be considerably less for systems having vertically oriented updrafts. Furthermore, in North America, squall lines are sometimes composed of convective elements which are more supercellular in character than are found in the tropics. For these systems, the structure of the downdraft circulation may be quite different, with a considerable amount of the air feeding the cold pool originating from ahead of the squall line.

In conclusion it has been demonstrated that there
are many similarities between two-dimensional and quasi-three-dimensional simulations of the early development of a tropical squall line. Although this study is limited, because a comparison has only been made for one particular case, it suggests that in some circumstances two-dimensional simulations can be used as a more economical tool for investigating the nature of squall lines.

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