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THE STRUCTURE AND DYNAMICS OF MOIST ABSOLUTELY UNSTABLE LAYERS IN A SIMULATED SQUALL LINE

George H. Bryan and J. Michael Fritsch
Pennsylvania State University, University Park, PA

1. INTRODUCTION

Moist absolute instability is a thermodynamic state wherein a *saturated* layer of air exhibits a lapse rate greater than moist adiabatic. Moist absolutely unstable layers (MAULs) can form as a result of lifting an initially sub-saturated, conditionally unstable environment. It is traditionally argued that MAULs quickly overturn (i.e., in a matter of minutes), since all parcels displaced vertically within the layer will accelerate in the direction in which they are displaced. Nevertheless, observations and numerical simulations (e.g., Kain and Fritsch 1998, Bryan and Fritsch 2000) suggest that MAULs may persist for considerably longer periods of time (up to 30 min) and over large areas (tens of km across a squall line and hundreds of km in the along-line direction).

This paper presents a high resolution (Δx = 125 m) numerical simulation of a squall line. This resolution allows for explicit representation of *in-cloud* turbulent processes. Using the output from this simulation, the conceptual model from earlier work on the structure and lifecycle of MAULs is refined. The relationship between MAULs and the various regions of squall lines (e.g., convective and stratiform regions) is also addressed.

2. DESIGN OF NUMERICAL SIMULATIONS

The numerical model used for this study is described in detail in Bryan and Fritsch (2002a). The governing equations are integrated using the Runge-Kutta technique as formulated by Wicker and Skamarock (2002) for compressible models. The simulations use the Kessler microphysics scheme that includes only warm rain processes. The subgrid turbulence parameterization is similar to the one presented in Deardorff (1980).

The domain for this experiment is 300 km in the across-line direction with open boundary conditions, and 60 km in the along-line direction with periodic boundary conditions. The analytic temperature and moisture profiles of Weisman and Klemp (1982) are imposed as an initially horizontally homogenous environment. A squall line is initiated with a north-south line thermal with a maximum perturbation of 2 K centered 1.5 km above the surface. Simulations were conducted using various wind profiles, however, only results from a wind profile with 10 m s^{-1} of shear over the lowest 2.5 km are presented here.

Bryan and Fritsch (2002b) argue that resolution of order 100 m is required for proper behavior of the subgrid turbulence closure in cloud-scale numerical models. Furthermore, with such resolution, *resolved* turbulent eddies stretch and distort the plumes of high equivalent potential temperature (θ_e) that rise from the boundary layer into mid-levels (see, e.g., Fig. 2 of Bryan and Fritsch 2002b). In contrast, with 1 km grid spacing, the high θ_e plumes can rise in a relatively laminar manner. Consequently, with 125 m resolution, the removal of the absolute instability is accomplished partly by *resolved turbulent mixing*, as opposed to simulations with grid spacing of order 1 km in which mixing is accomplished primarily by parameterized subgrid terms.

These three factors – i.e., a grid spacing consistent with the design of the subgrid model, the change from laminar to turbulent flow, and overturning of MAULs by resolved rather than parameterized processes – give us confidence in the utility of very high resolution to study the structure and dynamics of MAULs. Furthermore, the general structure of the region of absolute instability does not change appreciably when resolution is increased from 250 m to 125 m, suggesting a convergence of results. Of course, high resolution *observations* of MAULs would be required to confirm the accuracy of the model-produced structure. The model results suggest that thermodynamic observations with extraordinarily high horizontal resolution would be required to assess the processes that occur in MAULs.

3. STRUCTURE OF MAULS

The total depth of moist absolute instability at 3 hr is shown in Fig. 1a. This variable (hereafter referred to as total MAUL depth) is the sum of the depths of all MAULs in a column, i.e., this variable does not necessarily represent an uninterrupted layer of instability. Along the gust front, total MAUL depth tends to be deeper and generally more uniform than the conditions elsewhere in the system. Roughly 10-15 km behind the gust front, a less uniform structure emerges, with almost regularly-spaced "pockets" where moist absolute instability is much shallower or nonexistent. About 5-10 km farther back, the total MAUL structure is less coherent, and characterized by occasionally larger values (> 3 km).

The depth of the deepest *continuous* layer of moist absolute instability in a column is shown in Fig. 2b. For this figure, only the depth of the deepest MAUL is plotted – even though other MAULs may exist in the column. This figure shows that the region of deep instability along the gust front is also the deepest continuous (in a vertical sense) MAUL in the squall line. Farther back into the system, the depths of individual MAULs are almost everywhere less than 1 km.

A plot of the total number of MAULs in a column (Fig. 2c) completes the picture. This figure shows that the very deep (> 3 km) total MAUL depths that exist about 20 km behind the gust front are composed of many discrete MAULs.

Cross-line cross sections of θ_e (Fig. 2) further illustrate the structure of MAULs in the squall line. The deep, continuous MAUL above and ahead of the surface gust front forms as the advancing cold pool lifts

Corresponding author address: George H. Bryan, 503 Walker Bldg., University Park, PA 16802; email: bryan@essc.psu.edu

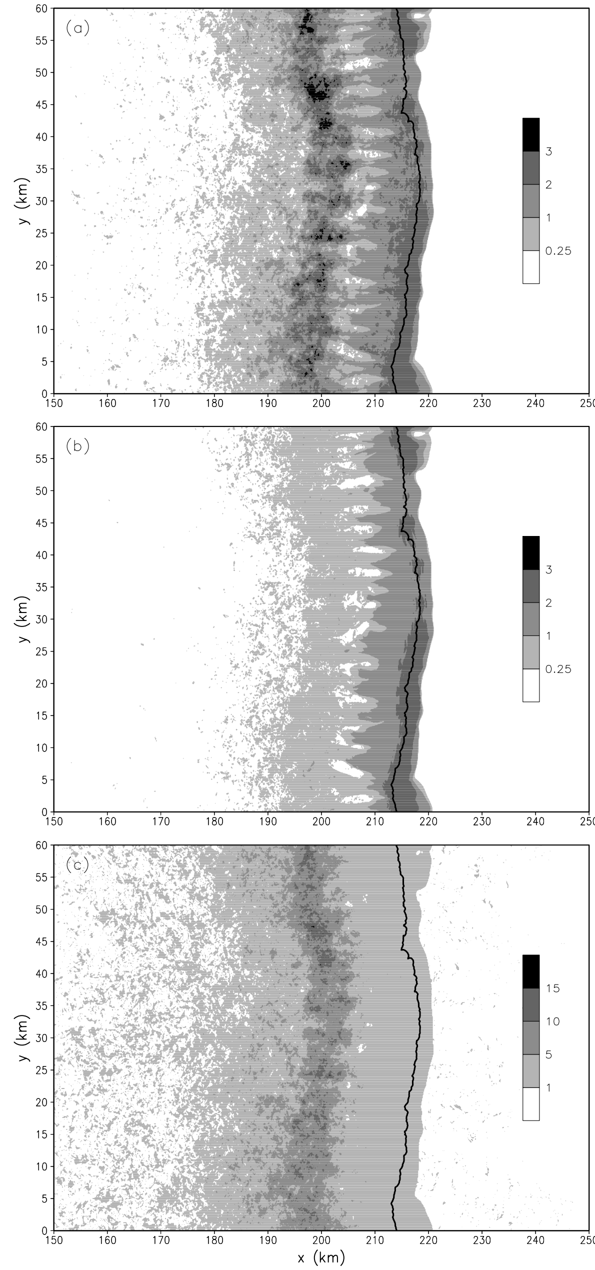

Fig. 1. Properties of the MAUL at 3 h. (a) Total depth (km) of moist absolute instability. (b) Depth (km) of the deepest continuous layer of moist absolute instability. (c) Total number of moist absolutely unstable layers in the column. In each panel, the location of the surface gust front is indicated with a thick black contour.

a layer of conditionally unstable air to saturation. This dynamically-forced MAUL extends relatively unchanged for about 10 km. Since the properties of the pre-squall-line environmental air and the properties of the cold pool are similar along the entire north-south length of the domain, this "gust-front" MAUL has nearly uniform properties along the line. For instance, the MAUL structure from about x=208 km to x=218 km in both Figs 2a and Fig2b are very similar.

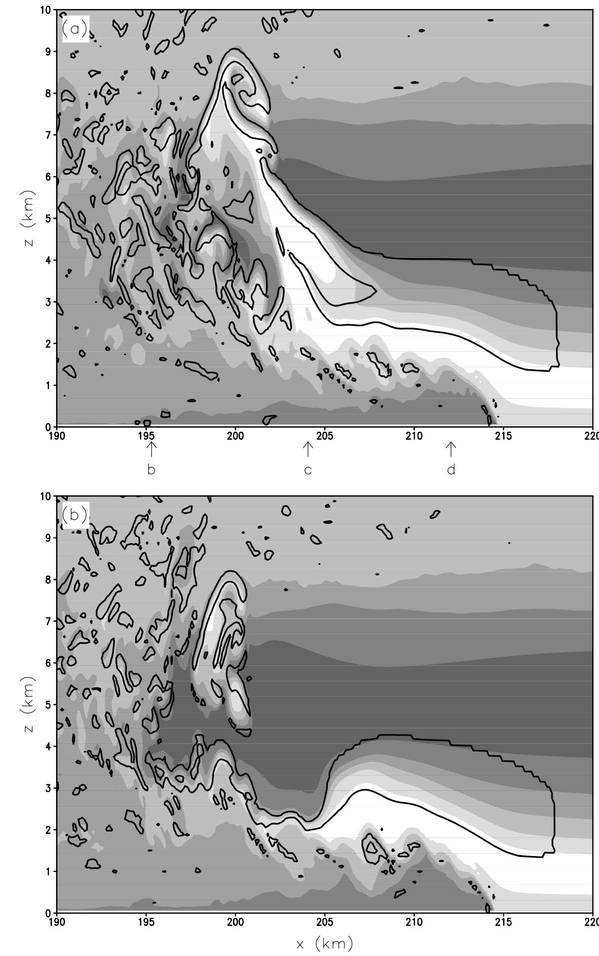

Fig. 2. Cross-line cross sections of θ_e (shaded) at 3 hr and: (a) y=9 km; (b) y=7.5 km. Shading interval is 4 K, with the darkest shade corresponding to 326 K and the lightest shade corresponding to 342 K. Areas of moist absolute instability are indicated by the thick black contour.

Farther upstream, the MAUL structure varies considerably. At y=9 km (Fig. 2a), a deep plume of high θ_e air extends from the gust-front MAUL to the upper-troposphere. Absolute instability exists along the top of this plume, though MAUL depths are much shallower. Two rotating eddies, one starting to develop at ~6.5 km and another, more well-developed, centered at ~8.5 km, are features that often develop along plumes such as this.

In contrast, a cross-section at y=7.5 km (Fig. 2b), only 1.5 km away from the previous cross section, reveals completely different processes. Here, the high θ_e plume is deflected downward by compensating subsidence associated with the deep cellular plumes. The MAUL depth in this plume becomes very shallow, as the θ_e field narrows in the convergent flow. The MAUL depth is further reduced by the total evaporation of cloud water along the top of the MAUL (owing to the warming of downward-moving air) and the resulting drop in humidity to subsaturated levels.

The cross section in Fig. 2b cuts across one of the "pockets" of shallow MAUL depth shown in Figs. 1a and 1b, whereas the cross section of Fig. 2a cuts through a section where relatively deep (> 1 km) total MAUL depth extends farther back into the system. The two cross sections show how the rather laminar conditions in the initial MAUL give way to deep cellular convection and strong compensating subsidence characteristic of the convective region of squall lines.

Still farther upstream, about 15 km behind the surface gust front, both cross sections in Fig. 2 show a similar pattern – overturning and mixing by small-scale turbulent eddies. These convective elements do not fit the conceptual model of thunderstorm cells, given their small scale and (relatively) weak vertical velocities. These moist convective eddies seem to accomplish much of the mixing of high θ_e air, drawn initially from the pre-squall-line boundary layer, with low θ_e air drawn from mid-levels. In fact, a broad path for vertical transport not associated with cellular towers can be seen in both Figs. 2a and 2b – that is, a plume of high θ_e air that extends from just above the cold pool, and rises gradually to upper-levels. (This plume is more apparent in Fig. 2b, since there is no cellular tower in this cross section.) This vertically expanding high θ_e plume intertwines with a slightly descending plume of mid-level, low θ_e air from in front of the line. The mixing of these two plumes is accomplished effectively by the many moist convective eddies. Ultimately, these processes create a deep (~8 km) layer of nearly-uniform θ_e – i.e., the stratiform region. The role of moist absolute instability in possibly enhancing this *mesoscale* mixing process, and the apparent link between MAULs and the stratiform region of squall lines, will be the subject of a future paper.

4. THE THREE MAUL REGIMES

From this analysis, three different MAUL regimes (MRs) emerge. The first regime, the laminar MR, forms along and ahead of the surface-based gust front. The properties of the laminar MR are similar along the entire length of the squall line (at least in this simulation). An approximately along-line cross section (Fig. 3a) illustrates these nearly uniform conditions, as well as the generally laminar character of this regime.

The second regime, which we shall call the cellular MR, is characterized by deep cumulonimbus-like cells that develop from the laminar MR (e.g., Fig 3b). Since, by definition, conditions in MAULs are unstable, small perturbations can rapidly develop into deep cells. Vertical motions quickly increase to values greater than 20 m s^{-1} as the cells expand into the cool mid-level environment. Compensating subsidence around the cells "pushes" low θ_e air downwards from mid-levels toward the high θ_e air that does not rise through cells. In some locations, the moist unstable state can be eradicated by the evaporation of all of the cloud water in these descending branches (e.g., at about y=28 km in Fig. 3b). Thus, there are two ways to remove moist absolute instability: 1) overturn the layer through turbulent processes; or 2) return the parcel to subsaturated conditions through moist processes.

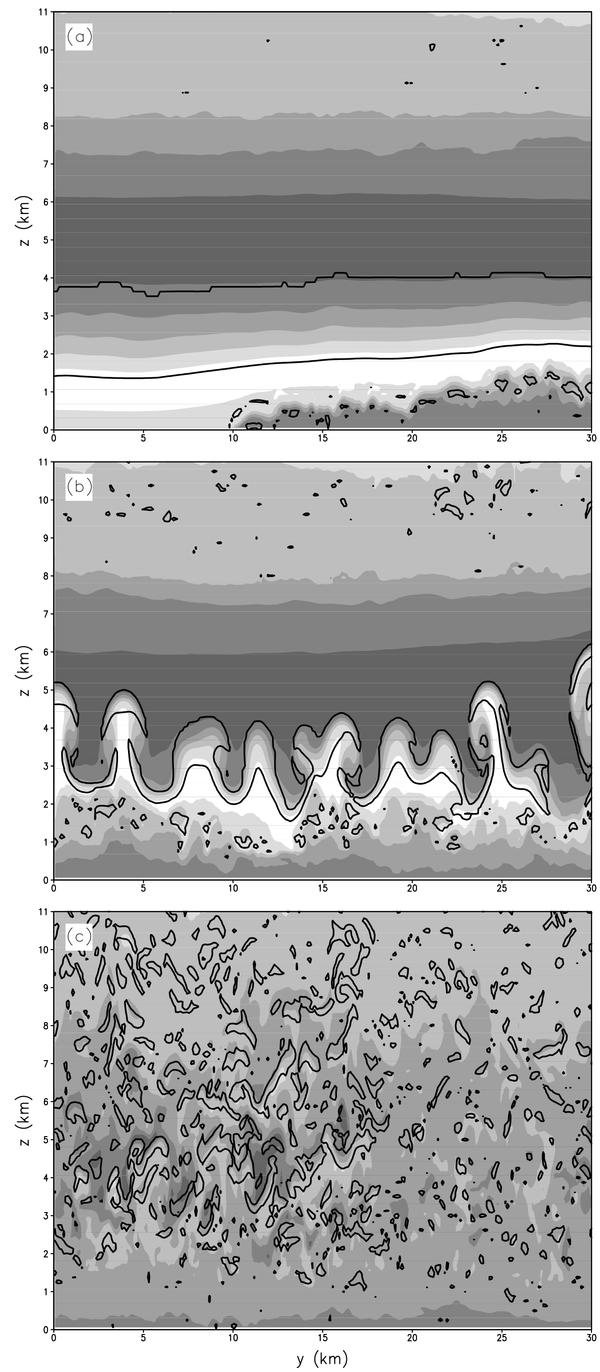

Fig. 3. Along-line cross sections of θ_e (shaded) at 3 hr and: (a) x=215 km; (b) x=207 km; (c) x=195 km. Shading is the same as in Fig. 2. Areas of moist absolute instability are indicated by the thick black contour.

The third regime, the turbulent MR, is dominated by moist turbulent eddies a few km (or smaller) in scale (Fig. 3c). This regime expands rapidly in depth from about 1 km deep just behind (or even underneath) the cellular MR to about 8 km in depth just 10 km farther

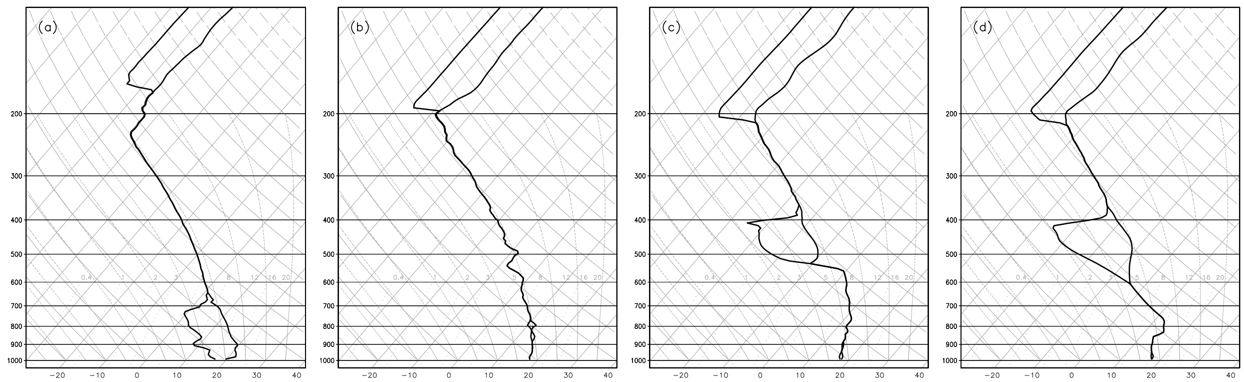

Fig. 4. Skew-T-log p soundings at 3 hr. The locations of the soundings are indicated at the bottom on Fig. 2a, except for (a), which is located at x=176 km.

upstream. The turbulent MR is dominated by the mixing of high θ_e air from low-levels with low θ_e air from mid-levels. The end result of this mixing process, and the end of the three MAUL regimes, is the stratiform region of the squall line.

5. MAGNITUDE OF INSTABILITY

The magnitude of lapse rates within a MAUL provides a measure of the intensity of the unstable state. In the laminar MR, the lapse rates are nearly dry adiabatic (e.g., Fig. 4d). Despite this very steep lapse rate, and the depth (~2 km) of the laminar MR, it is curious that it takes 10-15 km for deep cells to develop. Since the mean flow in the laminar MR is about 15 m s^{-1}, air parcels experience moist absolute instability for 11-17 min before *beginning* to overturn. Conventional theory suggests that overturning would ensue immediately under these conditions. Note, however, as outlined in Bryan and Fritsch (2000), the presence of uniform conditions *everywhere along the line* would tend to inhibit the development of cellular structure. Additionally, the imposed horizontally-homogeneous initial state (and surface conditions) probably contributes to the slow breakdown of the laminar MR.

The most intense MAULs are found along the top of developing cells. In the case of Fig. 4c, the lapse rate within the shallow MAUL atop a growing cumulonimbus is about –35 K km^{-1} – a lapse rate that is very close to the autoconvective lapse rate where density actually increases with height. These intense lapse rates are caused by differential advection and latent heating: above the growing cell, vertical motion rapidly cools air, while inside the cloud latent heat is released and potentially warm (i.e., high θ_e) low-level air is being advected upward. When structures such as that shown in Fig. 4c appear in rawinsonde data, they are typically dismissed as unphysical artifacts of the instrumentation; i.e., it could be argued that the sounding package emerged from the cloud wet, and show an artificial cooling since water evaporated from the temperature sensor. However, this model simulation shows that these structures can be physical.

Lapse rates in the turbulent MR can be of any intensity, though they are usually not much greater than dry adiabatic (e.g., Fig. 4b). The length scales of absolute instability in this region tend to be the size of the moist turbulent eddies, e.g., usually less than 1 km in depth.

The turbulent MR eventually culminates with the creation of a deep layer of ascending, saturated, moist-adiabatic conditions overlaying a descending subsaturated layer – i.e., an “onion” sounding (Fig. 4a). It is interesting to note that the moist neutral profile created by this numerical model does not follow a pseudoadiabat on a skew-T diagram. Rather, the lapse rate is slightly less than pseudoadiabatic (Fig. 4a). This structure is consistent with the model formulation, which retains the heat capacity of liquid water – an effect that is neglected in most numerical models (and in the pseudoadiabatic lapse rate).

Acknowledgements

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