Response of convective storms to low–level cooling

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I. INTRODUCTION

Convective storms are often observed to develop in the afternoon, after which the boundary layer typically cools nocturnally. The present study uses idealized numerical simulations to investigate the mechanisms for the maintenance, propagation, and evolution of nocturnal-like convective systems.

II. METHOD

The 3D simulations used the cloud model described by Bryan and Fritsch (2002), with Δx=Δy=250 m, and a stretched vertical grid with Δz=100–250 m. The simulations used ice microphysics, but excluded surface and radiative processes, as well as Coriolis accelerations. The initial conditions were homogeneous, with convective initiation by a line thermal that included random noise. The simulations reported here used a mean midlatitude MCS sounding with a deepened moist layer (i.e., "DEEP" from Parker and Johnson 2004)

Artificial "nocturnal–like" cooling was added after 3 h of simulated time by defining a reference temperature,

$$T_{ref} = 301\text{ K} - (t - 3\text{h}) \cdot 3\frac{\text{K}}{\text{h}}, \qquad (1)$$

and at each timestep setting the temperature at all points below 1 km AGL to be:

$$T = \min\left(T,\ T_{ref}\right). \qquad (2)$$

This created an isothermal layer whose temperature decreased from the initial surface temperature (301 K) at a rate of 3 K/h.

III. RESULTS

The control simulation, which does not include artificial cooling, produces a long–lived squall line that is surface–based and cold pool–driven (i.e., surface parcels are lifted by the outflow boundary). The simulation passes through a phase of "strengthening", during which the outflow temperature falls, and system size and speed both increase. After roughly 3 hours, the control simulation then remains in a "quasi–steady" phase indefinitely, with nearly constant convective intensity, outflow temperature, and forward speed.

In the experiments with artificial cooling, any subsequent changes in motion speed, cold pool temperature, etc., are therefore attributable to modifications of the environment, not to the maturation of the squall line itself. The simulation that includes low–level cooling evolves from the quasi–steady stage into two additional stages: "stalling", and "elevated".

As the low–level cooling renders a smaller cold pool temperature deficit (relative to the pre–line environment), the system's forward speed decreases ("stalling"; Fig. 1). Also, as the cold pool's strength ("C") decreases in relation to the vertical wind shear ("ΔU"; Fig. 2), the stalling system exhibits a secondary peak in updraft strength (Fig. 1). This is consistent with the theory for strong gust front lifting developed by Rotunno et al. (1988). The system remains surface–based despite increasing CIN and decreasing CAPE (Fig. 1). Lifting during the stalling stage is by a bore in the stable layer, although the bore's speed and structure remain akin to those of a density current.

With additional cooling, surface air is no longer lifted to its LFC because its CAPE=0 J/kg (Figs. 1,3). As the low–level environment becomes increasingly stable, the dynamics become akin to a gravity wave's, and the system's speed increases (Fig. 2). The near–surface flow branch is best described as "underflow"; despite some small vertical excursions in the vicinity of the bore, air in the stable layer mainly passes beneath the system without participating in the convection (Fig. 3).

The present results are somewhat novel in that no larger scale front or low–level jet stream is required in order to sustain the simulated storms in an environment with a stable boundary layer. In the case where a surface–based squall line matures before it experiences low–level cooling, several key concepts emerge.

- The lower troposphere can be cooled by a surprising amount (roughly 10 K) without disturbing the flow of surface–based parcels into a mature, cold pool–driven squall line. Even when CAPE is small and CIN is large, the surface cold pool is sufficient to lift low–level parcels to their LFCs.
- Some cooling of the pre–line environment can actually lead to an increase in the system's intensity, as the environmental shear can better offset the tendency for parcels to be swept rearward over the outflow.
- A mechanism exists for the perpetuation of the squall line as the boundary layer stability increases. The evolution from a density current, to a density current–like bore, and then to a gravity wave–like bore, provides continual lifting as the system becomes elevated. This evolution also entails changes in the squall line's forward speed.

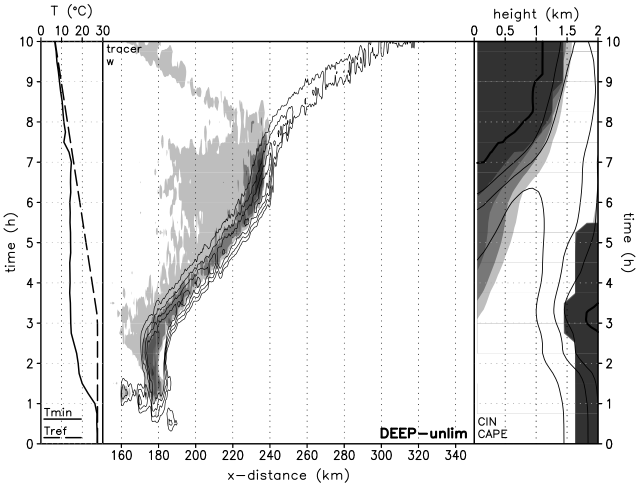

FIG. 1: Artificially cooled simulation over time. Left–hand panel: values vs. time for the reference temperature used in equation 2 (T_{ref}) and the minimal surface temperature on the domain (T_{min}). Center panel: Hovmoller diagram for 5 km AGL, with along–line maxima in boundary layer tracer concentration (shaded from light to dark) and vertical velocity (contoured at every 5 m/s). Right–hand panel: Vertical profile of environmental CIN (shaded from dark to light) and CAPE (contoured every 500 J/kg, bold at 0) vs. time.

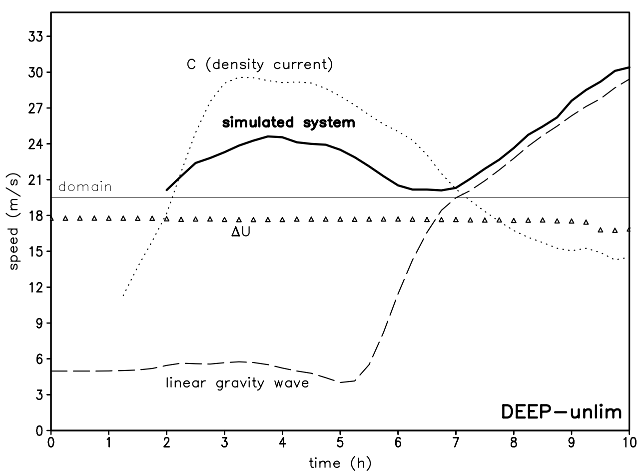

FIG. 2: Speeds relevant to the motion and intensity of the artificially cooled simulation. Actual simulated system's speed is in bold. Theoretical density current speed for the surface outflow, "C", is dotted. Theoretical linear gravity wave speed is dashed. Magnitude of the 0–3 km vector wind difference ("ΔU") is indicated with triangles. Note that the domain moves eastward at 19.2 m/s (thin horizontal line) in Fig. 1.

The present simulations mimic the impacts of nocturnal cooling upon existing squall lines. It is clear that active convective systems can survive after sunset, and can even intensify. Many such nocturnal systems, previously thought to be "elevated", may actually be "surface–based".

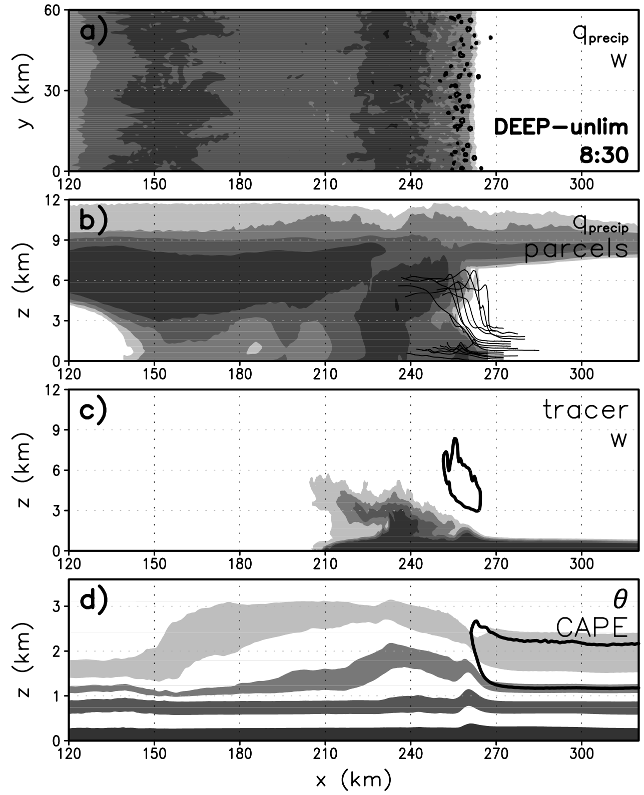

FIG. 3: Selected fields at t=8:30 of the artificially cooled simulation. a) Plan view of averaged precipitation mixing ratio (shaded from light to dark) and 5 km AGL vertical velocity (contoured at 10 m/s). b) Vertical cross section of averaged precipitation mixing ratio (shaded as in a) and parcel trajectories from the simulation. c) Vertical cross section of along–line maxima in tracer concentration (shaded from light to dark) and vertical velocity (contoured at 10 m/s). d) Vertical cross section of averaged potential temperature (shaded from dark to light) and CAPE (contoured at 500 J/kg).

IV. ACKNOWLEDGMENTS

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V. REFERENCES

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