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Discrete Propagation in Numerically Simulated Nocturnal Squall Lines

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1. Introduction

Fovell's (2002; "F2002") simulations showed that a squall line exerts a substantial influence on its upstream environment, the region into which the storm is propagating. The influence is spread by gravity waves (GWs), excited by temperature perturbations large and small occurring in and around the storm's main convecting region. The first and least subtle of these carries the deep tropospheric subsidence provoked by the onset of latent heat release. This subsidence propagates quickly, warming the bulk of the troposphere and enhancing the lower-tropospheric flow towards the storm. The environmental alterations can persist until the convection ceases.

This initial signal, however, is routinely found to be followed by another, slower moving GW propagating in the original wave's wake. This wave, characterized by lower-tropospheric ascent, is provoked by localized diabatic and adiabatic cooling on the upstream side of the main storm updraft. This subsequent adjustment establishes a "cool and moist tongue" of air extending ahead of the storm for some kilometers as this GW progresses upstream. The air in this tongue has been made more favorable for convection – and thus may potentially support the initiation of new convection upstream of the established storm.

In F2002's simulations, however, new upstream convection did not form for want of a "spark". Herein, we examine a customized ARPS run in which upstream convection is generated. Compared to F2002, the present simulation has deeper (7.5 km) shear as well as realistic surface fluxes and radiative processes. The simulation commences at 6PM local time and is integrated past sunrise.

The spark comes in the form of transient, high frequency GWs that are continually generated in re-

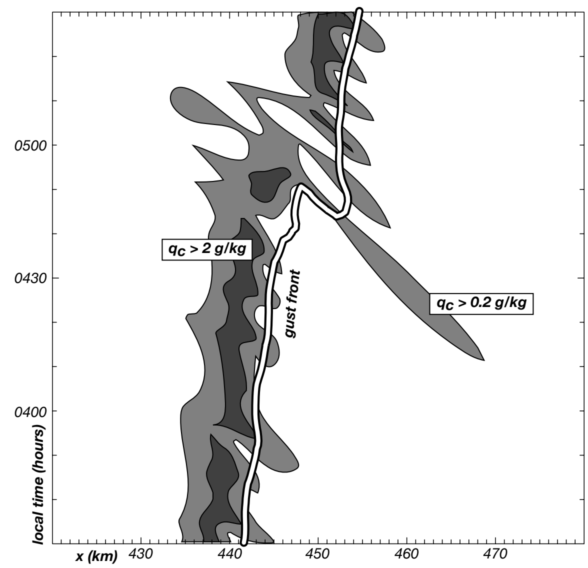

Fig. 1: Hovmoller diagram of cloud water (q_c) at the 3 km level between 0330 and 0530 local time. Surface gust front location superposed.

sponse to temporally varying heating in the main convecting region. These waves are trapped by the upper tropospheric forward anvil outflow. Shallow clouds sporadically form in the tongue, in air forced to ascend by the GW updrafts, as the boundary layer cools overnight. A fraction of those clouds become positively buoyant and are subsequently carried towards the main storm, reinvigorating the established convection as they become incorporated. These clouds may play a key role in keeping the storm vigorous even as the environmental CAPE is eroded.

A still smaller number of clouds are able to develop into deep convection prior to incorporation. These new developments weaken the parent storms located downwind. This accomplishes a fundamentally discrete propagation, increasing the storm's effective propagation speed. Below, the simulation is examined and preliminary conclusions are offered.

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2. Initiation of upstream convection

Figure 1 shows a Hovmoller diagram of cloud water (q_c) at the 3 km level spanning a period in which an upstream convective development occurs. The reference frame is translating eastward at 14.5 m s^{-1}, slightly slower than the storm's average nocturnal motion. The cloud first seen above $x = 469$ at 0410 local time started as a shallow feature in the tongue, $\approx$ 25 km ahead of the surface gust front position. The cloud's development obviously brings about a weakening of the established storm to its west.

This particular cloud began precipitating prior to merging with the parent convection. This caused a sudden eastward jump in the gust front position. On a radar, the upstream development would take the appearance of a new line, oriented parallel to the established convection, but with an echo-free gap initially separating the two. The gap would progressively narrow owing to the two features' disparate motions. The established convection moves eastward at the speed of its cold pool, that typically being faster than the lower-to-middle tropospheric winds carrying the upstream clouds.

Figure 2 presents vertical velocity and cloud water fields for three times preceding a period of upstream development. A series of relatively coherent $\approx$ 20 km wavelength internal gravity waves are seen propagating upstream of the storm with a storm-relative phase speed of $c \approx 20$ m s^{-1}. These waves were generated in response to the temporally varying heating within the multicellular squall line's convective region. Vertical motions associated with the waves are not especially strong; the largest values are $\approx$ 0.5 m s^{-1} and centered at about 7 km or so.

However, the waves are occasionally able to bring air to saturation, generating shallow clouds appearing first on a GW phase line between downdraft and updraft (e.g., above $x = 485$ km in Fig. 2a). The wave-relative airflow is westward and thus nonbuoyant parcels reach their maximum ascent after having passed through the GW updraft. Many of these little clouds dissipate rapidly; the figure shows two that survive to move towards the parent storm. These clouds had become positively buoyant.

3. Mechanism of upstream initiation

The upstream GWs appear to be partially trapped by, and ducted beneath, the forward anvil outflow, reminiscent of the wave trapping in the storm's trailing region (Yang and Houze 1995). The anvil is a saturated layer of reduced stability, capping the more stable environment beneath. Figure 3 presents vertical profiles of storm-relative wind (U), squared Brunt-Vaisalla frequency (N^2 or N_m^2) and the Scorer parameter (l^2) at the location shown in Fig. 2c. The saturated Brunt-Vaisalla frequency N_m (Durran and Klemp 1982) is used in the anvil cloud.

The Richardson number (not shown) is in excess of $\frac{1}{4}$ everywhere, and there is no critical level for a c = 20 m s^{-1} GW, though Lindzen and Tung (1976) ducting may still be possible since $U - c$ is small in the anvil layer. Additionally, the Scorer parameter exhibits a sharp decrease with height, a situation conducive to trapping GWs (e.g., Scorer 1949; Crook 1988) . The Scorer parameter is defined in part as

$$l^2 = \frac{N_*^2}{(U-c)^2} - \frac{U_{zz}}{(U-c)},$$

where N_* represents N or N_m and U_{zz} reveals the wind profile's curvature.

The first term is plotted in the figure, and it evinces a distinct minimum at $z = 8.7$ km, in the lower portion of the forward anvil. Though both N_* and $U - c$ are decreasing with height, the former is shrinking faster. Waves with horizontal wavelengths $L_x < \frac{2\pi}{l}$ should be trapped and this term alone would cause wavelengths shorter than about 23 km to be trapped beneath this level. In addition, the curvature in this region is strongly negative; inclusion of this term makes $l^2 < 0$ at 8.1 km, effectively trapping all waves beneath that level.

4. Episodic reestablishment of the cool/moist tongue

Each new upstream development exerts a significant impact on its surroundings, most immediately exciting deep tropospheric subsidence that propagates away from the new convection in both directions. The subsidence that approaches the pre-existing convection is likely responsible for weakening the parent storm. The downward motion spreading farther ahead acts to sweep away the cool and moist tongue, rendering the new convection's own upstream environment less convectively favorable. It takes time, but the tongue eventually starts reforming.

The recurrence interval between upstream developments is roughly 2 hours. Figure 4's perturbation vapor mixing ratio plots capture the first hour following a new development. The eastward propagating subsidence's impact on the tongue is clearly seen in panel (b). By Fig. 4c, the upstream convec-

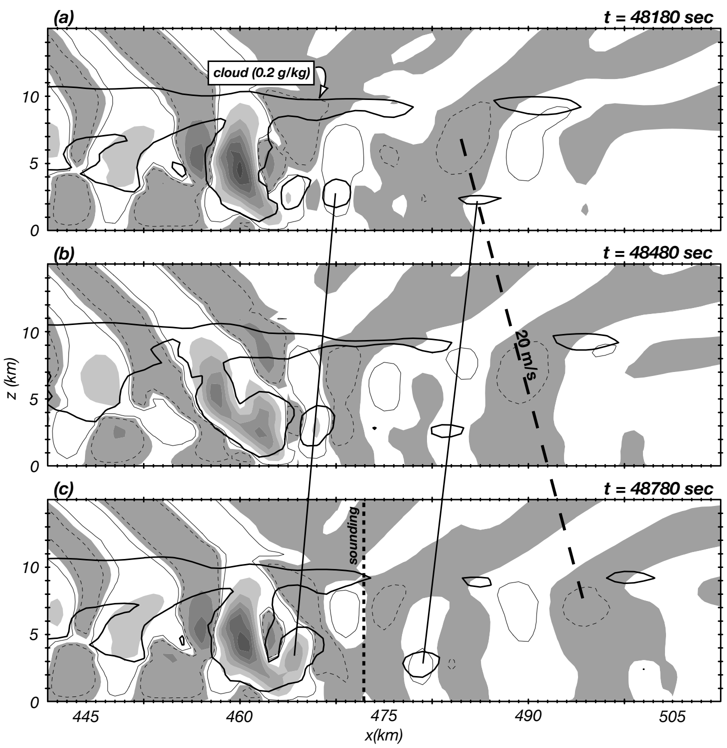

Fig. 2: Vertical velocity (w; shaded) with superposed ± 0.5 m s^{-1} w contours and cloud outline.

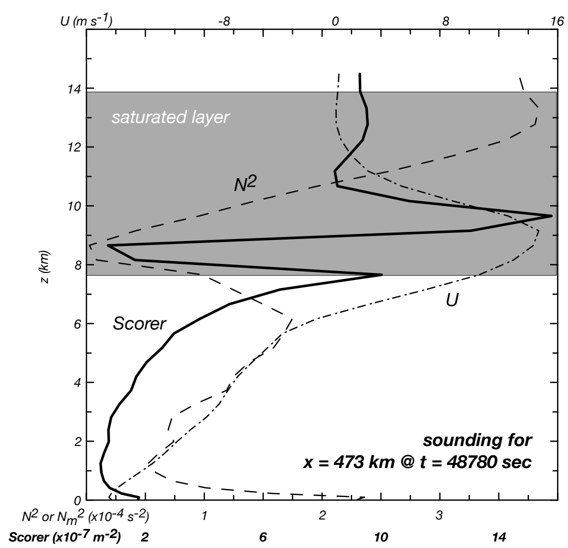

Fig. 3: Upstream sounding (see Fig. 2c) showing storm-relative horizontal velocity (U), square of Brunt-Vaisalla frequency (N^2 or N_m^2), and Scorer parameter's leading term, based on 20 m s^{-1} phase speed.

tion has merged with the parent storm and tongue reestablishment commences shortly thereadter (Fig. 4d). The next development will occur about one hour after the time depicted.

5. Discussion

This model storm exhibited episodic generation of new convection upstream of the established line, the spark for which came from trapped high-frequency GWs provoked by transient heating in the established storm's convecting region. The following aspects facilitate significant upstream development:

1. *A deep layer of moderate shear*, making storm-relative upper tropospheric westerlies further strengthened and molded into a jet profile by the squall line's circulation. The ground-relative winds above 7.5 km were about 7.5 m s^{-1} faster than the storm speed.
2. *A warm forward anvil of reduced stability*, established *in situ* and/or exported from the convecting region, the latter hastened by storm-relative westerlies aloft. These two items combined to decrease $U - c$ and l^2 in the anvil, assisting in the partial trapping of GWs.

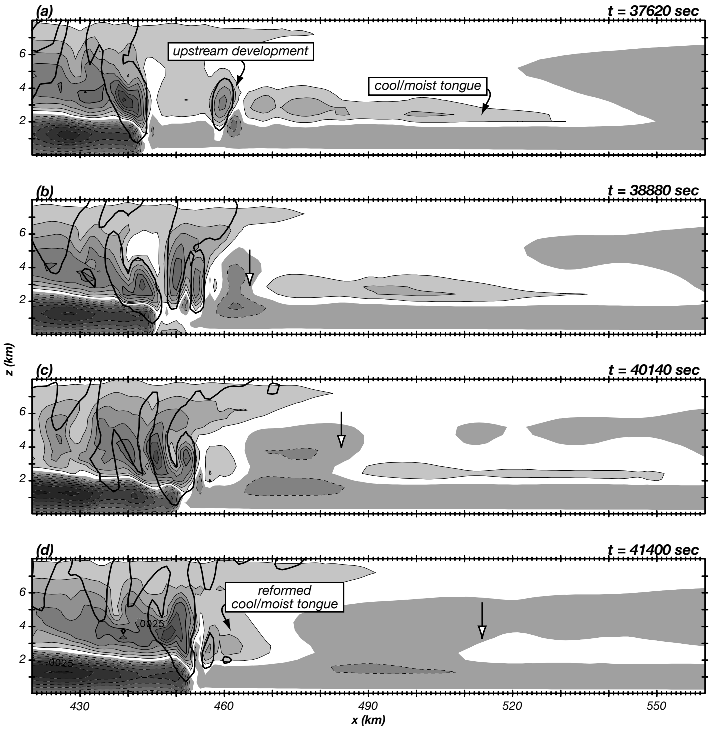

Fig. 4: Perturbation vapor mixing ratio (shaded and contoured) for four times following an upstream development with cloud outline and maximum deep tropospheric subsidence locations marked by arrows.

3. *Small diabatic and adiabatic cooling on the convecting region's forward side*, establishing of the convectively favorable cool and moist tongue.

4. *Radiative processes.* Heating (cooling) at the anvil cloud's base (top) reduced its stability, while clear sky IR cooling raised the relative humidity of the tongue air. However, nocturnal surface cooling leading to low-level stabilization appears to have been more important.

Items # 1 and 2 are important to the trapping and ducting of the high-frequency GWs in these moderately sheared cases. Simulations without deepened shear are less likely to have transient GW activity upstream, presumably because they could not be trapped. The presence of GWs is not a sufficient condition, however. A case excluding atmospheric and surface radiative processes generated plenty of trapped waves and a few shallow clouds upstream, but no deep convection. The cool, moist tongue was quite pronounced yet a spark was lacking.

Though radiative processes appear crucial, cloud-related processes are insufficient in isolation and the absence of clear sky IR does not preclude upstream redevelopment. This suggests that nocturnal surface cooling is the crucial element. Perhaps placing an especially stable layer beneath the trapped GWs influences their strength. Crook (1988) showed that a cold pool propagating through a stable layer could generate undular bores out ahead of the pool. While such waves are not seen in the present simulation, they could provide another mechanism for convective development upstream.

6. References

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Acknowledgments. This work was supported by NSF grant ATM-0139284.