10.6 DO SUPERCELL THUNDERSTORMS PLAY A ROLE IN THE EQUILIBRATION OF THE LARGE-SCALE ATMOSPHERE?

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1. INTRODUCTION

Supercell thunderstorm formation has traditionally been treated as the result of a one-way, non-scale interacting process. Specifically, supercells are regarded as ***products*** of a larger-scale environment, and are presumed to form only when certain combinations of environmental conditions exist. Additional or refined environmental conditions are required for supercell by-products such as hail, strong winds, and tornadoes.

We propose an alternative treatment of this problem, based on ***why*** the atmosphere requires supercell storms to form under such environmental conditions. In other words, what ***role*** do these storms have in large-scale balances, and how does this feed back to the storm scale?

Our objective herein is to motivate the ultimate goal of this study, which is to determine connections (or lack thereof) between supercell storms and the state of the large-scale atmosphere. A first step toward this goal is to quantify the effect of supercell (and tornadic) storms on their environment. Strategies for doing so are given in section 3.

2. BACKGROUND

In an unsaturated layer of the atmosphere, convective motions commence once large-scale processes such as surface heat fluxes, radiative cooling, and differential temperature advection have increased the temperature lapse rate in this layer past the dry adiabatic rate (see Bretherton 1993). The vertical circulations associated with the convection mix high (low) potential temperature air upward (downward) and thereby reduce the lapse rate of the layer of air back toward the dry adiabatic rate. As summarized by Bretherton (1993), this is a one example of *adjustment*, in which the "internal state of a system changes so as to stay in quasi-equilibrium with time-varying forcings." Convective and other adjustment processes are usually assumed to occur over much faster times (τ_a) than the time scale (τ_f) of the external forcing[1]. Cumulus parameterization schemes are based on these ideas of convective adjustment toward some equilibrium state.

Convection involving a cloud – cumulus convection – is more complicated than the example above because it also involves condensation and the exchange of air between the cloud and its environment through entrainment, detrainment, and cloud decay (Bretherton

[1] This is otherwise known as "recovery time" in the lexicon of the severe storms community.

1993). The effect of mixing of cloud air with the environment is a diabatic process that renders real cumulus convection irreversible. Once precipitation is formed (the moist cumulus convection becomes "deep"), and begins to fall out of the cloud the thermodynamics of deep convection involve an additional diabatic process. The nature of the deep convective adjustment also depends on the evaporation of precipitation, especially in downdrafts that reach the subcloud layer, and on the presence (and strength) of an environmental mean flow and vertical shear. A final complication is that for some modes of cumulus convection, the assumption that $\tau_a << \tau_f$ may not be valid.

Nonetheless, rawinsonde observations taken immediately after major deep moist convection (DMC) events in the tropics show that such convection adjusts the environmental stratification toward a moist neutral lapse rate and consequently reduces the convective available potential energy (CAPE) (e.g., Frank and Molinari 1993). Through this process, tropical DMC vertically transports heat and moisture, and helps maintain the quasi-balance of the tropical atmosphere under the influence of surface heat fluxes and radiation. Large-scale circulations such as the Hadley Cell can be said to be in "statistical equilibrium" with DMC, whose downdrafts lower subcloud entropy and effectively static stability, which then feeds back to the larger scale circulations (Emanuel et al. 1994).

In continental midlatitude regions, *extratropical cyclones* play an important role in meridional (and also vertical) transport of heat and moisture. Energy budget calculations suggest that the poleward heat transport by six extratropical cyclones around the globe can roughly compensate for the meridional imbalance in radiative heating (Palmén and Newton 1969). However, we are reminded by the persistent existence of strong meridional temperature gradients that extratropical cyclones fail to homogenize temperature at the surface (e.g., Swanson and Pierrehumbert 1997). A state of barotropy is never truly attained, though the generation of synoptic eddies is presumed to balance their dissipation by linear and nonlinear processes (Sun and Lindzen 1994).

A long history of theories based on the Charney-Stern (Charney and Stern, 1969) criterion for equilibration of synoptic eddies, has led to the realization that homogenization of potential vorticity (PV) along isentropic surfaces (Stone, 1978; Held, 1982), especially those located at around 700 mb in midlatitudes, may provide the basis for a baroclinic neutralization and stabilization theory (reviewed in Kirk-Davidoff and Lindzen 2000). Theories of this type allow for the prediction of equilibrium surface temperature gradients in the presence of PV homogenization of varying degrees by assuming midlatitude dynamics that are largely governed by quasi-adiabatic (along isentropes) and dry mixing of air masses by synoptic scale eddies (e.g. Solomon and Stone 2001). Nevertheless, these studies have thrown into sharp relief the importance of cross-isentropic transport by convection (Kirk-Davidoff and Lindzen 2000) and the related influence of moisture transports on the static stability (Juckes 2000)—in fact, the perturbations to the PV of a region in these models are as much a function of strongly diabatic convective fluxes as they are of quasi-adiabatic midlatitude eddy fluxes. Thus interactions between these different scales act in concert to determine an overall balanced state.

So where does this leave midlatitude DMC? First recall that, unlike in the tropics, convective instability in the continental midlatitudes is *not* necessarily released immediately upon creation by larger-scale processes. Instead, it can be stored (and increased) for periods of up to several days, implying effectively equivalent time scales for the creation and ultimate release of the instability, or $\tau_a \sim \tau_f$ (Doswell and Bosart 2001). Moreover, upon release of such stored instability, the DMC can be relatively more intense than typical oceanic tropical convection, and capable of producing hail, damaging surface winds, and tornadoes. We conjecture, that complex, and relatively unexplored interplays between vertical transports of heat, water, and momentum by DMC and those associated with synoptic eddies are important for understanding weather and climate of North America.

Midlatitude convective storms often, though certainly not always, occur in the vicinity of baroclinic zones. They can transport large amounts of mass vertically up through the depth of the troposphere whereupon it can be transported horizontally by strong upper-tropospheric winds; intense convective downdrafts similarly can transport large amounts of mass vertically downward. Vertical transport of convective instability in DMC storms is roughly an order of magnitude faster than the resupply associated with synoptic scale processes (Fritsch et al. 1976). In this light, Doswell and Bosart (2001) have suggested that midlatitude DMC exists "whenever the redistribution of heat by synoptic-scale processes is not sufficient to mitigate the imbalances resulting from differential heating at the surface."

Now recall that the longevity, intensity, and relative infrequency of supercell thunderstorms distinguish them from "ordinary" convective storms; these characteristics are related to the unique supercell dynamics, which result in larger, stronger, and longer-lived drafts, and ultimately can be expected to yield a relatively higher mass transport (e.g., Schlesinger 1994). Hence, it is plausible to extend Doswell and Bosart's (2001) idea and argue that supercell storms occur when *extraordinary* synoptic-scale imbalances exist and need be mitigated. The challenge then is to determine the magnitude and character of the effect of a single (or even multiple) supercell storm on the larger scale. We view this as analogous to (though distinct from) the known feedbacks on the synoptic scale by mesoscale convective systems (e.g., Stensrud 1996; Bartels and Maddox 1991).

It is clear that midlatitude DMC acts to reduce convective instability locally. Limited observations presented by Fritsch et al. (1976) demonstrate the near complete removal of CAPE by a squall line within about one hour of the arrival of the squall line at the sounding site (Fig. 1). Schlesinger (1990) and Schlesinger (1994) used an idealized supercell simulation to investigate the feedback of such DMC to the environment in which it was embedded. Budget calculations showed that for an area averaged about the supercell, the supercell caused: an upper-tropospheric warming, a lower-tropospheric cooling, and an overall moistening throughout. A similar but comparatively weaker effect on the temperature and moisture budgets from simulated tropical DMC was also shown (Schlesinger 1994). This certainly confirms that, like all DMC, supercells result in stabilizing their environments in terms of thermodynamic convective instability.

It is well established that supercell formation is also favored in an environment characterized by large vertical shear of the horizontal winds. The simulated supercell of Schlesinger (1990) reduced appreciably the mean south-north tropospheric shear. Such "downgradient" momentum transport has also been shown in simulated storms by Lilly and Jewett (1990), and in observations of tropical squall lines (see LeMone and Moncrief 1993 and references therein), although "counter-gradient" transport has also been observed. Returning to Doswell and Bosart's proposed context for understanding the occurrence of DMC, it is interesting to consider that the large vertical wind shear required by and then reduced by supercell storms also is associated with the criterion for baroclinic instability. On the synoptic scale, the thermal wind relationship implies an equivalence between vertical wind shear and baroclinity, as measured by horizontal thermal contrast. On the scale of a thunderstorm or even its mesoscale environment, such a balance is not plausible. It is conceivable that there is some equilibrium state involving both ordinary convective instability and vertical wind shear that cannot be achieved through "ordinary" (nonsupercellular) DMC.

On a final note, we recall that persistent convection from squall lines and other mesoscale convective systems can alter the synoptic-scale weather pattern (e.g., Stensrud 1996). Short-lived, nonsupercellular convection is unlikely to have a substantial effect on the large-scale atmosphere. Supercells are more persistent than ordinary DMC, and also tend to have stronger and larger vertical drafts (both up and down) than ordinary DMC. Hence, even an isolated supercell might have measurable consequences on the environment far beyond that of ordinary DMC storms. Reduction of environmental vertical wind shear (and removal of environmental CAPE) owing to the effects of isolated supercell storms would need to be shown to be over substantial spatial regions in order to show possible feedbacks of supercells to their environment.

3. STRATEGIES

A numerical modeling approach is well suited to the task of examining interactions between the convective scale and larger scales. Our initial plan is to pursue simulations of past and recent U.S. tornado outbreaks, which represent extreme examples of supercell activity. Ultimately, the modeled cumulus convection will need to be explicitly represented over the entire domain: parameterized convection necessarily involves making assumptions about the effect of DMC on the environment that are likely to be detrimental to the goal of understanding that interaction. We also plan to pursue idealized modeling such as of radiative-convective equilibrium states (e.g., Robe and Emanuel 1996), although applied to continental midlatitude atmospheres. Analyzing the results in terms of entropy production and dissipation may be particularly fruitful here.

Numerical modeling studies might not prove to be completely conclusive, since it's not obvious how to force a nonsupercell storm in an environment favorable for supercells, though it's possible that a properly-constructed diagnosis of the simulations could isolate the effects of the mesocyclonic circulations. Therefore, it would be valuable to obtain rawinsonde (or dropsonde) observations ahead of and in the wake of supercell storms. Details of the environmental changes could be compared to similar soundings obtained ahead of and being ordinary (nonsupercell) storms.

We anticipate that our proposed alternative treatment of supercells, based on the possible role of these storms in the equilibration of the large-scale atmosphere, will additionally offer a unique perspective of supercell (and perhaps tornado) genesis, as well as provide a first step toward addressing questions on severe convective storm frequency and intensity in global climate change scenarios.

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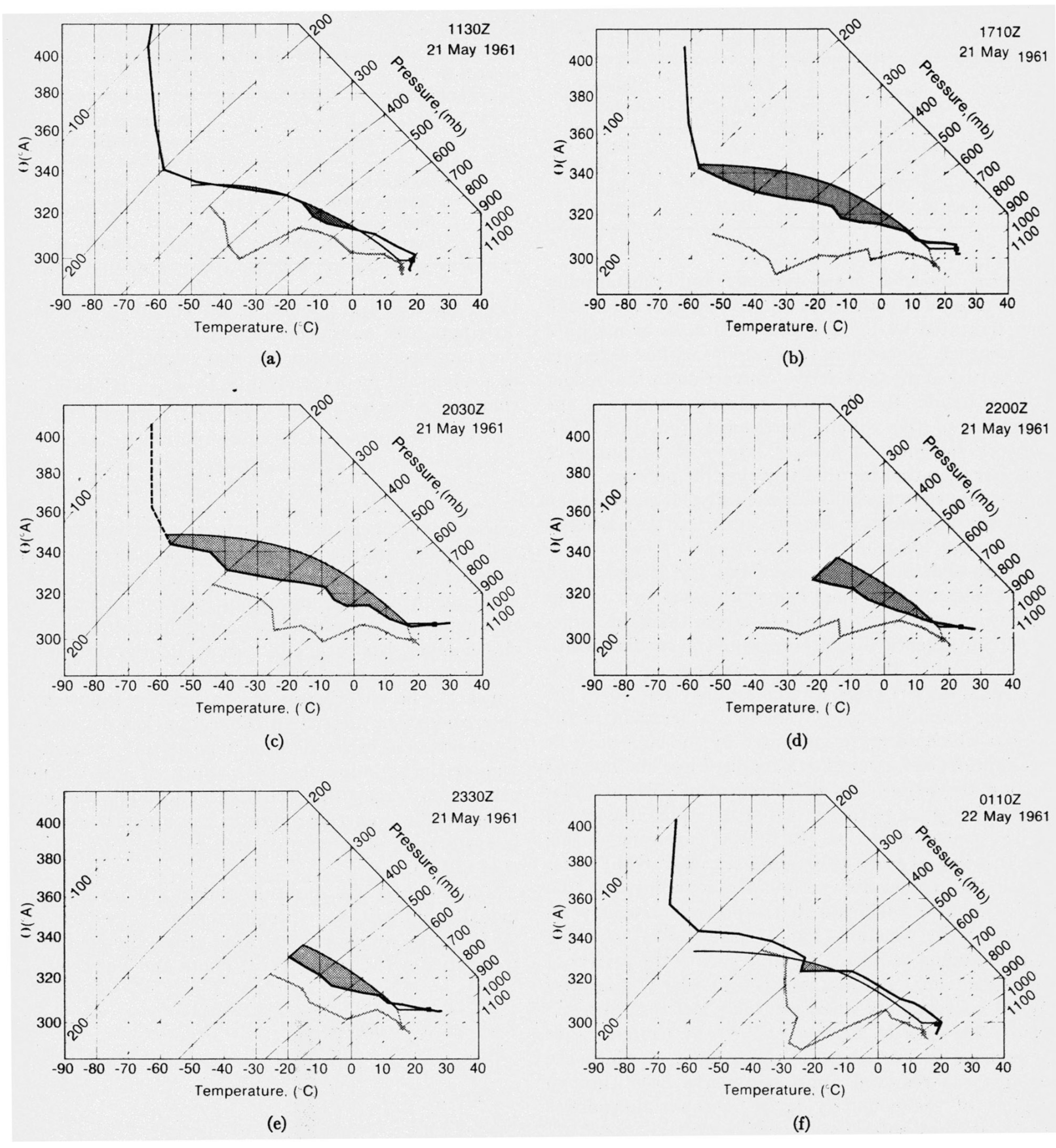

FIG. 1. Sequence of soundings at Oklahoma City, OK, showing the development of potential buoyant energy (shaded) and its subsequent destruction by the passage of a squall line. From Fritsch et al. (1976).