Papers in the Earth and Atmospheric Sciences   Earth and Atmospheric Sciences, Department of

10-2011

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ABSTRACT

The sensitivity of storm longevity to the pattern of deep convection initiation (e.g., multiple, quasi-linearly arranged initial deep convective cells versus an isolated deep convective cell) is examined using idealized cloud-resolving simulations conducted with a low-shear initial environment. When multiple deep convective cells are initialized in close proximity to one another using either a line of thermals or a shallow airmass boundary, long-lived storms are produced. However, when isolated deep convection is initiated, the resultant storm steadily decays following initiation. These results illustrate that a quasi-linear mechanism, such as a preexisting airmass boundary, that initiates multiple deep convective cells in close proximity can lead to longer-lived storms than a mechanism that initiates isolated deep convection.

The essential difference between the experiments conducted is that an isolated initial storm produces a shallower cold pool than when a quasi-linear initiation is used. It is argued that the deep cold pools promote deep forced ascent, systematic convective cell redevelopment, and thus long-lived storms, even in environments with small values of vertical shear. The difference in cold pool depth between the simulations is attributed to differences in the horizontal flux of cold air to the gust front. With a single initial storm, the few convective cells that subsequently form provide only a limited source of cold air, leading to a cold pool that is shallow and incapable of fostering continued updraft redevelopment.

1. Introduction

Environments characterized by weak vertical wind shear have generally been given limited attention in the literature, in large part because of the well-documented direct relationship between severe weather occurrence and vertical shear. However, such weak shear environments have been observed to support severe weather (Benjamin et al. 2004; Davies 2006; Houston and Wilhelmson 2007a, 2007b; Schlatter et al. 2008) so explorations into the essential mechanisms that regulate strength, propagation, and longevity of storms in such environments is warranted. In this article we address storm[1] longevity. Specifically, we seek an explanation for the previously documented sensitivity of storm longevity to the pattern of deep convection initiation in low-shear environments.

Robust sensitivity studies directed at understanding fundamental storm dynamics have almost exclusively been the domain of model-based research. As such, most of the prior work documenting the sensitivity of storm longevity to the pattern of initiation has been undertaken using numerical models. For example, Lilly (1990) and Brooks (1992) documented the sensitivity of storm longevity to the characteristics of the thermal bubble used to

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[1] As in the work of Houston and Wilhelmson (2011), the term "storm" is defined as a continuous volume of precipitation. Based on this definition, the storm is the aggregate contribution from multiple convective cells and thus has a spatial scale that exceeds that of the individual cells.

initialize their cloud-resolving simulations. Both Lilly and Brooks used strongly sheared environments for their experiments. However, Weisman and Klemp (1982) used an environment without vertical wind shear and found that an isolated storm lasted no longer than 3000 s. Employing the same environment and the same numerical model used by Weisman and Klemp (1982), Weisman and Rotunno (2004, hereafter WR04) found that when storms were initiated as a *line*, the storms persisted for more than 21 600 s. Parker (2007) found the same sensitivity of longevity to the pattern of initiation (i.e., isolated versus quasi-linear). Parker concluded that unlike an isolated storm, multiple initial storms could interact to produce a stronger cold pool that enabled upscale organization and therefore longevity. Parker's experiments were conducted in an environment with moderate-to-strong shear. Nevertheless, his results, along with the results of Weisman and Klemp and Weisman and Rotunno, serve to further focus this work. Specifically, we ask the following: In a low-shear environment, what is it about a quasi-linear pattern of initial deep convection that is more favorable for long-lived storms than an isolated pattern of initial deep convection?[2]

The work presented here is one component of a larger effort on the part of the authors to examine storm maintenance, propagation, longevity, and rotation in an environment modeled off of the 27 May 1997 central Texas event. This event was characterized by back-building, tornadic supercells that developed and traveled along several preexisting airmass boundaries in place within an environment that should have otherwise been unfavorable for supercells and tornadoes (Houston and Wilhelmson 2007a, hereafter HW07a). Houston and Wilhelmson (2011) used the results from a set of five experiments to examine the propagation of storms simulated in an environment similar to that of the 27 May 1997 event. The results from two of these five experiments are used here.

A total of three experiments, conducted using a cloud-resolving model initialized with a sounding from the low-shear environment of the 27 May 1997 event, are used for this work. Each experiment differs according to the pattern of initial convection. An overview of the experiment design employed in this work is provided in section 2 and results are presented in section 3. A

discussion and summary of the results follow in sections 4 and 5.

2. Experiment design

The Illinois Collaborative Model for Multiscale Atmospheric Simulations (ICOMMAS) is used for this work. ICOMMAS is an idealized cloud-resolving model that has been used previously to examine cloud-scale processes (e.g., Houston and Niyogi 2007; Houston and Wilhelmson 2011). A complete description of ICOMMAS is provided by Houston (2004) with key elements cataloged by Houston and Wilhelmson (2011, hereafter HW11). The following list summarizes a few of the key characteristics of the model configuration used for the simulations discussed here:

- microphysics—Straka three-class ice, two-class liquid, single-moment parameterization described by Gilmore et al. (2004);
- subgrid-scale turbulence—1.5-order closure parameterization of Klemp and Wilhelmson (1978);
- surface fluxes of heat and moisture, topography, and surface drag—excluded;
- computational domain—100 km × 100 km × 20 km in size with a horizontal grid point spacing of 500 m and a vertical grid point spacing of 50 m in the lowest 1 km geometrically stretched to 450 m at the top of the domain;
- domain boundary conditions—lateral boundaries are open and vertical boundaries are rigid and free slip; and
- time step and integration duration—time step for low-(high-) frequency modes is 1.5 s (0.375 s) and the integration time is nominally 7200 s (10 800 s for the BndCold experiment introduced below).

The results from three experiments are presented in this work. The vertical profiles of temperature, moisture, and wind used to initialize these simulations are illustrated in Fig. 1. This sounding represents the high-CAPE, low-shear environment east of the dryline in the 27 May 1997 central Texas tornadic event and is based on the ''modified Calvert sounding'' synthesized by HW07a using a sounding released near Calvert, Texas, as part of the Texas A&M Convection and Lightning Experiment (TEXACAL; Biggerstaff et al. 1997). The reader is referred to HW11 for a complete description of the development of the sounding used for these experiments.

Each of the three experiments differs in the method used to initiate deep convection. In the first experiment (SingleThrm), a single sustained thermal is used. The sustained thermal is imposed through a modest maximum

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[2] The results of Lilly, Brooks, Weisman and Klemp, Weisman and Rotunno, and Parker, along with those presented here, could also be used as guidance regarding initialization methods in idealized cloud-resolving models. However, the goal of this work is not to offer further evidence for the sensitivity of storm longevity to the techniques used to initiate storms but to address why storm longevity is sensitive to the pattern of initiation.
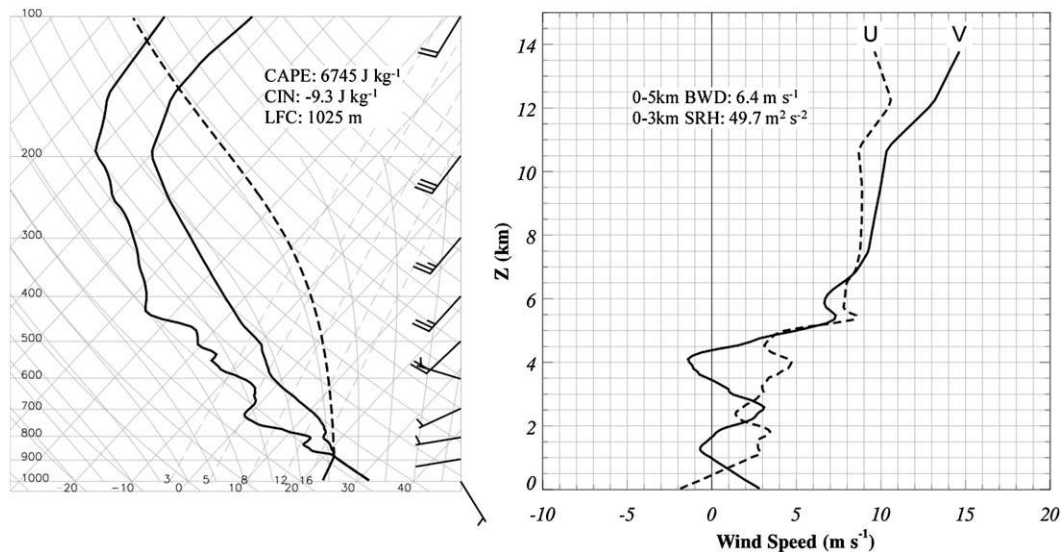
FIG. 1. Thermodynamic and wind profiles of the initial environment used for the simulations presented here. The thick dashed curve in the left panel represents the temperature of a parcel using a 1000-m-deep mixed layer. The thick dashed (continuous) curve in the right panel represents the u (v) wind.

thermal perturbation of 1 K, which is held fixed for a finite duration (1200 s) within the lower half of an ellipsoid region that is centered at a height of 500 m and has a lateral diameter of 10 km and a vertical diameter of 1 km. The second experiment (MultipleThrm) uses six sustained thermals, each spaced ~13 km apart along a roughly southwest-to-northeast line (Fig. 2a). This approach is similar to that of Skamarock et al. (1994), Weisman and Davis (1998), Bluestein and Weisman (2000), and Parker (2007), except that the spacing between perturbations is considerably smaller in this work. In the final experiment (BndCold), a preexisting airmass boundary, resembling a shallow cold front, is used. The cold front is imposed as an arc extending from the northern domain boundary to the southwest corner with a −1-K potential temperature perturbation in a 1000-m block northwest of the front (Figs. 2b and 3a). The wind field to the northwest of the front is prescribed through a linear interpolation between a surface wind of (3.21, −3.83) m s^{-1} and the reference state sounding at 1000 m. The prescription of this boundary follows the observations of the cold front of the 27 May 1997 event documented by HW07a and is the same initialization procedure used by HW11 to initialize their shallow cold front. The early evolution of the cold front and resulting deep convection is illustrated in Fig. 3. Note that by 3000 s (Fig. 3d) the cold front cannot be distinguished from the thunderstorm-generated gust front. Snapshots of the precipitation fields for the SingleThrm, MultipleThrm, and BndCold experiments appear in Fig. 4.

3. Results

In the SingleThrm experiment the simulated storm decays steadily following initiation (Fig. 5). However, the storms simulated in both the MultipleThrm and BndCold experiments persist throughout the 2- and 3-h (respectively) simulation lengths (see Figs. 4 and 5). These results are consistent with previous sensitivity studies discussed in section 1 and therefore further illustrate the sensitivity of storm longevity to the pattern of convection initiation. By extension, these results also illustrate that a quasi-linear mechanism, such as a preexisting airmass boundary, that initiates multiple deep convective cells in close proximity can lead to longer-lived storms than a mechanism that initiates isolated deep convection. While it is most certainly true that 1) not all airmass boundaries that initiate deep convection support upscale growth and (presumably) storm longevity (Dial et al. 2010) and 2) preexisting airmass boundaries can also initiate isolated deep convection, the results from these experiments indicate that, all else being equal, isolated initiation is less favorable for storm longevity in this weak-shear environment than quasi-linear initiation.

At a minimum, the initiation of deep convection requires parcel ascent above the level of free convection (LFC) and minimal cloud dilution thereafter, such that the realization of buoyancy through parcel ascent exceeds the reduction in buoyancy due to dilution (Houston and Niyogi 2007). The conceptual model of Rotunno et al. (1988, hereafter RKW) and analytical density current solutions in sheared flow (Xu 1992) predict that parcel
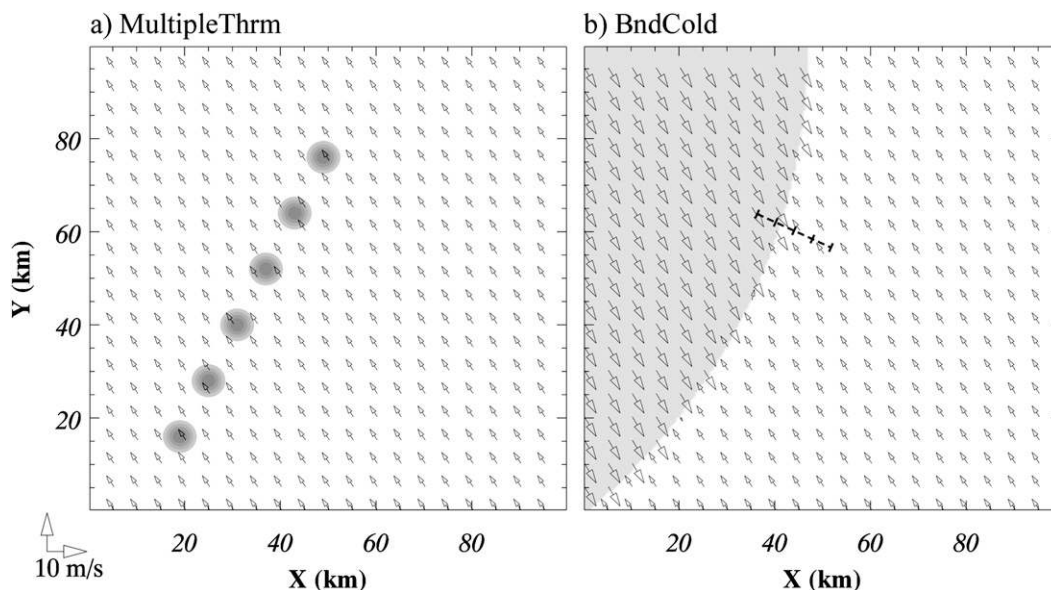
FIG. 2. (a) Distribution of initial thermals in the MultipleThrm experiment. Perturbation potential temperature at a height of 500 m is shaded at an interval of 0.2 K (darker shading indicates more positive values) and the wind field at the surface is indicated by arrows. (b) Initial position of the cold front in the BndCold experiment. Surface equivalent potential temperature is shaded at an interval of 4 K (darker shading indicates lower values) and surface winds are indicated by arrows. Dashed line indicates the position of the cross section illustrated in Fig. 3.

ascent at the gust front of a spreading cold pool should be deepest where the shear vector and the density gradient are in the opposite directions. RKW further the argument by asserting that parcel ascent is deepest when the vertical shear of the ambient flow and the solenoidally generated circulation in the cold pool are quasi-balanced (henceforth referred to as RKW theory). Thus, parcel ascent to the LFC is most likely to occur on the downshear side of a cold pool and under conditions in which the quasi-balance between the vertical shear and the cold pool circulation is achieved.

In an environment for which the cold pool circulation is stronger than the vertical shear (Fig. 6a), the gust front relative flow in the cloud-bearing layer is primarily rearward (Fovell and Dailey 1995; WR04). In an environment for which the cold pool circulation is weaker than the vertical shear (Fig. 6c), the gust front relative flow in the cloud-bearing layer is primarily forward. In both circumstances, the residence time of parcels within the zone of forced ascent at the gust front is short and thus the net vertical displacement is relatively small (WR04).

Ultimately, the failure of the SingleThrm experiment to support a long-lived storm is attributable to the inability of the environment to support updraft maintenance and/or the systematic redevelopment of new updrafts along the spreading storm-generated cold pool (supercell processes would only be relevant in higher shear environments). Conversely, the longevity of the storms in the MultipleThrm and BndCold experiments is a consequence of the repeated redevelopment of new updrafts along the gust front.[3] Based on RKW theory and density current dynamics, repeated updraft redevelopment should occur on the downshear side of spreading cold pools, and where updraft redevelopment fails to occur, the cold pool circulation should either be too strong or too weak relative to the vertical shear.

The most vigorous updraft redevelopment in these simulations occurs on the east and southeast sides of the cold pool. The 0–1-km shear vector is $5\hat{\mathbf{i}} - 3\hat{\mathbf{j}}$ and the 0–2.5-km shear vector is $3.5\hat{\mathbf{i}}$; thus, the redevelopment is indeed occurring on the downshear side of the cold pool. Examination of the gust front relative flow across the cold pool reveals a front-to-rear flow in the cloud-bearing layer (Fig. 7) similar to that reflected under conditions in which cold pool circulation is stronger than the vertical shear (Fig. 6a). A more robust assessment of the relationship between the cold pool circulation and the vertical shear if facilitated using the ratio $C/\Delta u$ (RKW), where C represents the net generation of vorticity at the edge of the cold pool and Δu is the vertical differential of

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[3] Unlike some previous research that utilizes preexisting airmass boundaries to initiate deep convection (e.g., Jewett and Wilhelmson 2006), the cold front simulated in the BndCold experiment becomes indistinguishable from the storm-generated gust front shortly after cold pool formation (Fig. 3).
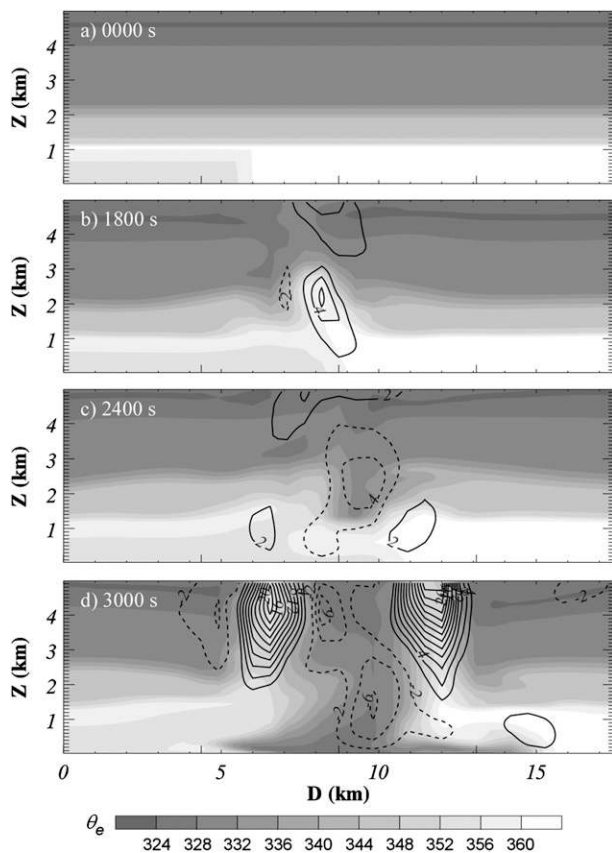
FIG. 3. Cross sections of equivalent potential temperature (shaded at an interval of 4 K following the key at the bottom of the figure) and vertical velocity (contoured at an interval of 2 m s^{-1}) for the BndCold experiment at (a) 0, (b) 1800, (c) 2400, and (d) 3000 s. The location of the cross section is illustrated in Fig. 2.

the wind in "low levels." The variable C is calculated using $C^2 = -2\int_0^H B\,dz$, where H is the depth of the cold pool and B is the buoyancy, defined here to include the virtual temperature correction and hydrometeor loading. Based on RKW theory, as $C/\Delta u$ increases beyond a value of 1, the gust front relative flow in the cloud-bearing layer would become more rearward (cf. Fig. 6a) and the ascent at the gust front would become weaker and shallower. The values of $C/\Delta u$ for the MultipleThrm and BndCold simulations are much larger than 1 (10.3 and 18.2, respectively[4]). However, systematic redevelopment of convective cells occurs on the gust fronts of both the

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[4] The value of C reported here is calculated by averaging within the region along and 20 km behind the gust front and over a 30-min time frame during the mature stage of storms in each experiment. The value of Δu is the component of the vertical differential of the wind normal to the gust front in the 0–2.5-km layer (positive values indicate a wind shear vector in the opposite direction of the density gradient, i.e., "forward").

MultipleThrm and BndCold simulations, leading to long-lived quasi-linear systems in both cases. The occurrence of long-lived quasi-linear deep convection in low-shear environments is notable not because it is unique—it has been previously documented both observationally and numerically (e.g., Fovell and Ogura 1989; Coniglio and Stensrud 2001; Evans and Doswell 2001; WR04)—but because it illustrates that system sustenance in these simulations requires considering more than the relationship between the cold pool circulation and the vertical shear.

Vertical cross sections through the cold pools of the three simulations (Fig. 7) reveal an important difference: the cold pools in the BndCold and MultipleThrm simulations are consistently deeper than that of the SingleThrm experiment. Time series of maximum cold pool depth (Fig. 8, plotted as a function of the time since the cold pools of each experiment reach the surface) illustrate that the cold pool of the SingleThrm experiment becomes shallower than the cold pools of the other two experiments very quickly after surface cold pool formation. It is also clear from Fig. 8 that the MultipleThrm and SingleThrm distributions diverge around the time that outflow mergers first occur in the MultipleThrm experiment. Thus, despite the weak shear that characterizes the environment used for these experiments and the resulting expectation of weak/shallow ascent at the gust front, the forced ascent associated with this deeper cold pool invariably leads to the systematic updraft redevelopment and the overall longevity of the convective system.

To the degree that the cold pool can be represented by a density current, the depth of ascent at a gust front will be proportional to the ambient vertical wind shear normal to the gust front (Xu 1992; Liu and Moncrieff 1996; Xu et al. 1996; Xue et al. 1997) and inversely proportional to the ambient static stability (Liu and Moncrieff 2000; Xue 2002). The vertical shear normal to the gust front is actually marginally larger for the SingleThrm simulation. This difference in the gust-front-normal shear is a consequence of slight differences in the orientations of the gust fronts. Moreover, the ambient static stability of the simulations is largely identical. Thus, the difference in simulated cold pool depths cannot be attributed to either the vertical shear or static stability. Instead, it appears that the deeper cold pools in the BndCold and MultipleThrm simulations are the result of a larger horizontal flux of low-θ_e air toward the leading edge of the cold pool that can be attributed to the multiple convective cells, and therefore multiple convective downdrafts, that collectively contribute to the system's cold pool. In contrast, the few convective cells (originally just one) of the SingleThrm experiment are capable of providing only a limited supply
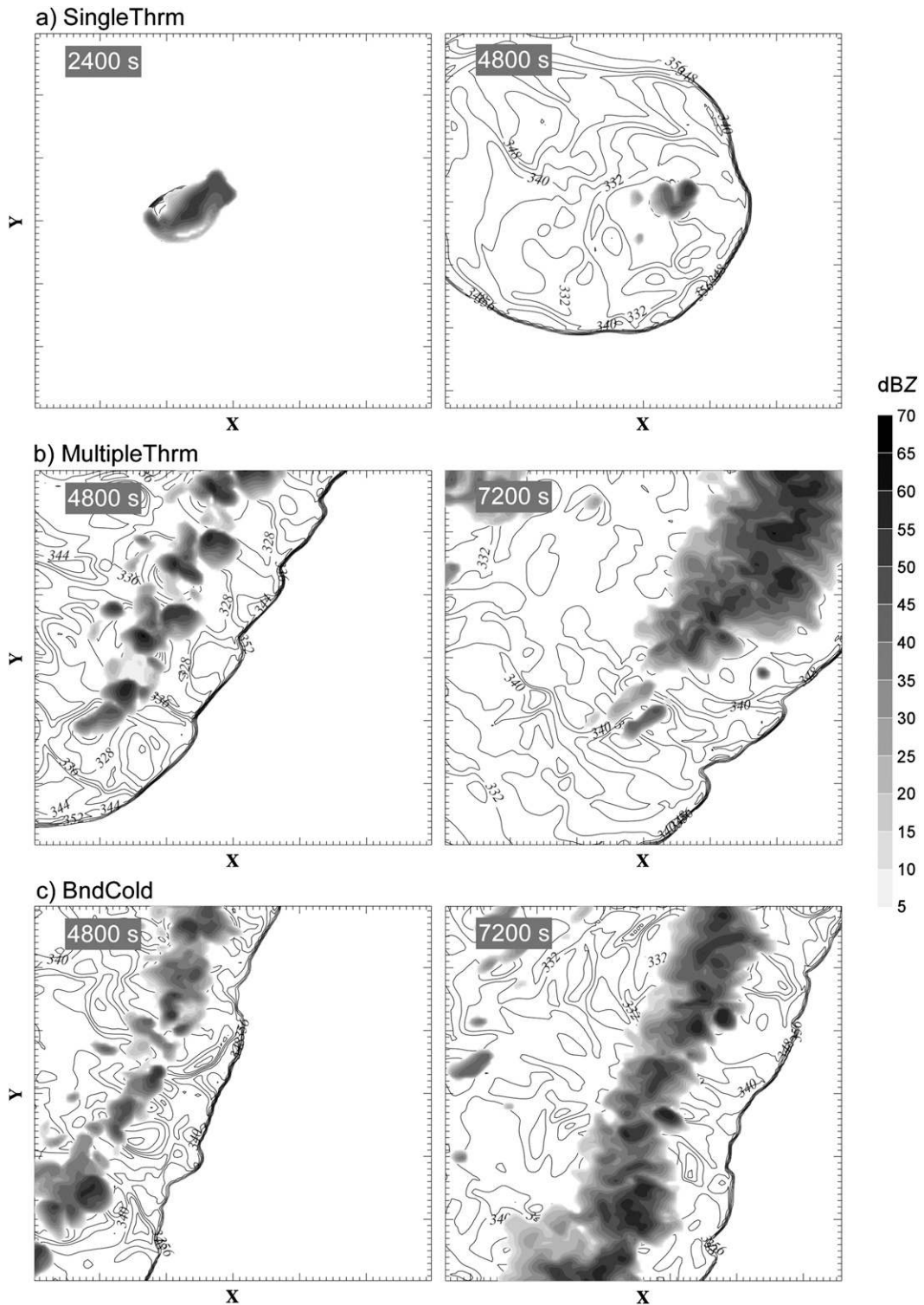
FIG. 4. Summary of the experiments used: (a) SingleThrm, (b) MultipleThrm, and (c) BndCold. Near-surface equivalent potential temperature is contoured at an interval of 4 K and simulated radar reflectivity is shaded every 5 dBZ. Simulated reflectivity is computed following Smith et al. (1975). The distance between "large" tick marks is 10 km (the sizes of the subdomains illustrated in each panel are the same but the bounds are different).
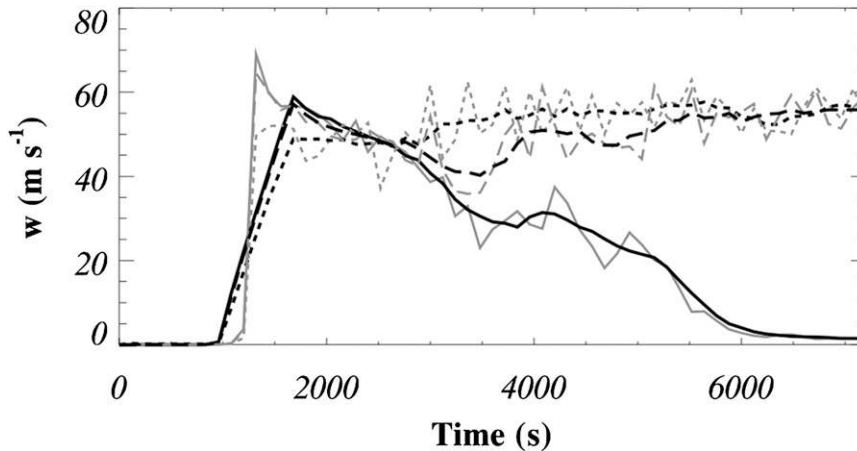
FIG. 5. Time series of maximum vertical velocity at a height of 7.5 km for the SingleThrm (continuous curves), MultipleThrm (dashed curves), and BndCold (dotted curves) experiments. The black curves represent a 600-s centered running mean and the gray curves represent the actual values at an interval of 120 s.

of low-θ_e air to the collective cold pool. An example of this collective contribution to the cold pool of the BndCold experiment is illustrated in Fig. 9. Note that, within the sampled time period, multiple downdraft surges north and south of the (dashed) reference line reinforce the cold pool. In other words, the BndCold simulation behaves as a 2D slab-symmetric convective system in which the low-θ_e outflow behaves as if it were not allowed to spread away in the symmetric direction. In contrast, the SingleThrm simulation behaves as a 3D isolated system in which the outflow radiates away from the source. Two-dimensional simulations conducted in this environment (not shown) yield a convective system that can support updraft redevelopment through the duration of integration, thereby confirming this analogy.

The cold pool of the MultipleThrm experiment is sustained collectively in the same way. However, unlike the BndCold experiment, redevelopment does not occur along a line transecting the entire domain but is instead bounded by the position of the northernmost and southernmost initial thermals. Between these two positions the cold pool can be reinforced from downdraft surges from both the north and south (as in the BndCold experiment). Beyond these positions, the outflow radiates away from the source as in the SingleThrm experiment.

The proposed response in cold pool depth to the flux of cold air has some precedent in previous theoretical work on density currents. In this prior work, the analytical density current solution of Benjamin (1968) and Xu (1992) is used to explain the response. This solution dictates that density current depth and propagation speed are governed by flow–force balance (also called

pressure–momentum balance). Flow–force balance is the condition in which the horizontal pressure gradient across the density current is balanced with the momentum flux. For a system in flow–force balance, if the density current is "too deep," the positive (hydrostatic) pressure perturbation within the density current will be too large and the negative (Bernoulli) pressure perturbation above the density current will be too small relative to the momentum flux associated with the ambient flow impinging upon the density current and the rearward flow above the density current (Xu 1992). When controlling for the density through dimensionalization, flow–force balance predicts that in an inviscid fluid, the depth and propagation speed of the density current are governed solely by the vertical shear.

Xu et al. (1996) and Xue et al. (1997) conducted numerical experiments to test the veracity of the analytical solution and demonstrated that density currents initialized with the depth and shape that the analytical solution predicts remain quasi-steady with depths and propagation speeds predicted by the analytical solution. For simulated density currents that were initialized to be deeper than the analytical solution, flow–force balance produced an erosion of the cold air back to a height consistent with the balanced state. However, Xue et al. (1997) showed that for a density current initialized to be considerably shallower than the predicted depth, the source of cold air in the density current was incapable of supplying enough mass to the density current for flow–force balance to be achieved and the resultant density current was unsteady, shallower than expected, and possessed generally weaker forced ascent along its leading edge. Therefore, when a density current is
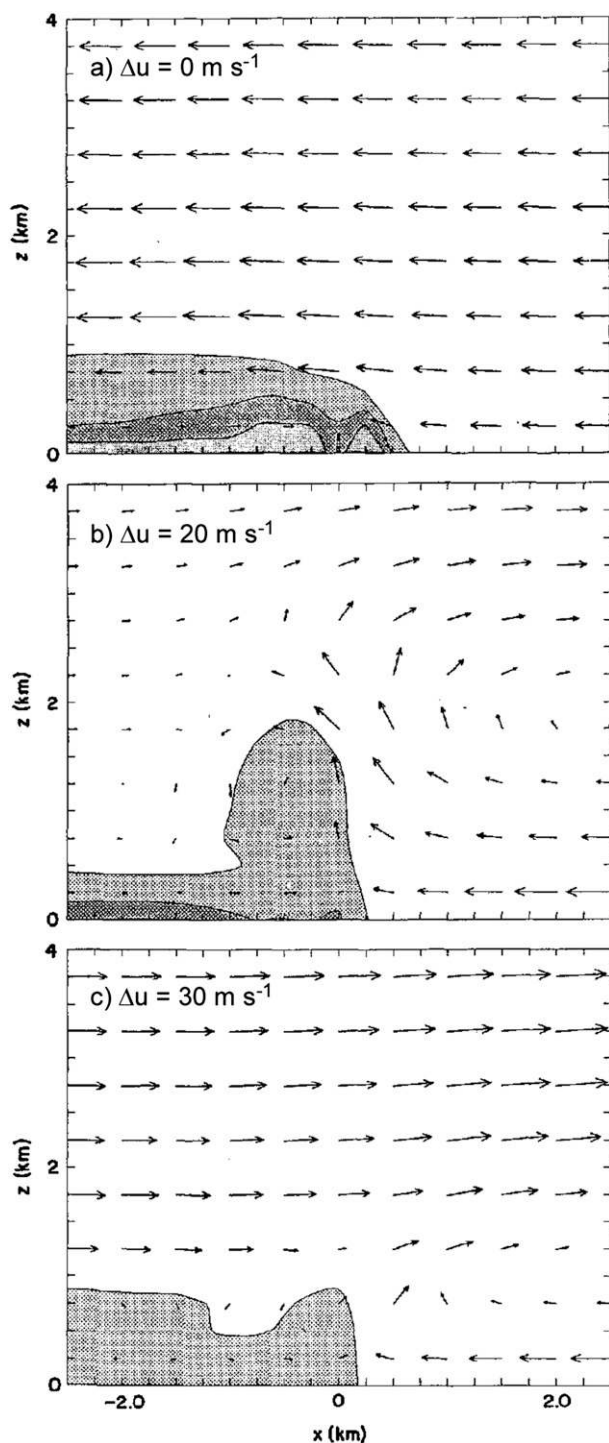
FIG. 6. Figure 20 from Rotunno et al. (1988). Cross sections of simulated density currents in environments with different values of vertical wind differentials: $\Delta u =$ (a) 0, (b) 20, and (c) 30 m s^{-1}. Arrows represent the cold pool relative wind vectors (two grid lengths represent 15 m s^{-1}) and negative potential temperature perturbations are shaded at a 2-K interval.

incapable of achieving flow–force balance, the depth of the density current and, by extension, the magnitude of the forced ascent at its leading edge depend not only on the vertical shear but also on the amount of cold air available.

The results of Xu et al. (1996) and Xue et al. (1997) seem to support the conclusion that the shallow depth of the cold pool in the SingleThrm experiment compared to the BndCold and MultipleThrm experiments is attributable to an insufficient supply of cold air. However, a more robust assessment requires determining the expected density current depth in this environment. In doing this, several limitations in applying either the analytical solution or the numerical results of Xu et al. (1996) and Xue et al. (1997) to this situation become evident. Based on the results of Xu (1992), even in the presence of vertical shear, the analytical depth will be approximately half of the domain height. A domain height equivalent to the depth of the troposphere in this environment would yield an analytical depth of ~6 km. Xue et al. (1997) and Xue (2000) argue that the inversion often found above a well-mixed planetary boundary layer could be considered a fair proxy for a rigid lid and thus could serve as the top of the "domain." The simulations of Xue (2002) indicate that, in the presence of an inversion, density currents assume quasi-steady depths that are somewhat deeper than the analytical solution predicted using the height of the inversion for the domain height, but considerably shallower than the height predicted using the height of the full domain. For those density currents that are not confined to the low levels of the atmosphere, Bryan and Rotunno (2008) demonstrated that the Boussinesq approximation used by Benjamin (1968) and Xu (1992) to derive the analytical solution, and used by Xu et al. (1996) and Xue et al. (1997) to conduct numerical tests of the analytic solution, yields density currents that are too deep.

The preceding illustrates that while the analytical solution provides insight into the forces that regulate density current depth, it is nontrivial to apply this solution to assess the sufficiency of the supply of cold air to a density current in a deep troposphere with an inversion. As such, an additional set of numerical experiments is conducted. These experiments are conducted to identify the maximum cold pool depth supported in the environment used in this work.

The supplemental experiments are conducted using a 2D domain initialized with the same profile of potential temperature that characterizes the initial environment of the SingleThrm, BndCold, and MultipleThrm experiments but without any moisture. The wind profile is based on the initial environment of the 3D experiments but is constructed to represent a cross section
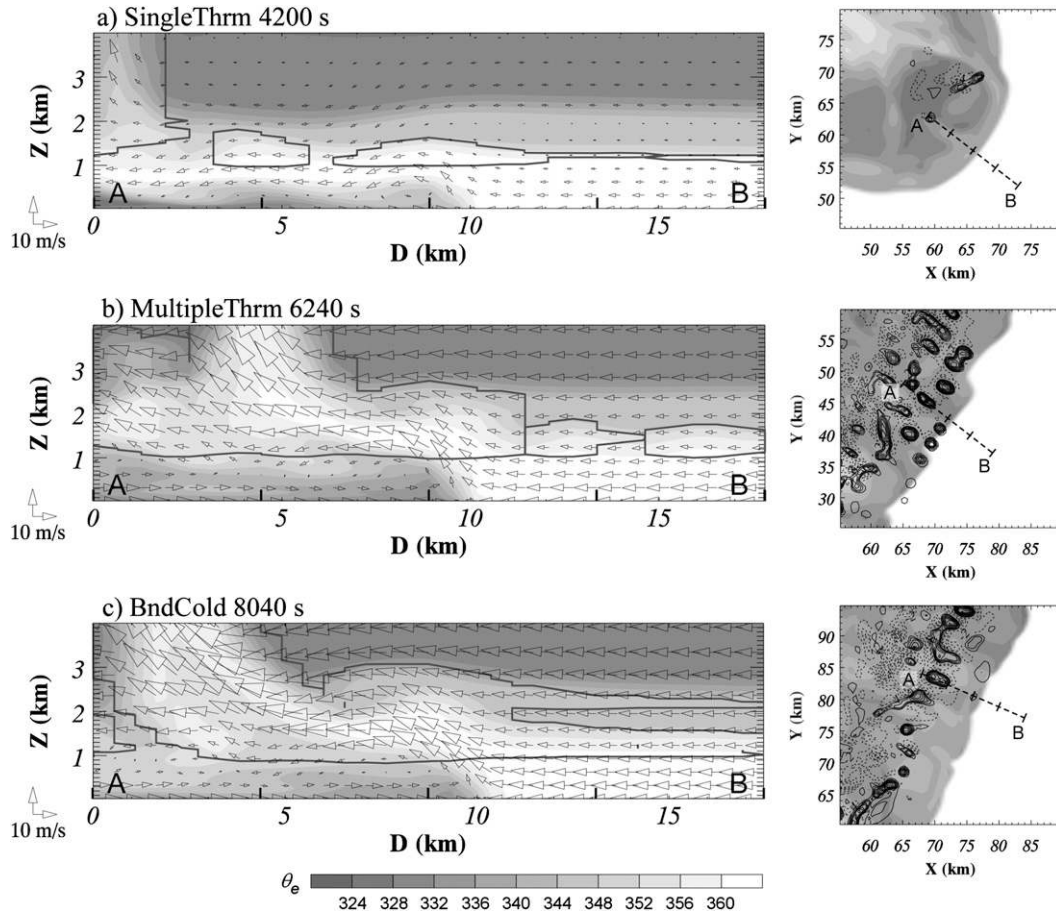
FIG. 7. Gust front relative flow in the (a) SingleThrm, (b) MultipleThrm, and (c) BndCold experiments. Arrows denote the gust front relative flow in the plane of the projection. In the cross sections, θ_e is shaded at an interval of 4 K following the key at the bottom of the figure and 5×10^{-8} kg kg^{-1} mixing ratio isopleths of the total cloud (the combined mixing ratios of cloud water and cloud ice) are contoured in gray. In the plan-view images, near-surface values of θ_e are shaded at an interval of 4 K and vertical velocity at 3000 m above ground is contoured at an interval of 2 m s^{-1}.

normal to the gust front of the BndCold simulation. The domain is 30 km long, 10 km tall, and composed of grid cells with a $\Delta x = 100$ m and a $\Delta z = 50$ m stretched to 100 m at the top of the domain. The cold pool is imposed using a block of cold air with a uniform temperature perturbation of -5 K and no initial flow within it. The block is 10 km wide and the depth differs in each of the six experiments, ranging from 0.5 to 7.5 km. The temperature perturbation within the block is restored at every time step, thereby providing a constant source of cold air. An automatic grid translation is used so that the gust front remains fixed relative to the grid. The source of cold air translates with the grid; therefore, the distance between the gust front and the cold air source remains virtually constant.

Results from these simulations are presented in Fig. 10. The profile of the density current depth (Fig. 10a) appears

to asymptote at approximately 2200 m, indicating that this depth is roughly the maximum density current depth that the combination of temperature stratification and vertical shear characterizing this environment will support. The sensitivity of the density current depth to the depth of the source agrees with the results of Xue et al. (1997): namely, for sources that are too shallow, the mass of cold air is insufficient to support the maximum depth allowed by this environment. These supplemental simulations also illustrate that the maximum vertical velocity at the gust front (Fig. 10b) is proportional to depth. Thus, an insufficient source also yields reduced ascent at the gust front. Given that the maximum depth is more than 2.5 times the depth of the cold pool simulated in the SingleThrm experiment, it is clear that these results support the conclusion that the source of cold air in the SingleThrm experiment is insufficient to generate a cold
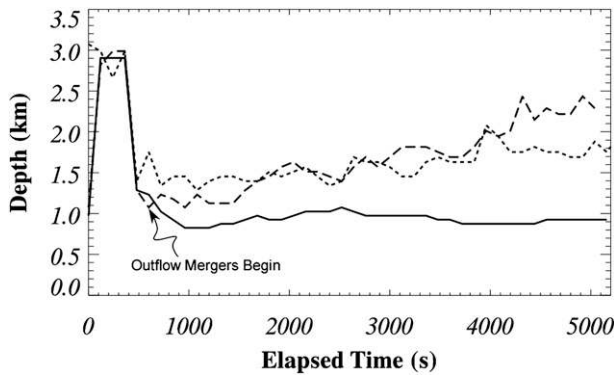
FIG. 8. Time series of cold pool depth for the SingleThrm (continuous curve), MultipleThrm (dashed curve), and BndCold (dotted curve) experiments. "Elapsed time" is the time since the cold pools of each experiment reach the surface.

pool with a depth and magnitude of gust front ascent as large as this environment is capable of producing. In contrast, both the BndCold and MultipleThrm experiments are capable of supplying a mass of cold air that can sustain a deep cold pool (depth >2 km), foster systematic convective updraft redevelopment, and therefore support storm longevity.

The previous analysis leads to the principal conclusion of this work: the difference in longevity between storms developing from a quasi-linear initiation mechanism and storms developing from an isolated initiation mechanism is primarily attributable to differences in cold pool depth. This conclusion presumes that the environments in which discrete convective updraft redevelopment occurs in these experiments are largely the same, except for differences in gust front ascent. However, existing convection can modify (precondition) the environment for subsequent updraft formation through the vertical transport of higher-θ_e air into the lower-to-middle troposphere. This higher-θ_e air can reduce the dilution of subsequent convective clouds, creating an environment that is more favorable for updraft regeneration and consequently more supportive of storm longevity. Therefore, it is important to consider the possibility that the multiple convective cells of the MultipleThrm or BndCold experiments could affect the storm longevity through this preconditioning.

To explore the importance of preconditioning, we first characterize the environment on the periphery of updrafts in each of the experiments. Focus is placed on the value of θ_e around these updrafts. Updrafts are identified through a blob-coloring technique,[5] the cloud edge

associated with each updraft is found, and the values of θ_e 2 km beyond the cloud edge along eight radials emanating from the updraft core are cataloged. Analysis is conducted on updrafts that are $\geq$5 m s^{-1} at a height of 3 km and within 10 km of the gust front. The time series of the means and standard deviations for the periphery θ_e is illustrated in Fig. 11. Times at which the mean θ_e for the SingleThrm updrafts is significantly different from either the MultipleThrm (Fig. 11a) or BndCold (Fig. 11b) distributions are noted with black (95% confidence) or white (99% confidence) squares.

The environments on the periphery of updrafts in the SingleThrm and MultipleThrm experiments are not significantly different for the majority of the time that updrafts $\geq$5 m s^{-1} at a height of 3 km are present within the SingleThrm experiment. This is not true of the SingleThrm and BndCold experiments, for which the mean θ_e on the periphery of updrafts in the two experiments is significantly different. From Fig. 11c, it is apparent that the maximum vertical velocity values in updrafts near the gust fronts of both the MultipleThrm and BndCold experiments are larger than in the SingleThrm experiment shortly after storm-generated cold pools appear at the surface (elapsed time of 0 in Fig. 11). A more appreciable departure in the peak updraft magnitudes is seen shortly before 2000 s have elapsed. Even as late as 2000 s, the values of θ_e on the periphery of updrafts in the SingleThrm and MultipleThrm experiments are not significantly different. Thus, while the difference between the longevity of the SingleThrm and BndCold storms could be attributed in part to the preconditioning of the lower-to-middle troposphere by existing convection, there is no evidence that preconditioning can explain the difference in the longevity of the SingleThrm and MultipleThrm storms. Instead, we contend that it is the difference in cold pool depth, which manifests well before 2000 s have elapsed (Fig. 8), that explains the difference in storm longevity.

Given the prominent role found to be played by the cold pool in regulating the longevity of storms initiated through an isolated versus quasi-linear mechanism, it is reasonable to consider the degree to which these results depend on the parameterization of microphysics that is used. There is a growing consensus (e.g., Milbrandt and Yau 2006; Mansell and Wicker 2008; Dawson et al. 2010) that the single-moment class of parameterizations, like the one used for this work, does a poorer job of representing cold pool structures than do multimoment schemes (schemes that predict more than just one moment of the drop size distribution). Therefore, the degree to which these results would change if a multimoment microphysics parameterization was used is an issue that, while beyond the scope of this work, should be demonstrated. It is

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[5] Blob coloring is a technique adopted in image processing for feature identification.
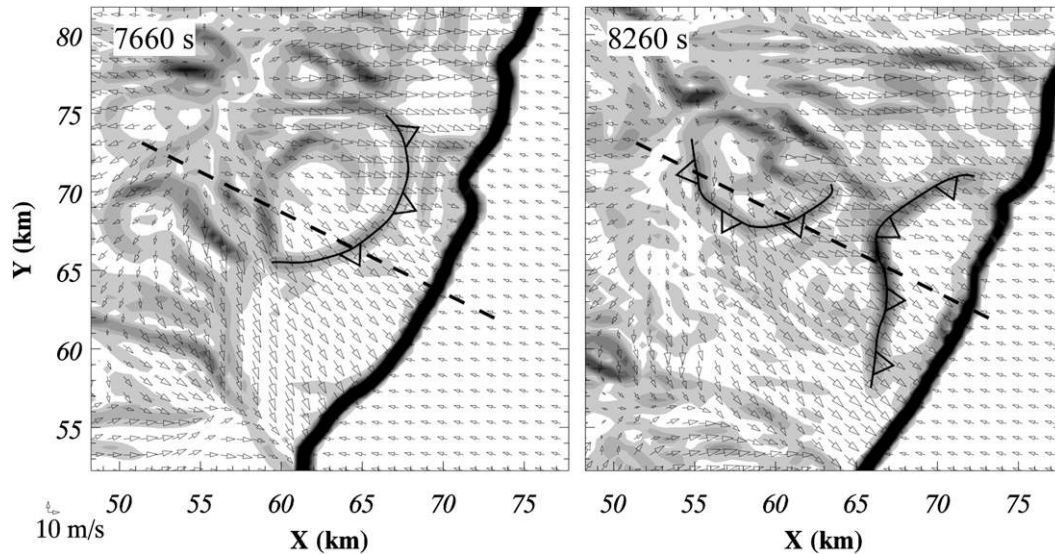
FIG. 9. Illustration of the collective contribution to the cold pool from multiple downdraft surges at 7660 and 8260 s for the BndCold experiment. The magnitude of the horizontal buoyancy gradient at the surface is shaded at an interval of 2×10^{-5} s^{-2} (darker shading represents higher values) and the surface wind field is illustrated with arrows. Gust fronts associated with downdraft surges are annotated. The dashed line is included for reference and serves to illustrate the collective contribution to the cold pool.

important to note that the improved representation of cold pool structure that might be realized when using a multi-moment scheme will not necessarily alter the principal conclusion of this work: the sensitivity of storm longevity to the pattern of deep convection initiation depends on the cold pool depth. This conclusion would need to be reevaluated only if the impacts of a multimoment parameterization on the cold pool are sensitive to the pattern of deep convection initiation. It is also important to note that the single-moment parameterization used for the simulations presented here was also used by HW11, who compared a simulation conducted in the same reference state environment (but with an additional airmass boundary) to surface observations of temperature from the 27 May 1997 event and found the temperature perturbation within the simulated cold pool to be very similar to the observed cold pool temperature perturbation.

4. Discussion

The results presented herein implicate the cold pool depth in the sensitivity of storm longevity to the pattern of deep convection initiation. These results also illustrate that RKW theory, which asserts the importance of the balance between the vertical shear and the cold pool circulation to the magnitude and depth of the ascent at the gust front, does not adequately describe the processes responsible for longevity in this low-shear environment: despite values of $C/\Delta u \gg 1$ for the MultipleThrm and

BndCold simulations, systematic redevelopment of convective cells occurs on the gust fronts of both simulations leading to long-lived quasi-linear systems in both cases. This is not the first time that such a conclusion has been reached. Based on the appearance of long-lived quasi-linear systems in environments with little to no vertical shear (e.g., Fovell and Ogura 1989; Coniglio and Stensrud 2001; Evans and Doswell 2001; WR04), WR04 concluded that "squall-line longevity, without reference to system strength and structure, is not found to be as sensitive to shear as in the past studies." WR04 posit that the systematic redevelopment that leads to long-lived storms in such low-shear environments is a consequence of boundary collisions behind the gust front and (for environments with shear confined to a layer well above the surface) the interaction between the ambient vertical shear and the horizontal buoyancy gradient on the leading edges of the precipitation shafts of decaying convective cells well behind the gust front. In both explanations, the forced ascent at the leading gust front does not directly contribute to updraft redevelopment and therefore storm longevity. However, what we find is that system sustenance can still occur on a gust front even in conditions in which the cold pool circulation is considerably stronger than the vertical shear. In these situations, the depth of the cold pool must be considered.

According to RKW theory, as $C/\Delta u$ increases beyond a value of 1, the ascent at the gust front becomes weaker and shallower. Because C scales with H, a deeper cold
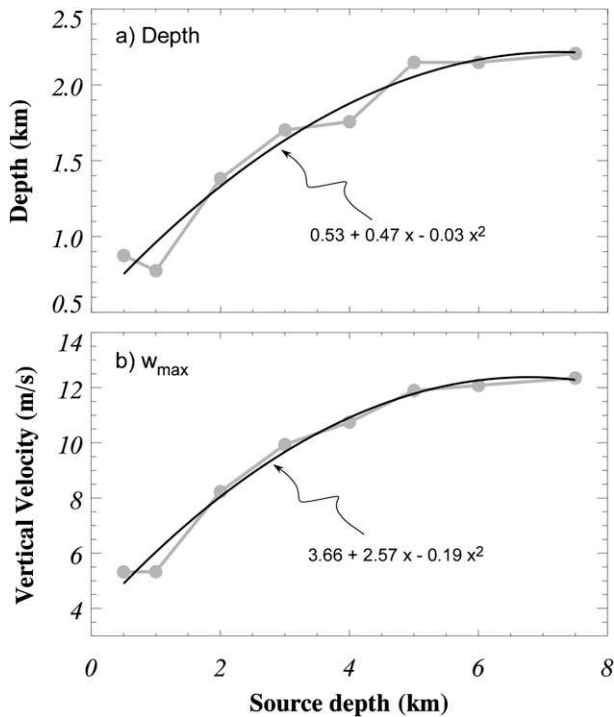
FIG. 10. Variation in the (a) depths and (b) maximum vertical velocity of simulated density currents as a function of the source depth (gray curve). Black curves are second-order curve fits to these distributions.

pool will yield a larger $C/\Delta u$. Thus, based on RKW theory *alone*, a deeper cold pool should be less favorable for the redevelopment of deep convective cells at the gust front of a convective system in a low-shear environment. Ostensibly, as the depth of a cold pool increases, the likelihood that air will be lifted to its LFC also increases, as would the likelihood of convective cell redevelopment. Thus, systematic redevelopment would seem to be more, not less, likely in conditions supportive of deeper cold pools.

The results from the simulations conducted for this work illustrate this inconsistency. In the low-shear environment used for these experiments, the experiments that produce the deepest cold pools (MultipleThrm and BndCold) and the largest values of $C/\Delta u$ (10.3 and 18.2, respectively) are the ones that support long-lived deep convection. This inconsistency is more than just another reason that RKW theory should not be used to assess squall line longevity. This inconsistency indicates that the inability of RKW theory to account for storm longevity in low-shear conditions is not because the convective cell redevelopment at the gust front can be ignored, but because the convective cell redevelopment at the gust front is a function of more than just the shear and the cold pool
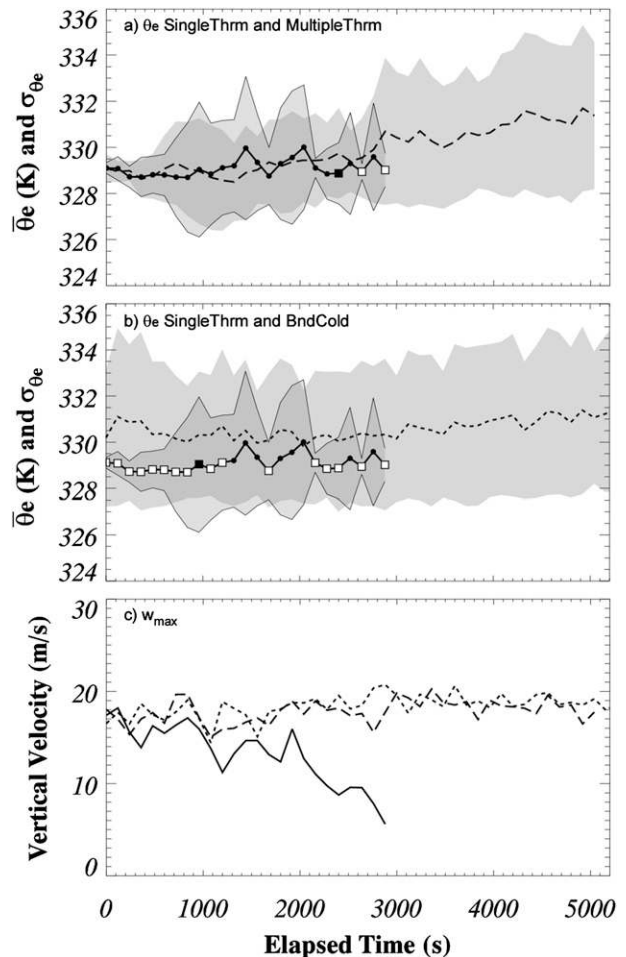

FIG. 11. (a),(b) Time series (plotted as a function of the elapsed time since the cold pools of each experiment reach the surface) of mean equivalent potential temperature ($\bar{\theta}_e$, thick curves) and standard deviation (σ_{θ_e}, shaded regions span $\bar{\theta}_e \pm \sigma_{\theta_e}$) on the periphery of updrafts for the (a) SingleThrm and MultipleThrm experiments and (b) SingleThrm and BndCold experiments. The SingleThrm profile appears as a thick black curve and a dark-shaded region bounded by thin gray lines. Data points marked with black (white) squares indicate times at which the SingleThrm mean differs significantly at the 95% (99%) confidence level from the (a) MultipleThrm or (b) BndCold mean. (c) The maximum vertical velocities in updrafts near the gust front of the SingleThrm (continuous curve), MultipleThrm (long dashed curve), and BndCold (short dashed curve) experiments.

circulation; it is also a function of the depth of the cold pool.

5. Summary

Results are presented from a set of experiments conducted using a low-shear environment in an effort to determine why a quasi-linear pattern of initial deep convection is more favorable for long-lived storms than

an isolated pattern of initial deep convection. When multiple deep convective cells were initialized in close proximity to one another using either a line of thermals (the MultipleThrm experiment) or a 1-km-deep and arced airmass boundary (the BndCold experiment), long-lived storms were produced. However, when isolated deep convection was initiated (the SingleThrm experiment), the resultant storm steadily decayed following initiation. These results illustrate that a quasi-linear mechanism, such as a preexisting airmass boundary, that initiates multiple deep convective cells in close proximity can lead to longer-lived storms than a mechanism that initiates isolated deep convection.

The principal difference between the MultipleThrm and BndCold experiments that produce long-lived deep convection and the SingleThrm experiment that does not is the depth of the storm-generated cold pool: the depth of the MultipleThrm and BndCold cold pools is as much as twice that of the SingleThrm cold pool. The forced ascent associated with these deeper cold pools leads to the systematic updraft redevelopment and longer-lived convective systems.

Previous research along with supplemental density current simulations confirm that cold pool depth depends not only on the vertical shear and temperature stratification of the environment, but also on the source of cold air. If the source is sufficient, the cold pool will achieve the theoretical maximum depth supported by the vertical shear and temperature stratification. In contrast, an insufficient source will yield a shallow cold pool. In the experiments with quasi-linear initial storms, the resulting multiple convective cells feed a communal cold pool that provides ample cold air to the cold pool, leading to a depth that approaches the maximum depth supported in this environment. However, in experiments with a single isolated storm, the few convective cells that develop only provide a limited source of cold air to the cold pool and systematic updraft redevelopment is not permitted, leading to a storm system that steadily decays.

The possible impacts of environment preconditioning by the multiple convective cells of the MultipleThrm and BndCold experiments were also considered. Such preconditioning could produce an environment that is more favorable for updraft regeneration and consequently more supportive of storm longevity. The mean environments around the periphery of updrafts near the gust fronts of the SingleThrm and MultipleThrm experiments were found to not be significantly different prior to the appearance of appreciable differences in the strength of the storms in the two experiments. Thus, it was concluded that preconditioning could not explain the difference in the longevity of the SingleThrm and MultipleThrm storms. Statistically significant differences

were found between the environments on the periphery of updrafts in the SingleThrm and BndCold experiments; thus, the difference in storm longevity for these two experiments could be partly explained by preconditioning.

These experiments also demonstrated that system sustenance can occur via convective cell redevelopment on the gust front even in conditions in which the cold pool circulation is considerably stronger than the vertical shear. In these situations, the depth of the cold pool must be considered. However, based on RKW theory *alone*, a deeper cold pool in a low-shear environment should be less favorable for the redevelopment of deep convective cells at the gust front, even though the likelihood that air will be lifted to its LFC should increase with increasing cold pool depth. This inconsistency indicates that the previously documented inability of RKW theory to account for storm longevity in low-shear conditions is not because the convective cell redevelopment at the gust front can be ignored but because the convective cell redevelopment at the gust front is a function of more than just the shear and the cold pool circulation; it is also a function of the depth of the cold pool.

The experiments conducted for this work only tested a small collection of initial patterns of convection. A number of additional experiments could be developed, steered by how different patterns might affect the depth of the cold pool and therefore storm longevity. Such experiments could involve changing the orientation of the initial line of convection, changing the number/spacing of thermals in multiple thermal experiments, or initializing thermals in clusters instead of lines (e.g., Jirak and Cotton 2007; Jewett and Wilhelmson 2006).

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