OPERATIONAL IMPLICATIONS OF THE SENSITIVITY OF MODELLED THUNDERSTORMS TO THERMAL PERTURBATIONS

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ABSTRACT

A series of simulations has been carried out in a numerical thunderstorm model with a variety of thermal perturbations initiating the storms. The model shows sensitivity in both the formation of the initial storm and, more importantly, in the development of secondary storms on the outflow of the first storm. Of particular importance to the operational community, the differences in size and shape of the thermal perturbation are small enough that they would not be noticeable over most the range of current and planned operational radar systems. The results also imply that storm growth is sensitive enough that even perfect observations early in the storm lifetime are insufficient to provide long (~1 hour) lead times for accurate warnings of severe weather events.

1. INTRODUCTION

Numerical weather prediction (NWP) has been an important part of the forecasting process for many years. Models have become more sophisticated over time and have been run at higher resolution as computational power has increased, to the point where horizontal grid spacing on the order of 100 km is now common in NWP models. This resolution is still too coarse to resolve important scales of weather events of importance to the operational forecaster and to the public. The technological capability to carry out operational NWP forecasts on much finer scales will soon be available. The development of mesoscale and cloud-scale forecast models for use at individual operational forecast offices has been proposed (Droegemeier 1990; Lilly 1990). It has been suggested that cloud-scale models could be initialized from single-Doppler radar observations of the atmosphere (Sun et al. 1991) and that the subsequent evolution and behavior of individual storms could be predicted accurately by the model for several hours, a mode which I will refer to as *explicit prediction* (Droegemeier 1990). Brooks et al. (1992b) argued against explicit prediction of convective weather on the cloud scale, while supporting the use of a quasi-Monte Carlo approach with cloud-scale models in a forecast mode at regional or local forecast offices. One of the important questions in the use of such models is the sensitivity of the model to changes in the ways storms are initiated. This is of interest operationally for two distinct reasons. The first is in the potential for cloud-scale models to be used as forecast tools. Clearly, if the models are extremely sensitive to details in their initiation, then their adaptation to operational requirements will be more difficult than if they are insensitive. A second area of importance concerns the basic nature of convective behavior and our ability to observe it. If the model is sensitive to small perturbations, it is possible that similar small perturbations in the atmosphere might cause significant changes in the behavior of thunderstorms. This is critical in the design or radar scan strategies and the use of radar data, since the early stages of thunderstorm initiation and growth occur at low levels in the atmosphere, where radar coverage is necessarily sparse. In this paper, I present a brief examination of the sensitivity of thunderstorms simulated with a research-level cloud-scale model to systematic changes in the specification of an initiating warm 'bubble'.

The model for this study was developed by Klemp and Wilhelmson (1978) and has been used in a large number of *research* studies of convective phenomena (e.g., Wilhelmson and Klemp 1981; Rotunno and Klemp 1982, 1985; Weisman and Klemp 1982, 1984; McPherson and Droegemeier 1991). It is nonhydrostatic, uses a Kessler scheme (no ice phase) to parameterize microphysical processes, and is run typically at a horizontal grid spacing on the order of 1 km. A similar model (Wicker and Wilhelmson 1990) with an improved numerical scheme and with an ice phase included in the microphysical parameterization was used in a forecasting experiment in 1991 (Brooks et al. 1992c). Because of the long history of use of the Klemp-Wilhelmson (KW) model, it was felt to be a more appropriate choice for examining the sensitivity of a cloud model to its initialization. In the version of the KW model we will use, storms are initialized with a warm bubble in the form of an ellipsoid. The perturbation potential temperature within the bubble is given by

$$\theta' = 0.5\theta_{max}\left(1 + \cos\left\{\pi\left[\left(\frac{x - x_{cnt}}{h_{rad}}\right)^2 + \left(\frac{y - y_{cnt}}{h_{rad}}\right)^2 + \left(\frac{z - z_{cnt}}{z_{rad}}\right)^2\right]^{\frac{1}{2}}\right\}\right) \qquad (1)$$

where θ_{max} is the maximum perturbation, located at the centroid of the bubble at x_{cnt}, y_{cnt}, z_{cnt}. h_{rad} is the semiaxis of the bubble in the horizontal direction and z_{rad} is the semiaxis in the vertical direction. The integrated buoyancy (B) over the volume of the bubble is

$$B = 70.6\left(\frac{\theta_{max}}{\theta_o}\right)h_{rad}^2 z_{rad} \qquad \left(in\ m^4\ s^{-2}\right) \qquad (2)$$

where θ_o is the environmental potential temperature. Now, the use of a warm bubble is obviously physically unrealistic. Convection in the atmosphere does not start from isolated warm blobs of air. We use it here because of the 'historical' use of this method to initialize storms in cloud models, particularly KW, and its relative simplicity. Other researchers have used more complicated methods of storm initialization, such as a surface heating function (e.g., Kopp and Orville 1990), in an effort to mimic a more 'physical' mechanism. Given our present (lack of) understanding of storm initiation, it is not obvious, however, that such methods are more physically realistic, particularly in environments of strong low-level convergence forced by mesoscale processes.

Even though the bubble is unrealistic, the sensitivity of the model to small changes in the bubble is still important. In the future, the technological capability to use cloud models initialized with Doppler radar observations in a forecast or warning mode will be available. In the best case, presumably, in the early stages of storm development, equivalent to the time the bubble is inserted into current cloud models, three-dimensional fields containing inhomogeneities representing the incipient storm would be put into the model. If the bubble method shows that the model is sensitive to perturbations in one variable (temperature), it is unlikely that the model will become insensitive to that variable, or to other variables, when the full fields are used to initialize the model. This is above and beyond problems with putting data from the relatively coarse radar observations into the model, or the even greater problem of filling in gaps in radar coverage and the region below the radar beam.

Using the KW model, Weisman and Klemp (1982) stated that variations in the size of the bubble and the magnitude of the temperature excess over a "wide range of conditions" could have a "pronounced quantitative effect on the initial storm growth, but have less of an effect on subsequent storm redevelopments", although they showed no supporting results. McPherson and Droegemeier (1991) have shown that this models is sensitive in at least one case. In their work, a series of simulations with different initial bubbles produced two distinct classes of behavior following similar evolution to a splitting storm at about one hour after initialization. In the first class, the right-moving storm of the pair becomes a classic long-lived supercell, while in the second,the right mover dies soon after the split. Brooks and Wilhelmson (1992) have shown an example of simulations where changing the magnitude of the perturbation from 5 K to 4 K produces a storm bearing a strong resemblance to a low-precipitation supercell thunderstorm rather than a 'classic' supercell.

The goal of this paper is to examine the apparent conflict between the description of the model as insensitive (Weisman and Klemp 1982) and as sensitive (McPherson and Droegemeier 1991; Brooks and Wilhelmson 1992). Since it is possible that the differences in the studies reflect only that the model is sensitive in some environments and not in others, I will take one of the environments used by Weisman and Klemp and look at a wider range of changes in the bubble. Where the bubble size is changed, however, the changes are small when compared to the resolution of Doppler radar observations over most of the useable range of the radar. This is important particularly with regard to the ability of cloud models to be used in an explicit prediction mode, as well as in the use of the raw data in an effort to anticipate storm behavior from initial growth.

The environmental profile used in the model (Fig. 1) is the analytic sounding used by Weisman and Klemp (1982, 1984) with a surface water vapor content of 11 g kg^{-1}, yielding a convective available potential energy (CAPE) of

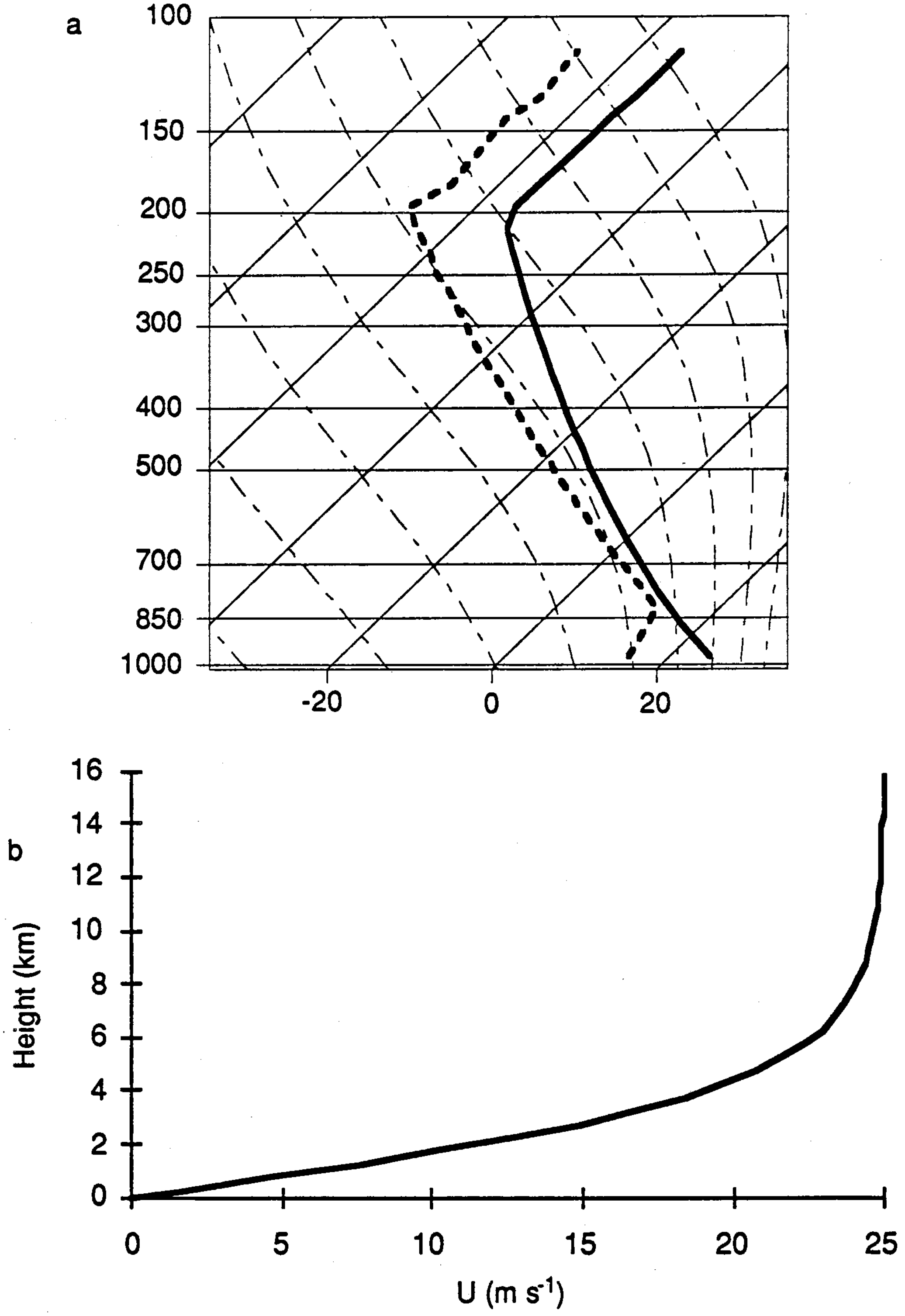

Fig. 1. Environmental conditions for simulations in text. a) Skew-T diagram. Temperature (solid line) and dewpoint (dashed) with moist adiabats drawn in. b) Westerly wind.

about 600 J kg^{-1}. The northerly wind component is zero and the westerly shear is concentrated in the lowest few kilometers. For details of the formulation of the profiles, see Weisman and Klemp (1982). The model is initially horizontally homogeneous, except for the thermal perturbation placed at the center of the domain.

Referring back to Eq. (2), there are three variables that control the total buoyancy perturbation in the ellipsoid for a given environmental thermodynamic profile, the horizontal semiaxis, h_{rad}, the vertical semiaxis, z_{rad}, and the maximum thermal perturbation, θ_{max}. Note that the total perturbation can be held constant while varying h_{rad} and z_{rad} simultaneously. This is of interest with respect to the shape of any perturbations that might be associated with the initial growth of thunderstorms. In attempts to simulate storms in environments with relatively high levels of free convection (LFC above ~750 mb) have proved challenging, another variable of importance is the height of the bubble, z_{cnt}, since the bubble typically extends above the LFC. In the next section, after presenting the results of some simulations with 2-km horizontal grid spacing, which can be compared with the Weisman and Klemp (1982) results directly, I will go on look at the effects of varying these other parameters. Although there are many ways to characterize numerically-modelled storms, attention here will be focused on the maximum updraft velocity as a simple and quick way to describe storm behavior.

2. RESULTS

2.1 2-km simulations

Weisman and Klemp initialized their 2-km horizontal resolution simulations with a bubble with a maximum temperature perturbation of 2 K, 10 km horizontal semiaxis, 1.4 km vertical semiaxis, and located with the center at 1.4 km altitude. For the environmental conditions in Fig. 1, they reported no sustained storm. This simulation has been repeated as part of this study and the maximum updraft in the domain is less than 1 m s^{-1}. More intense perturbations (θ_{max} = 5 K) result in storms that persist for an hour (Fig. 2). When the center of the bubble is raised to 2.4 km, approximately at the LFC, a long-lived storm develops. This storm is remarkable in that its maximum updraft is approximately 9 m s^{-1} for most of its life, while its maximum vorticity is on the order of .003 s^{-1}. Both of these values are much smaller than is found in most numerically-modelled classic supercells, which have, to date, been the only single-celled storms with such long lifetimes (e.g., Weisman and Klemp 1982, 1984; Brooks et al. 1992a). Physically, it appears that the lower bubble has to do more work in overcoming the stability associated with the negative area in the lower part of the thermodynamic chart. As a result, the updraft is weaker at the LFC. The stronger initial updraft in the high-bubble case creates enough low pressure near the LFC that potentially buoyant air from low levels is sucked into the storm, sustaining the updraft. The behavior displayed by the low-bubble storm has been seen in other unpublished model simulations in high-LFC environments. Given that severe storms are observed relatively frequently in such environments, the inability of the models to produce storms has been a source of concern. The long-lived nature of the high-bubble storm indicates that simply shifting the location of the bubble *may* provide the research community one artificial way of generating storms in high-LFC environments, assuming that one is interested only in qualitative determination of what kind of storm might be supported by an environment, or in the evolution of a storm in which there is no interest in the initial stages.

2.2 Sensitivity to maximum temperature

As illustrated by the development of a storm in an environment in which Weisman and Klemp were unable to sustain a storm simply by increasing the intensity of the bubble, θ_{max} is obviously an important quantity. With 1-km horizontal grid spacing a series of experiments have been run with θ_{max} varying from 2 K to 5 K, with the rest of the parameters held constant at h_{rad} = 10 km, z_{rad} = 1.4 km, and z_{cnt} = 2.4 km. As θ_{max} increases, the initial updraft grows more rapidly, but the 3-5 K storms reach approximately the same value, 25 m s^{-1}, while the 2 K storm is slightly weaker (Fig. 3). The most significant aspect of these simulations is the development of a second intense updraft on the outflow boundary from the first storm in all cases except 2 K, with the 5 K storm showing signs of a third intense updraft near 6000 s. The secondary storms appear to be a result of the stronger outflow associated with slightly more precipitation being generated in the warmer bubble cases. A similar mechanism has been hypothesized as the cause of the dichotomy in simulations in McPherson and Droegemeier (1991). The differences in the maximum updraft in the four storms is not large from approximately 1800 s to 3600 s. Although not shown, the differences in precipitation generation do not seem to be particularly large *except*

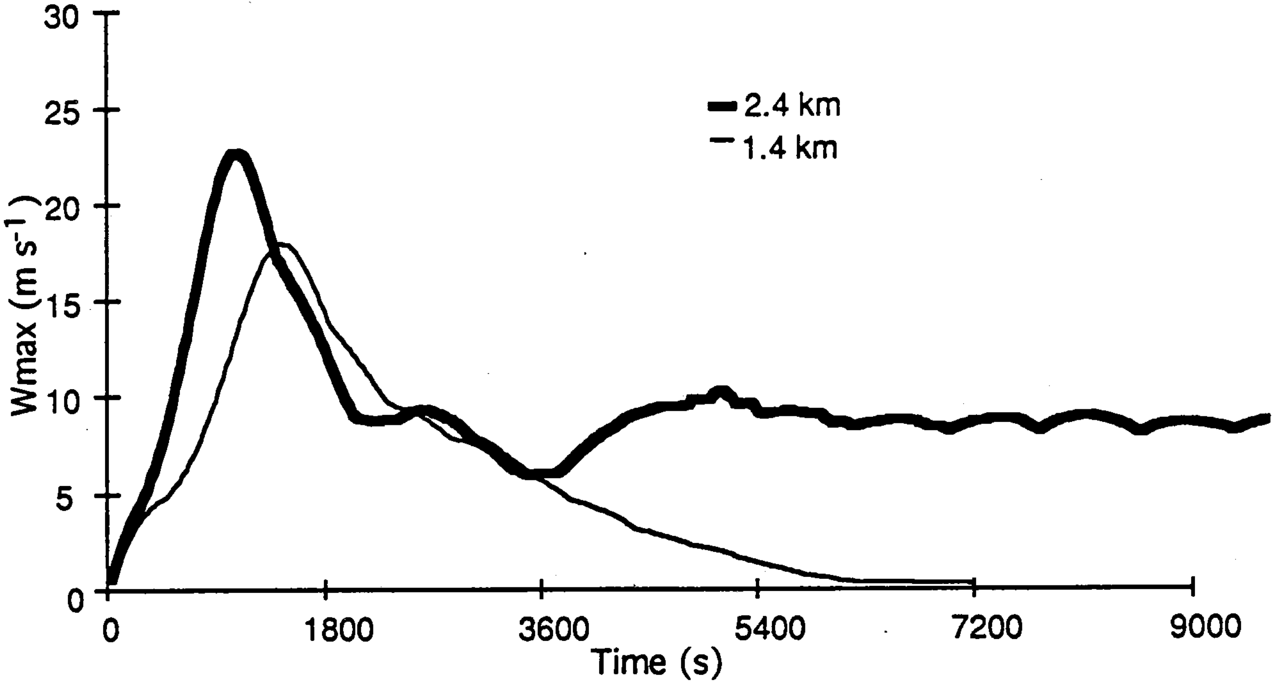

Fig. 2. Maximum updraft versus time for 2 km resolution simulations with maximum temperature perturbation of 5 K, as height of center of bubble varies from 1.4 to 2.4 km.

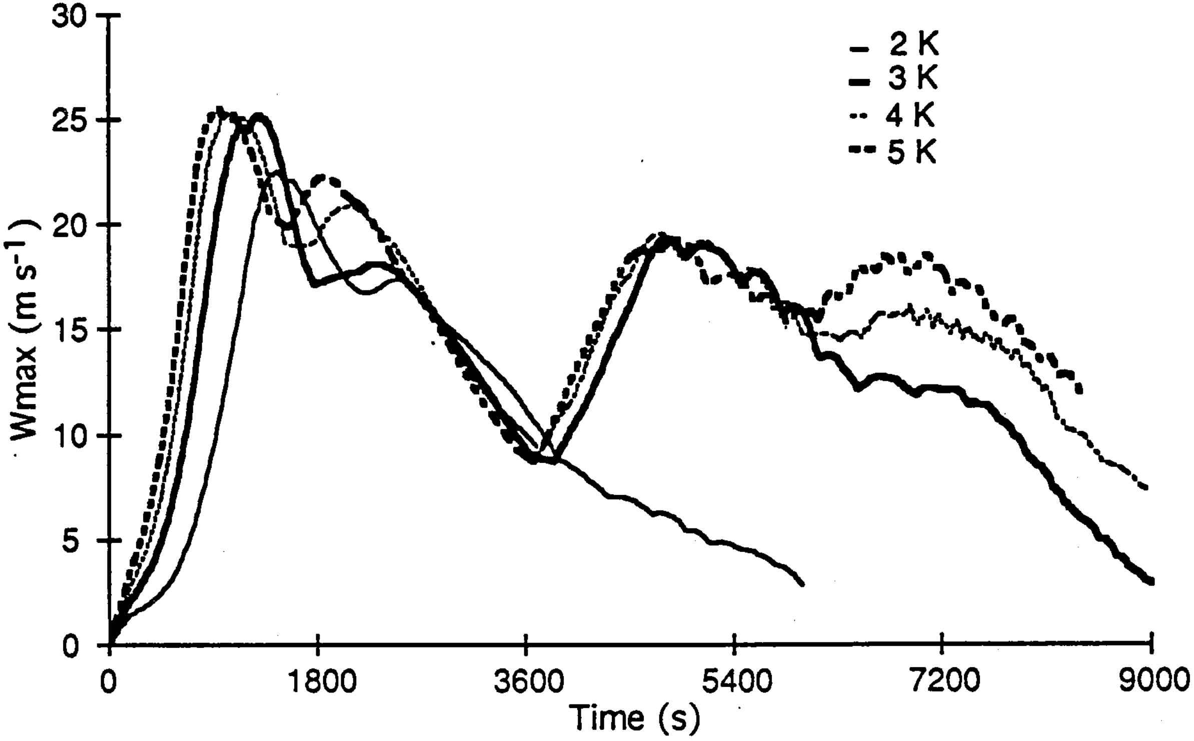

Fig. 3. Maximum updraft versus time for 1 km resolution simulations with center of 10 km radius bubble at 2.4 km for maximum temperature perturbations from 2 K to 5 K.

when viewed in hindsight, being aware of the different evolutions the storms would take. If one compared the storms at, say 2400 s, the conclusion would be that they are qualitatively the same storm. This represents a crucial difference between research and operational needs for modelling, since the operational community does not have the luxury of knowing the outcome of the forecast when they make it.

2.3 Sensitivity to bubble location

As stated before, one of the major problems facing numerical modellers of severe convection has been the difficulty in simulating storms in high-LFC environments. Given the existence of a long-lived, albeit relatively weak, storm in the 2-km simulations when the bubble was raised, a series of simulations was carried out moving the center of the bubble from 1.4 km to 2.4 km altitude and varying θ_{max} from 2 K to 2.5 K (Fig. 4). As the bubble is raised, the storms' longevity increases. Further, secondary storms develop with the warmer bubble at the two heights above 1.4 km. In order to get long-lived convection in the KW model, it is necessary to have a significant fraction of the thermal perturbation located at or above the LFC. Since the initialization is not physically realistic, it is impossible to do more than speculate about the relevance of this to the atmosphere. It may imply that, on days with high LFCs, mesoscale processes must be stronger in order to get convection initiated.

A particularly interesting pair of simulations is the 2.5 K bubble at 1.9 km and the 2.0 K bubble at 2.4 km. The two updrafts grow in an almost identical fashion over the first 1600 s, reaching peak values less than 1 m s^{-1} different. Both updrafts then decay to less than 10 m s^{-1}. In the case of the warmer, low bubble, a second updraft forms about 4200 s into the simulation, while the cooler, high bubble continues to weaken and no redevelopment occurs. This represents a pathological case in which the two storms develop along very similar paths for over an hour before the solutions diverge.

2.4 Sensitivity to bubble shape

Perhaps the most significant aspect of the simulations is a set in which the maximum thermal perturbation (2.5 K) and total buoyancy within the bubble is kept constant and the bubble is centered at the same location (2.4 km) in all cases. This is done by keeping the quantity, $h_{rad}^2 z_{rad}$, constant at 140 km^3, so that a bubble with a horizontal semiaxis of 10 km has a vertical semiaxis of 1.4 km, as in the original Weisman and Klemp (1982) study. Five simulations, with h_{rad} varying from 8 km to 16 km (z_{rad} varies from 2.2 km to 0.547 km), make up the set (Fig. 5). As the bubble becomes 'flatter' (h_{rad} increases and z_{rad} decreases), initial updrafts grow more rapidly. All of the storms, except the flattest one, produce a secondary storm on the outflow. The weakest secondary storm is associated with the 'tallest' bubble (h_{rad} = 8 km), which was the storm with the strongest initial updraft. The strongest secondary storm, however, is found in the case with the 10 km bubble, which had the second strongest initial updraft. Secondary storm updraft strength does not vary monotonically with the horizontal extent of the bubble. Instead, the strongest updrafts are found in an intermediate range of bubble size. This suggests that errors of either sign in the initial specification might lead to underprediction of the intensity of convection in this case. Other environmental conditions or initiation techniques might lead to other kinds of errors.

3. IMPLICATIONS FOR THE OPERATIONAL COMMUNITY

3.1 Use of radar observations

The growing availability of Doppler radar data for operational forecasting and warning responsibilities will allow the meteorological community to see thunderstorms with more detail than ever before. One of the critical issues that faces the field is the ability to anticipate thunderstorm development and to warn on severe weather events with sufficient lead time and accuracy for the public to respond. The sensitivity of the numerical model results to thermal perturbations may help provide guidance on the limits on that ability and indicate potential problem areas. Perhaps most important aspect is the ability of radar to see critical regions of storm development. Over most of its useful range of 240 km, the United States National Weather Service WSR-88D and similarly configured Doppler radars will be unable to distinguish between perturbations as different as the two extreme shapes discussed in the previous section (Fig. 6). As a result, if they were to occur in the atmosphere, the initial stages of development of the all of the simulated storms shown in Fig. 5 would be indistinguishable to the most advanced operational radars under

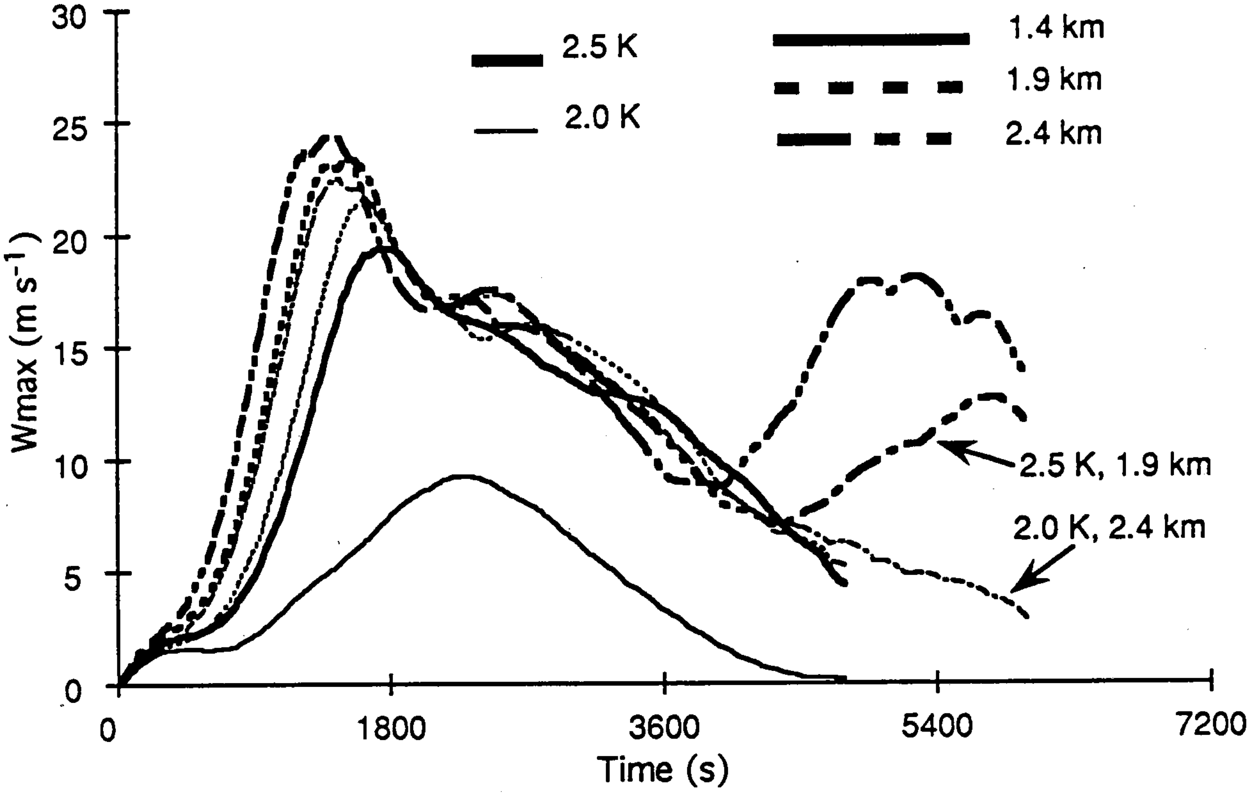

Fig. 4. Maximum updraft versus time for 1 km resolution simulations with 10 km radius bubbles and various maximum temperature perturbations and heights of center of bubble. Light lines for 2 K perturbation. Heavy lines for 2.5 K. Solid line for 1.4 km center, short dash 1.9 km, long and short dash 2.4 km.

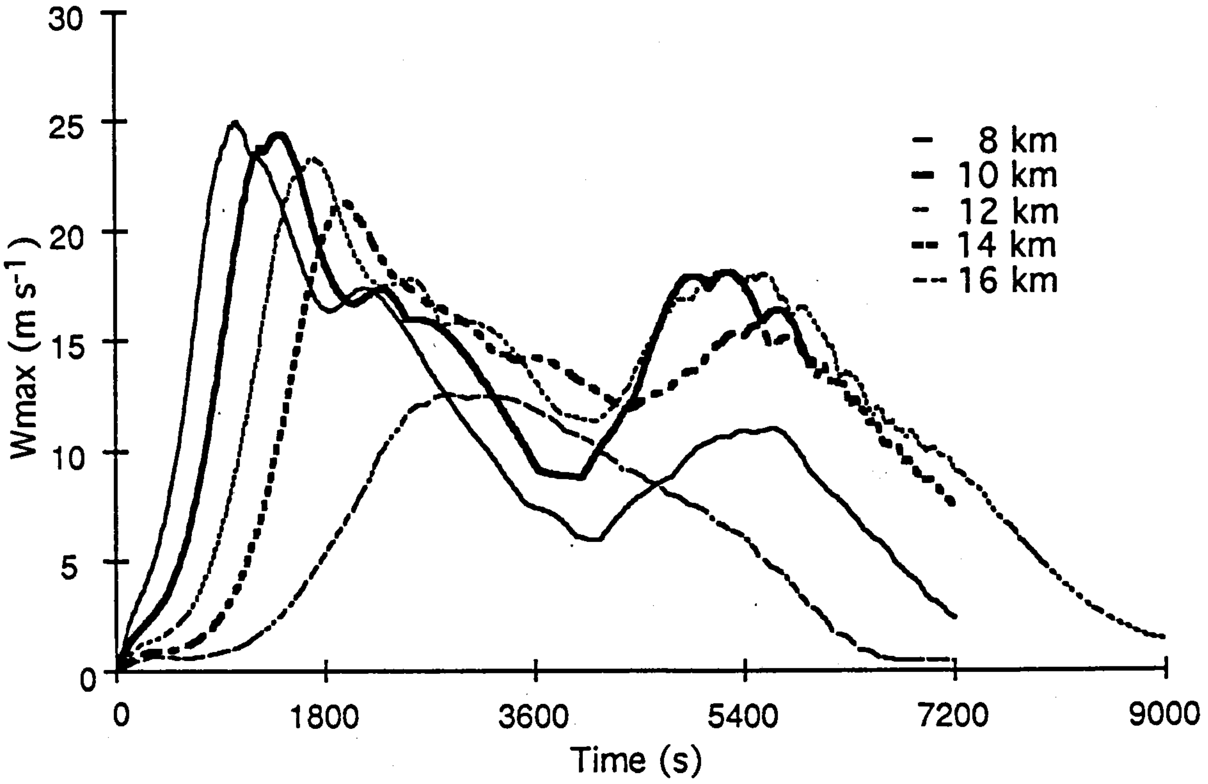

Fig. 5. Maximum updraft versus time for 1 km resolution simulations for 2.5 K bubbles centered at 2.4 km as horizontal radii varies. Vertical semiaxis varied to keep integrated buoyancy constant in all cases.

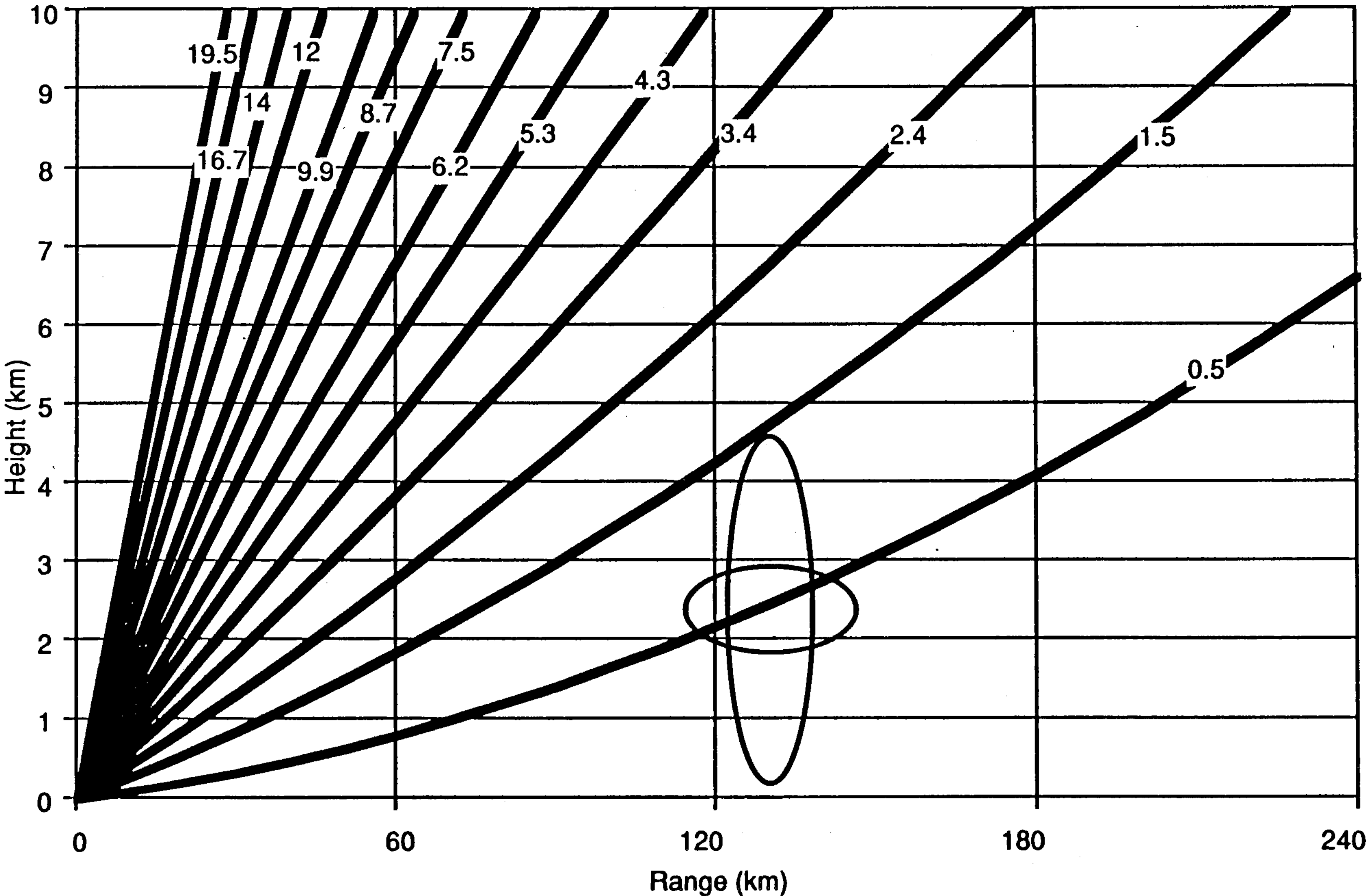

Fig. 6. Height versus distance plot of scans from one strategy for U.S. WSR-88D Doppler radars. Superimposed on scans are outlines of "widest" (horizontal semiaxis of 16 km) and "narrowest" (horizontal semiaxis of 8 km) bubbles discussed in section 2.

current scanning strategies. Furthermore, unless the storms were very close to the radar, the small differences in the storms that determine if there will be secondary development of new storms would be undetectable to the radar.

3.2 Use of numerical models

These results indicate the sensitivity of numerical thunderstorm models to their initiating impulse extends beyond the first updraft to include subsequent storm developments. Not only is the model sensitive on short time scales, it is also sensitive on long time scales, *even in cases where the sensitivity on the short time scale is small.* Droegemeier (1990) has proposed that Doppler radar data could be used to initialize numerical models of thunderstorms in an operational environment. Ignoring for the moment the questions of implementation, data quality, and difficulties of using single-Doppler data to determine three-dimensional wind, pressure, and temperature data, the results here raise serious doubts about the feasibility of this approach. Clearly, differences on scales finer than can be detected by Doppler radar over most of its range lead to significant changes in the evolution of the storms in the numerical model. Thus, even though cloud-scale numerical models are capable of reproducing a wide range of severe thunderstorm behavior, and have been shown to have some potential value in operational forecasting (Brooks et al. 1992b), it is very doubtful that that value lies in explicit prediction. Approaches other than explicit prediction need to be explored in the next few years so that operational implementation of small-scale models follows the development of the technology required to produce timely, small-scale forecasts.

4. CLOSING THOUGHTS

The underlying question that has not been answered here is the issue of storm initiation in the atmosphere. Even the most sophisticated technique used in numerical models is simple compared to the range of mechanisms that may be involved in initiating real storms. For some aspects of severe storm research, such as the development of a low-level mesocyclone within a mature supercell thunderstorm, details about how the thunderstorm is initiated may not be significant. For other aspects and for explicit prediction in an operational setting, however, the initiation is crucial. The deployment of new sensing systems, such as Doppler radars and wind profilers, along with long-term mesonetworks of surface stations, such as the Oklahoma mesonetwork, in which automated surface observing stations will be installed in every county in the state (Crawford et al. 1992), will provide valuable information that may help in studying the storm initiation problem, but solutions are not likely in the near future.

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