variables were used in the subgrid-scale mixing scheme (following the methodology of Stauffer et al. 1999). The results using these conservative variables were nearly identical to simulations that mix potential temperature and water constituents separately. An important result of our experiments with different formulations of turbulent mixing was that stronger mixing helps reduce the magnitude of the θ_e problem. In fact, by using large mixing parameters that are still within acceptable ranges, we were able to make the θ_e problem disappear. However, increased mixing is not necessarily desirable, since it damps the "real" meteorological features in the model. And even though enhanced mixing can make the θ_e problem go away, it does not tell us what is causing the problem.

3. ANALYSIS OF THE θ_e PROBLEM

Figure 2 shows a vertical cross section through the simulated thunderstorm. The shaded areas represent θ_e greater than the initial maximum value of θ_e. Notice how $\theta_{e\text{-max}}$ occurs inside the core of the growing cloud. In fact, the unphysically high values of θ_e always appear during rapid growth of the updraft (Fig. 3). Soundings from within the developing cloud are shown in Fig. 4. After the cloud top reaches the tropopause, and a nearly steady-state thunderstorm has been established in the model, the abnormally high $\theta_{e\text{-max}}$ is mixed away, and an approximately moist adiabatic lapse rate exists throughout the cloud.

The maximum updraft in this control simulation is 58.8 m s^{-1}. Since the CAPE of the initial sounding (with the warm bubble) is 2523 J kg^{-1}, the theoretical maximum possible updraft in this

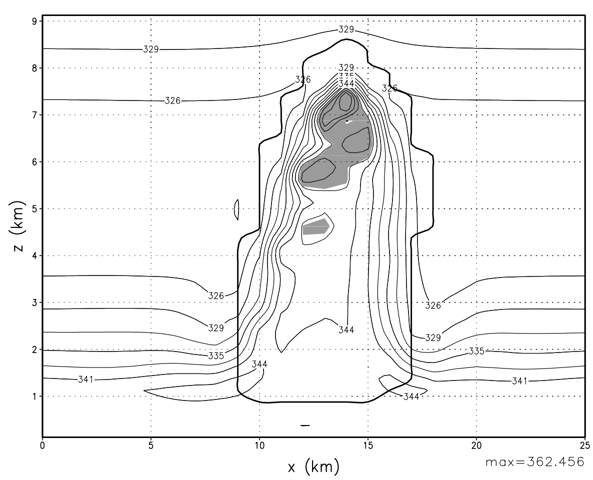

Fig. 2. *Cross section through the simulated thunderstorm, where θ_e is contoured every 3 K, shading represents θ_e > 347.4 K, and the thick contour is the cloud boundary.*

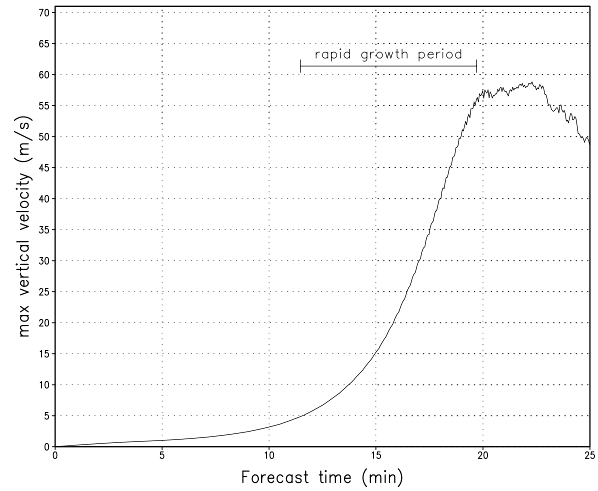

Fig. 3 *Time series of maximum updraft velocity (m s^{-1}).*

environment is 71 m s^{-1}. Recall that a CAPE-based theoretical maximum updraft assumes that ascent of a parcel is not affected by mixing or water loading; therefore, it is always a gross overestimate of actual updraft strengths. MM5 accounts for both water loading and turbulent mixing. The fact that the simulated cloud updraft is 83% of the maximum possible intensity is disturbing. In fact, a simulation in which water loading was neglected (but turbulent mixing was still included) produced a maximum updraft of 77.83 m s^{-1} – almost 7 m s^{-1} higher than theoretically possible!

As mentioned in the introduction, the θ_e problem is not unique to MM5. To see if a different cloud model produces this feature, we performed the same experiment with the Advanced Regional Prediction System (ARPS). Although the theoretical formulations of ARPS and MM5 are very similar, ARPS was specifically designed as a cloud model: the main differences between the two models are the numerical techniques used to integrate the primitive equations. Table 1 compares simulations from

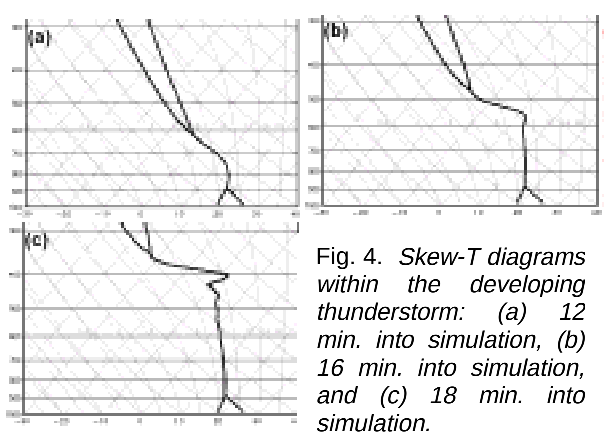

Fig. 4. *Skew-T diagrams within the developing thunderstorm: (a) 12 min. into simulation, (b) 16 min. into simulation, and (c) 18 min. into simulation.*