UNPHYSICAL THERMODYNAMIC STRUCTURES IN EXPLICITLY SIMULATED THUNDERSTORMS

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1. INTRODUCTION

This paper documents a peculiar thermodynamic feature that appears during cloud-scale ($\Delta x \leq 4$ km) simulations of cumulonimbus clouds in MM5 (*and other cloud-scale models*). Figure 1 presents the maximum value of equivalent potential temperature ($\theta_{e\text{-}max}$) below 300 mb from a simulation of a single-cell thunderstorm (details of the experiment will be described in section 2). Note how $\theta_{e\text{-}max}$ begins to drop at the beginning of the simulation due to turbulent mixing. After about 15 minutes, however, $\theta_{e\text{-}max}$ increases rapidly. In fact, $\theta_{e\text{-}max}$ rises well above the initial value of 347.4 K. The highest value of θ_e during the simulation is 363.9 K. This exceptionally large value of θ_e produced by the model is very disturbing.

This "θ_e problem" was found in MM5 simulations with every available microphysics scheme, and with every available PBL scheme. Simulations with a subgrid-scale turbulence scheme that is more appropriate for cloud-scale resolution (Bryan and Fritsch 2000) also contain the θ_e problem. Since every physics option tested in MM5 produced the θ_e problem, it seems likely that the numerical techniques used to solve the model equations are responsible for this unphysical evolution. We suspect that at least two components of the model contribute to and help magnify the θ_e problem.

2. DESCRIPTION OF SIMULATIONS

All MM5 simulations presented in this paper are performed on a domain of 64x64 grid points in the horizontal with 1 km grid spacing. There are 70 vertical levels with a constant grid spacing of 250 m. The warm rain microphysics option is used. Surface fluxes of heat, momentum, and moisture, the Coriolis terms, curvature terms in the momentum equations, and map scale factors are neglected.

The analytic temperature and moisture profiles from Weisman and Klemp (1982) are used to define a horizontally homogeneous initial state. The initial wind profile is unidirectional, with wind speed increasing linearly from –5 m s^{-1} at the surface to +5 m s^{-1} at 10 km. Clouds are initiated with a warm bubble that has a temperature perturbation of 1 K at the center. The θ_e problem also appears with different bubble strengths, and in simulations initialized with observed conditions.

Periodic lateral boundary conditions are used for these experiments. Although these boundary conditions are not ideal for thunderstorm simulations on such a small domain, this specification allows for direct comparison of simulations with different dynamics or numerical techniques in the interior of the domain. Other boundary conditions that are flow dependent (e.g., radiative boundary conditions) may affect the evolution of the storm by enhancing outflow/inflow at the lateral boundaries. We have also performed simulations with different types of open radiative boundary conditions; all produce the θ_e problem.

Unless stated otherwise, the turbulent mixing scheme used in these experiments is a slightly modified version of the "free-atmosphere" mixing in the Blackadar PBL code. Although this turbulence closure underestimates the effects of turbulent mixing at cloud-scale resolution, a new scheme with stronger mixing (Bryan and Fritsch 2000) helps to mix away the anomalously high θ_e and reduce its effect on the simulation. We have also designed experiments in which conservative

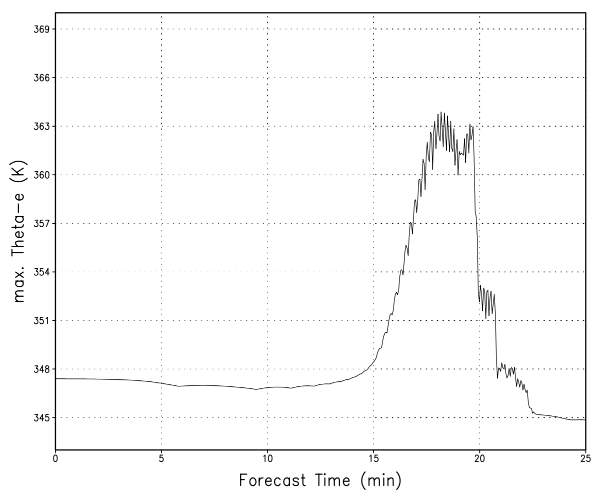

Fig. 1 *Time series of maximum θ_e below 300 mb during the simulation of a single-cell thunderstorm.*

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