10.2 ON ADEQUATE RESOLUTION FOR THE SIMULATION OF DEEP MOIST CONVECTION: THEORY AND PRELIMINARY SIMULATIONS

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1. Introduction

The proliferation of inexpensive high-performance computer workstations, massively-parallel architecture, and distributed-memory codes is accelerating interest in cloud-scale modeling. It is also creating an opportunity to explore the model configuration requirements for accurately simulating moist convective processes. Presently, 1 km horizontal grid spacing is commonly applied for convective cloud simulations. With this resolution, the thunderstorm and its main features (updraft, downdraft, etc.) are crudely represented. However, the commonly observed subcloud-scale rotating eddies (about 1 km in scale) that comprise much of the makeup of convective clouds are not accounted for. It is not clear if these structures affect the fidelity of the overall storm simulation.

Before examining this issue further, it is noteworthy that a number of recent studies are already using resolutions better than 1 km (e.g., Finley et al. 2000, McCaul and Cohen 2000, Niino and Noda 2000). Much of the motivation for the shift toward higher resolutions stems from an interest in understanding various components of convective storms, i.e., understanding sub-cloud-scale features and processes. For example, Adlerman and Droegemeier (2000) were interested in understanding the relationship between the cyclic mesocyclone and cyclic tornado scales. To explore such an issue, it was necessary to resolve shallow, low-level, sub-cloud-scale vortices that formed and dissipated on time scales on the order of a few minutes. By increasing the horizontal resolution to approximately 100 m, Adlerman and Droegemeier found that the general structure of the storm remained similar to coarser-resolution simulations, however, there were significant differences in the size of certain sub-cloud-scale features and that, overall, the process appeared to be accelerated. The differences in the simulations occurred in a relatively short period of time (≈ 2 h) and lead one to wonder how *the cumulative effect* of such differences, when occurring over time periods of 6 h or more and distances of 100 km or more, would change the structure, dynamics and evolution of mesoscale convective systems? Could it be that the size and amplitude of features such as mesohighs, mesolows, mid-level vortices and rear-inflow jets would differ significantly? Would the phase speed, total precipitation and the distribution of precipitation of convective systems be altered?

Recent studies such as Adlerman and Droegemeier (2000) suggest that the concerns raised here are becoming an important issue to an increasing fraction of the numerical modeling community. We believe this is for good reason. Consider the following analogy: It is possible to *resolve* mesoscale convective systems using 20 km grid spacing but, unless the effects of subgrid-scale moist convective updrafts and downdrafts are included (parameterized), it is not possible to *simulate* mesoscale convective systems. For thunderstorms, the analogous statement would be: It is possible to *resolve* individual thunderstorms with 1 km grid spacing but, unless the effects of subgrid-scale turbulent processes are included, it may not be possible to *simulate* thunderstorms. Therefore, the issue of whether or not subcloud-scale eddies are important has taken on additional relevance and a clear theoretical framework to guide the modeling community in configuring cloud models in a manner which will include turbulent processes is desirable.

Section 2 presents a theoretically based argument for specifying the resolution necessary to capture turbulent processes in cloud model simulations. The model configuration for our numerical simulations is detailed in Section 3. Some preliminary results showing how the character of the flow changes as the grid spacing becomes appropriate for large-eddy simulation are presented in Section 4. A brief summary follows in Section 5.

2. Subgrid-scale Turbulence

All models that have grid spacing larger than the Kolmogorov microscale require a subgrid-scale turbulence scheme. For most free atmospheric flows, this means that models with grid spacing larger than roughly 1 cm must parameterize the effects of subgrid-scale motions

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(i.e., turbulence). This condition arises because the viscous term in the Navier-Stokes equation is very small and, therefore, negligible when the grid spacing is larger than the Kolmogorov microscale. It is important to note that this term becomes negligible only through scale analysis. It actually accounts for an important physical process – kinetic energy dissipation – that cannot be neglected.

One way to include the effects of viscous dissipation in numerical models without actually having the viscous term is through large eddy simulation (LES). A complete treatment of LES models is not possible here, so the reader is referred to Wyngaard (1992). For the purposes of this work, it is sufficient to present two of the basic underlying assumptions of LES:

Assumption 1: The grid spacing (Δ) is within the inertial subrange; and
Assumption 2: The scale of the largest resolved eddies (L) is much larger than the grid spacing (Δ)*.

Since the subgrid turbulence schemes from LES have been included in cloud models for decades, it is important to review whether assumptions such as these are even valid for cloud models with $\Delta \cong 1\,\mathrm{km}$.

The first assumption assures that the simulation contains the *largest turbulent eddies*, which are the eddies that contain most of the kinetic energy in turbulent flows. In the inertial subrange, energy is transferred from these large eddies to much smaller scales. Ultimately, this energy is dissipated by eddies the size of the Kolmogorov microscale. In LES, it is sufficient to resolve the large energy-containing eddies, while parameterizing the rate of energy transfer to subgrid scales. In other words, LES assumes that one end of this "energy cascade" is actually resolved on the model grid, and the other end can be parameterized. It is unclear whether cloud-resolving models with $\Delta \cong 1\,\mathrm{km}$ satisfy assumption #1. Droegemeier et al. (1994) did not find a clear inertial subrange in their simulations of supercell thunderstorms, even with grid spacing of 250 m.

The second assumption is NOT a statement of resolution, i.e., it is not simply stating, "make sure that the feature you wish to simulate is well resolved." Rather, assumption #2 is *required in order for the flow to be turbulent*. Assumption #2 is essentially a property of the subgrid-scale turbulence closure that is used by LES. It can be shown that, if a LES subgrid model is used, the Reynolds number (R_e) of the simulated flow is dictated only by L and Δ, i.e.,

$$R_e \cong \left(\frac{L}{\Delta}\right)^{\frac{4}{3}}$$

(Wyngaard 1982). In boundary layer modeling with LES, L ~ 1000 m (the boundary layer depth), and Δ ~ 10 m (a typical grid spacing). Since L/Δ ~ 100, assumption #2 is satisfied, R_e is large, and the flow will be turbulent.

For many cloud modeling studies, L ~ 10 km (a typical depth and width of a thunderstorm), and Δ ~ 1 km. Therefore, in these cloud models, L/Δ is about 10. Considering that Δ is slightly larger than model grid spacing (see footnote), this ratio is actually less than 10, indicating that a*ssumption #2 is not satisfied for cloud models with 1 km grid spacing*. Thus, the Reynolds number cannot be much larger than 10, *and the flow cannot become turbulent.*

Considering that an L/Δ ratio of about 100 works well for studies of the planetary boundary layer, it is reasonable to use this relationship as guidance for the cloud modeling community. For L ~ 10 km, the relationship suggests that *100 m grid spacing may be necessary for the LES subgrid models to be appropriate for simulating deep moist convection.*

3. Model configuration

Based on the arguments in section 2, we are conducting numerical simulations with grid spacing as small as 100 m. The numerical model is a three-dimensional, nonhydrostatic, compressible cloud model that has been developed at Penn State. The governing equations are integrated using the Runge-Kutta technique of Wicker and Skamarock (1998). Further details can be found at the following web site:
http://www.ems.psu.edu/~bryan/model.

The simulations presented in this paper use the Kessler (1969) microphysics scheme that includes only warm rain processes. Ice processes were neglected due to limited computer resources – simulations with a mixed phase microphysics scheme are planned.

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* Actually, Δ should be the model's filter scale, not the model's grid spacing. Typically, the filter scale is slightly larger than the grid spacing, but of the same order of magnitude. For this discussion, we will assume that the filter scale and the model grid spacing are approximately equal.

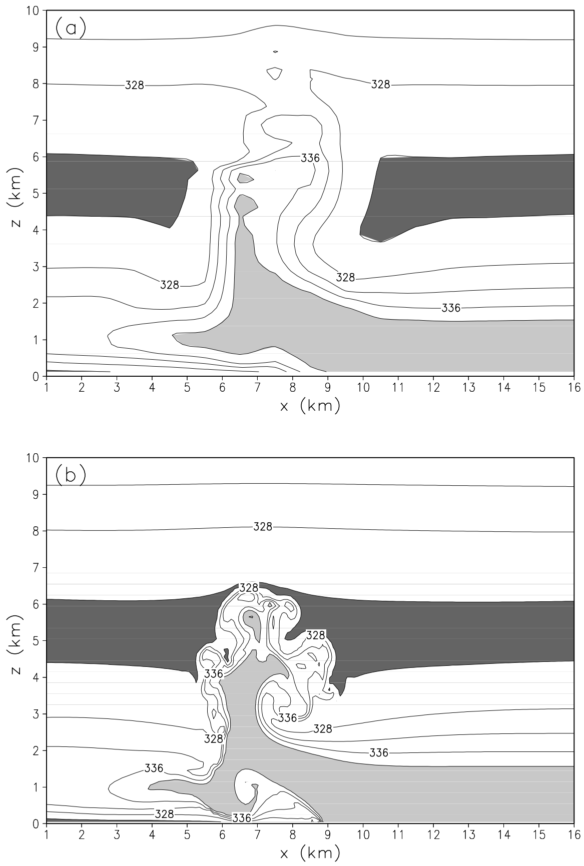

Fig. 1 Cross sections of equivalent potential temperature (K) after 15 minutes from (a) a simulation with 1 km horizontal grid spacing, and (b) a simulation with 100 m grid spacing. Contour interval is 4 K. Dark shading shows values less than 324 K, and light shading shows values greater than 340 K.

The subgrid turbulence parameterization is very similar to the one presented in Klemp and Wilhelmson (1978). Certain parameters in the turbulence scheme are set according to the results of Moeng and Wyngaard (1988).

The domain for these experiments is 24x24 km in the horizontal dimensions and 20 km deep. The west and east boundary conditions are open, and the north and south boundary conditions are periodic. The analytic temperature and moisture profiles of Weisman and Klemp (1982) were used to define a horizontally homogeneous environment, with the exception of a cold pool 2.5 km deep that extends from the west boundary to 7.5 km into the domain. To ensure the development of three-dimensional structures, random temperature perturbations less than 1 K are placed along the eastern edge of the cold pool. The initial wind profile is similar to the one used by Weisman et al. (1997).

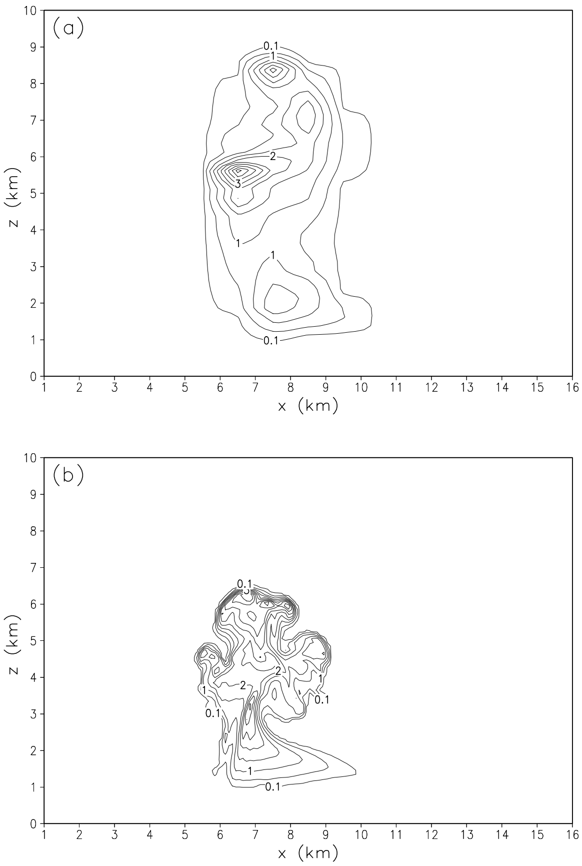

Fig. 2 Cross sections of cloud water mixing ratio (g kg^{-1}) after 15 minutes from (a) a simulation with 1 km horizontal grid spacing, and (b) a simulation with 100 m grid spacing. Contour interval is 0.5 g kg^{-1}. The 0.1 g kg^{-1} contour is also included.

Two simulations are compared in this paper. One has a horizontal grid spacing of 1 km and vertical grid spacing of 250 m, and will be referred to as the low-resolution simulation. The other simulation has horizontal and vertical grid spacing of 100 m, and will be referred to as the high-resolution simulation.

4. Preliminary Results

Figure 1 shows a cross section of equivalent potential temperature (θ_e) 15 minutes into the simulations. In the low-resolution simulation, the main updraft is poorly resolved (only about 6 grid points across) and most of the θ_e structure is smooth and essentially vertical. In contrast, the updraft in the high-resolution simulation contains significantly more structure, including sub-cloud-scale eddies along the sides and at the top. The structure of the surface-based cold pool is markedly different in the two runs. In particular,

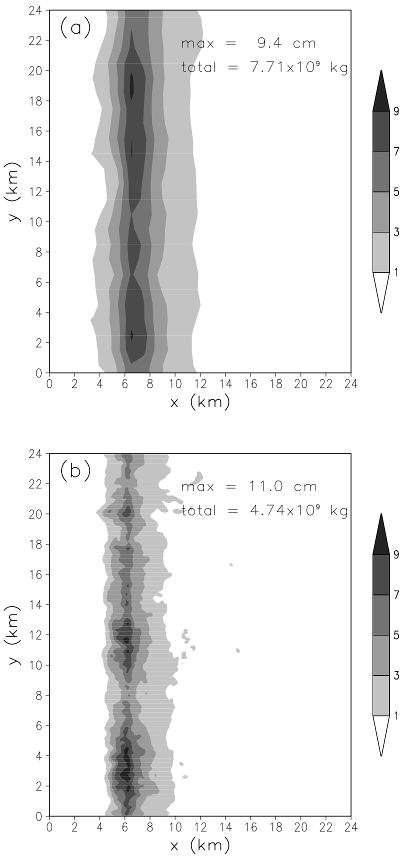

Fig. 3 Accumulated rainfall (cm) after 1 hour from (a) a simulation with 1 km horizontal grid spacing, and (b) a simulation with 100 m grid spacing. The maximum value (in cm) and the total domain-wide precipitation (in kg) are included.

note the plume of high θ_e air transported downward to the surface behind the gust front in the high-resolution simulation.

A cross section of cloud water mixing ratio (q_c) at the same time and location is presented in Fig. 2. Cloud top in the low-resolution simulation is more than two km higher than in the high-resolution simulation. Significant structural differences are also apparent, such as the character of cloud base, the maximum value of q_c in mid-levels, and the gradients along the cloud edges.

Most importantly, as it relates to the discussion in Section 2, the flow in the high-resolution simulation is considerably more turbulent than the flow in the low-resolution simulation. In our previous simulations of thunderstorms with roughly 1 km grid spacing, the main thunderstorm features and circulations tend to be laminar, i.e., they do not appear turbulent like real clouds. This observation holds for our simulations of several types of thunderstorms, including supercells, multicells, and thunderstorms embedded within mesoscale convective systems.

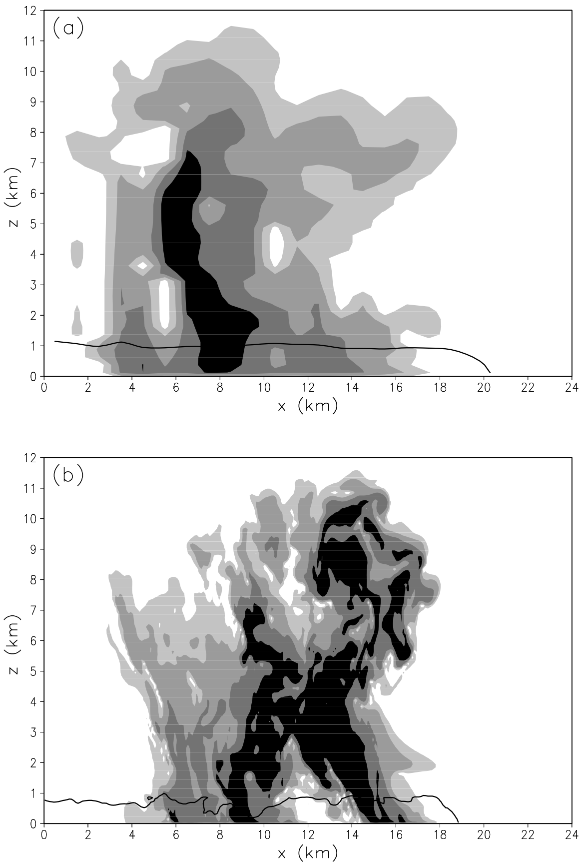

Figure 4. Cross sections of reflectivity (dBZ) 1 hour into the simulations. (a) Simulation with 1 km horizontal grid spacing, and (b) simulation with 100 m grid spacing. The four levels of shading correspond to, from lightest to darkest, 10-25, 25-40, 40-50, and > 50 dBZ. The thick black line is the 299 K potential temperature contour, which represents the approximate position of the cold pool.

Figures 1 and 2 show how different the simulations can become on very short time scales. After 1 hour, the differences become even more pronounced. For example, a plot of accumulated rainfall after 1 hour is presented in Fig. 3. The low-resolution simulation produces a maximum rainfall value of 9.4 cm, which is considerably less than the maximum of 11.0 cm in the high-resolution simulation. Even more interesting, the total domain-wide precipitation is much higher (about 60%) in the low-resolution simulation.

A cross section of estimated reflectivity after one hour is shown in Fig. 4. There are two cores of maximum reflectivity in the high-resolution simulation, as opposed to only one in the low-resolution simulation. Interestingly, one core of precipitation is falling at the surface only 2 km behind the gust front in the high-resolution simulation, while the only core in the low-resolution simulation is about 12 km behind the gust front.

5. Summary

These preliminary results indicate that much higher resolution than the approximately 1 km grid spacing used in many current cloud-scale models may be needed to fully simulate moist convective processes. An examination of the subgrid-scale turbulence closures used in most cloud models, combined with preliminary simulations, suggests that 100 m grid spacing is needed in order for the flow to become turbulent. Significant structural differences are seen in a simulation of a squall line after only 1 hour. The simulations suggest that specific details of thunderstorms (such as cloud-top height, the value of θ_e within moist downdrafts, and precipitation) will continue to be a forecast challenge due to uncertainties in model configurations – even if perfect initial conditions are supplied to the model.

It is important to realize that differences in solutions do not necessarily arise simply because cloud-scale features are resolved better with 100 m grid spacing. Rather, as model simulations encroach into the sub-100 m resolution range, it becomes possible for the flow to become turbulent – and *the addition of turbulence changes the physics of the convective process*.

We expect to conduct still higher resolution simulations than the preliminary experiments presented here, to extend these simulations to larger domains and over longer time periods, and to examine how the cumulative effects of including turbulent eddies affect the internal structure and dynamics of moist convective systems.

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