J4.4 GRID-SIZE DEPENDENCE OF CUMULUS PARAMETERIZATION

Steven K. Krueger and Yali Luo *
University of Utah, Salt Lake City, Utah

1. INTRODUCTION

The horizontal grid size in NWP models will continue to decrease. For example, it is now 40 km in the ECMWF model, and even less in many regional models. There are many reasons to decrease the horizontal grid size in LSMs. In general, as the grid size decreases, small-scale processes become better resolved so that the need to parameterize subgrid-scale processes also decreases. Stratiform cloud formation is one example. As the grid size decreases, the cloud fraction (i.e., cloud amount at a given level) tends towards a bimodal, 0 or 1, distribution, as shown in Table 1, which reduces the need to parameterize cloud fraction and cloud overlap.

In particular, as the grid size decreases, the processes that determine the location, timing, and intensity of convective rainfall should become better resolved, which should improve forecasts of convective precipitation. Triggering of convection will be better represented, due to increased resolution of mesoscale boundary-layer circulations, such as sea breezes, orographic circulations, and convective outflows. As the horizontal grid size decreases, many of the processes that determine the structure of mesoscale convective systems (MCSs) will also be better resolved. These processes include the interaction of vertical shear of the lower tropospheric horizontal wind with cold pools produced by evaporation of convective precipitation. This process is important for the formation and longevity of some types of squall lines (Rotunno et al. 1988).

However, until horizontal grid sizes decrease to 4 km or less, cumulus convection will still need to be parameterized (Weisman et al. 1997). As horizontal grid sizes decrease, parameterized convection becomes more localized. That is, a smaller fraction of the grid columns are *convective columns* (i.e., columns that contain areas of cumulus convection) and these columns include larger fractional areas of cumulus convection. What are the implications for cumulus parameterization as horizontal grid size decreases and convection becomes more localized? Can we quantify the implications? Do some aspects of the cumulus parameterization for large-scale models described in section 2 become inappropriate as horizontal grid size decreases? If so, which ones?

The basic idea of a LSM cumulus parameterization is that a grid column contains an ensemble of cumulus clouds and that the fractional area covered by the active cumulus updrafts is small. In this case, the primary large-scale effects of the cumulus ensemble, heating and drying due to cumulus-induced subsidence and moistening due to cumulus detrainment, are assumed to be distributed over the area of the grid column. In reality, the subsidence would spread over a Rossby radius of deformation. However, the horizontal variations of cumulus ensemble activity are assumed to be small because horizontal grid size is assumed to be much smaller than the size of large-scale disturbances. In addition, the horizontal grid size is large enough so that the parameterized cumulus convection is not localized. In effect, it is assumed that there are only two scales: cumulus scale and large scale,with a clear separation between them.

Table 1. Frequency of occurrence of clear (cirrus cloud amount $< 5\%$) and overcast (cirrus cloud amount $> 95\%$) conditions versus horizontal grid size, as simulated by a cloud resolving model with 2-km horizontal grid size. The average cirrus cloud amount was 38%.

grid size (km)	clear frequency (%)	overcast frequency (%)
512	22	8
256	28	9
128	36	12
64	44	17
32	49	22
16	55	29

As the grid size decreases and the mesoscale is resolved, the scale separation between resolved scales and cumulus scale becomes indistinct. However, if the cumulus parameterization problem is recast to one of localizing the convection, but still determining its intensity based on the closure principles used for LSM cumulus parameterization, the problem may be simpler and more tractable. The basis for this is the observation that, although the cumulus updrafts are localized, dry adjustment quickly distributes their subsidence effects over a large-scale area (a Rossby radius of deformation).

If a goal of reducing the horizontal grid size is to improve convective precipitation forecasts, then one must more accurately predict the occurrence of mesoscale convective systems (MCSs). To do this requires parameterizing the cumulus heating so that it resembles the actual mesoscale patterns of time-averaged convective heating (Pandya and Durran 1996). It also appears necessary to detrain a fraction of the parameterized cloud and precipitation particles to the grid scale to allow explicit calculation of the slow hydrometeor growth, fallout, and phase changes that are characteristic of MCSs (Molinari and Dudek1992).

Finally, the localization of parameterized convection in mesoscale models will make initiation or "triggering" of convection an important issue. The most difficult aspect of convection initiation seems to be predicting the first convective event in a region because it will by definition be triggered by a non-convective boundary layer convergence zone. The occurrence of such convergence zones is very

* *Corresponding author address:* Department of Meteorology, University of Utah, Salt Lake City, UT 84112. E-mail: skrueger@met.utah.edu

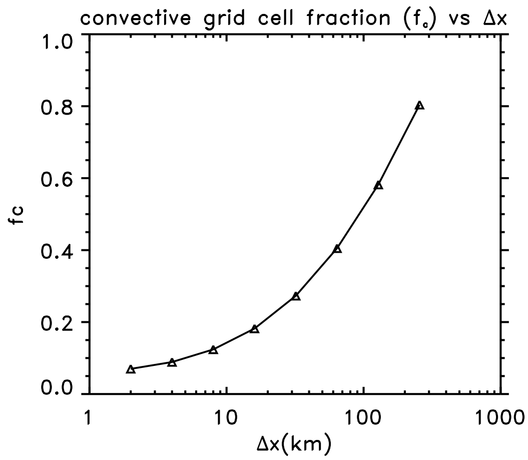

Figure 1: Fraction of grid cells that are convective grid cells for horizontal grid sizes from 2 km to 256 km.

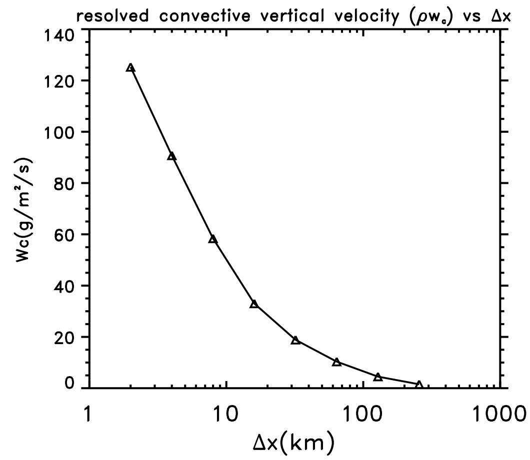

Figure 2: Resolved convective mass flux for horizontal grid sizes from 2 km to 256 km.

difficult to predict.

2. ANALYSIS

We used the results of a 29-day, 2D CRM simulation of mostly deep convective cloud systems over Oklahoma during the summer to quantify the dependence of some aspects of cumulus parameterization on horizontal grid size, at a single level (4.2 km MSL). The CRM's horizontal grid size was 2 km, so that it resolved both the cloud-scale and the mesoscale vertical motions associated with deep convective cloud systems. The cloud-scale vertical motions consist of strong and narrow cloudy updrafts and precipitation-driven downdrafts; they comprise the *convective* portions of a deep convective cloud system. The mesoscale vertical motions consist of broader and slower updrafts and downdrafts associated with the *stratiform* precipitation regions of a deep convective cloud system.

A mesoscale cumulus parameterization attempts to determine the characteristics of the convective portions of a deep convective cloud system. We identified the *convective grid columns* in the CRM simulation using the method of Xu (1995). The convective grid columns are the convective portions of the simulated deep convective cloud systems. Here, a *grid column* refers to an actual grid column in the CRM. A *grid cell* will refer to a hypothetical grid column in a mesoscale or large-scale model; we considered grid cells with horizontal grid sizes that range from 2 km to 256 km. A *convective grid cell* contains at least one *convective grid column.*

The convective grid cell fraction, $f_c(\Delta x)$, is the fraction of grid cells with horizontal grid size equal to Δx that are convective grid cells, when there is at least one convective grid cell in the CRM's 512-km horizontal domain. Figure 1 shows that f_c increases from 0.07 for $\Delta x = 2$ km to 0.80 for $\Delta x = 256$ km. The relationship is approximately

$$f_c(\Delta x) = 0.8\left(\frac{\Delta x}{\text{256 km}}\right)^{1/2},$$

for Δx in km. The total number of grid columns per unit area is proportional to $(\Delta x)^{-2}$. Thus, the number of *convective grid cells per unit area* is proportional to $(\Delta x)^{3/2}$.

Let w be the departure of the vertical velocity from the large-scale average vertical velocity, $w(\Delta x)$ be w averaged over a horizontal distance Δx, and $\bar{w}_c(\Delta x)$ represent the large-scale average of $w(\Delta x)$ over all grid cells of size Δx that are convective. Similarly, let $\bar{w}_n(\Delta x)$ refer to $w(\Delta x)$ averaged over all non-convective grid cells, and $\bar{w}(\Delta x)$ to $w(\Delta x)$ averaged over all grid cells. By the definition of w, $\bar{w}(\Delta x) = 0$. It follows that

$$\bar{w}(\Delta x) = f_c(\Delta x)\bar{w}_c(\Delta x) + (1 - f_c(\Delta x))\bar{w}_n(\Delta x) = 0.$$

Figure 2 shows that the *resolved convective mass flux,* $\rho\bar{w}_c(\Delta x)$, increases rapidly as Δx falls below 32 km. Figure 3 shows that the *resolved non-convective mass flux,* $\rho\bar{w}_n(\Delta x)$, increases slowly in magnitude as Δx falls below 16 km. To convert the mass fluxes into vertical velocities, divide by the density (0.77 kg m^{-3}).

The net upward *cumulus mass flux* at a given level is

$$M_c = \int \rho w \, d\sigma,$$

where

$$\sigma = \int d\sigma$$

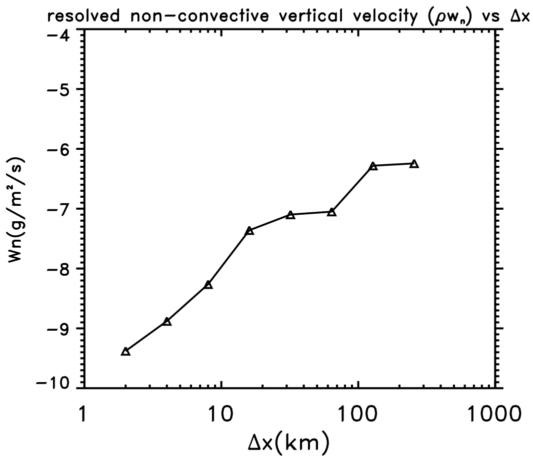

Figure 3: Resolved non-convective mass flux, for horizontal grid sizes from 2 km to 256 km.

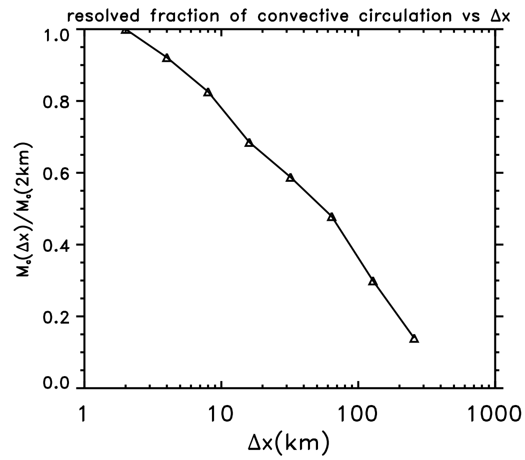

Figure 4: Resolved fraction of convective circulation for horizontal grid sizes from 2 km to 256 km.

is the fraction of the large-scale area covered by active cumulus clouds. We will approximate the area covered by active cumulus clouds by the area occupied by the convective grid columns. Then

$$\sigma = f_c(2 \text{ km})$$

and

$$M_c = \rho f_c(2 \text{ km})\, \bar{w}_c(2 \text{ km})$$

because for $\Delta x = 2$ km, each convective grid cell is a convective grid column. Similarly, the compensating subsidence due to cumulus convection is

$$\tilde{M} = -M_c.$$

Figure 2 shows that as $\Delta x \to 512$ km, $\rho \bar{w}_c(\Delta x) \to 0$, which implies that the compensating subsidence occurs increasingly within the convective grid cells. Conversely, as $\Delta x \to 0$, the active cumulus clouds (convective grid columns) and compensating subsidence tend to occur in different grid cells, and $\rho \bar{w}_c(\Delta x)$ increases toward the limiting value of

$$\rho \bar{w}_c(2 \text{ km}) = \frac{M_c}{\sigma}.$$

This suggests that we define the *resolved cumulus mass flux* as

$$\hat{M}_c(\Delta x) = \rho f_c(\Delta x)\, \bar{w}_c(\Delta x).$$

The *resolved compensating subsidence* is then $-\hat{M}_c(\Delta x)$.

As $\Delta x \to 0$ km, $\hat{M}_c \to M_c$ as the convective circulation becomes increasingly resolved. What is the fraction of the convective circulation that is resolved into its ascending and descending branches by the convective grid cells, as a function of grid cell size? It is

$$\frac{\hat{M}_c(\Delta x)}{M_c},$$

which is shown in Fig. 4.

As $\Delta x \to 512$ km, $\hat{M}_c \to 0$ as the convective circulation becomes increasingly subgrid-scale. What is the fraction of the convective circulation that is subgrid-scale (that is, occurs entirely within the convective grid cells) as a function of grid cell size? It is

$$\frac{M_c - \hat{M}_c(\Delta x)}{M_c} = 1 - \frac{\hat{M}_c(\Delta x)}{M_c}.$$

This is shown in Fig. 5.

An important question for mesoscale cumulus parameterization is: How does the *average convective column fraction* in the convective grid cells depend on Δx? Let $\alpha(\Delta x)$ be the average convective column fraction in the convective grid cells, w_u the average w in convective *columns,* and w_d the average w in non-convective *columns*. Then

$$\rho \bar{w}_c(\Delta x) = \rho \alpha(\Delta x) w_u + \rho(1 - \alpha(\Delta x)) w_d.$$

Note that w_u and w_d are independent of Δx:

$$w_u = \bar{w}_c(2 \text{ km}),$$

$$w_d = -\frac{\sigma}{1-\sigma} w_u,$$

and

$$\sigma = f_c(2 \text{ km}).$$

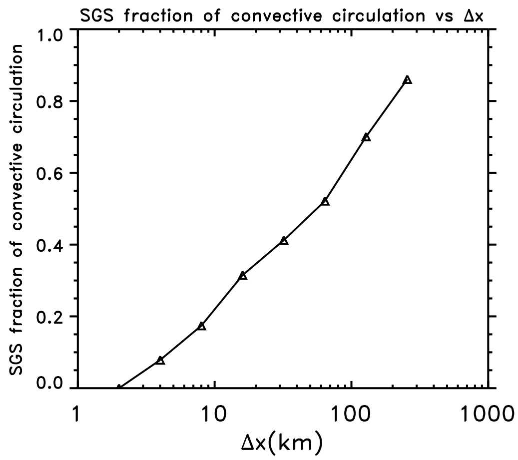

Figure 5: Subgrid-scale fraction of convective circulation for horizontal grid sizes from 2 km to 256 km.

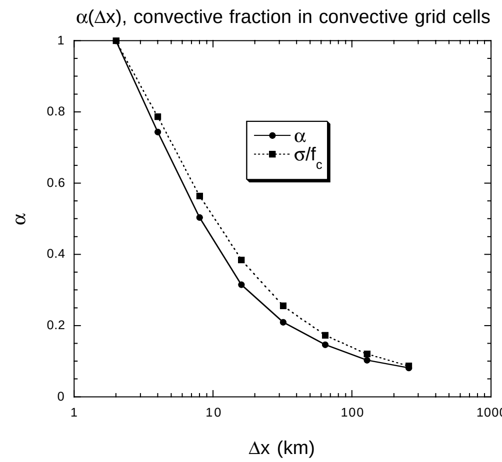

Figure 6: Average convective column fraction in the convective grid cells for horizontal grid sizes from 2 km to 256 km.

From these relations, we can solve for $\alpha(\Delta x)$ in terms of $\bar{w}_c(\Delta x)$:

$$\alpha(\Delta x) = \frac{\frac{\bar{w}_c(\Delta x)}{w_u} + \gamma}{1+\gamma},$$

where

$$\gamma \equiv \frac{\sigma}{1+\sigma}.$$

An approximate relation between α and f_c is

$$\alpha(\Delta x) \approx \frac{\sigma}{f_c(\Delta x)}.$$

Both of these expressions for $\alpha(\Delta x)$ are shown in Fig. 6, which shows that α increases rapidly as Δx decreases below 64 km.

ACKNOWLEDGMENTS. This research was supported by the Environmental Sciences Division of the U.S. Department of Energy (DOE) as part of the Atmospheric Radiation Measurement program, under grant DE-FG03-94ER61769.

REFERENCES

Molinari, J., and Dudek, M., 1992: Parameterization of convective precipitation in mesoscale numerical models: a critical review. *Mon. Wea. Rev.*, **120,** 326–344.

Pandya, R., and Durran, D. R., 1996: The influence of convectively generated thermal forcing on the mesoscale circulation around squall lines. *J. Atmos. Sci.*, **53,** 2924–2951.

Rotunno, R., Klemp, J. B., and Weisman, M. L. , 1988: Theory for strong, long-lived squall lines. *J. Atmos. Sci.*, **45,** 463–485.

Weisman, M. L., Skamarock, W. C., and Klemp, J. B., 1997: The resolution dependence of explicitly modeled convective systems. *Mon. Wea. Rev.*, **125,** 527–548.

Xu, K.-M., 1995: Partitioning mass, heat, and moisture budgets of explicitly simulated cumulus ensembles into convective and stratiform components. *J. Atmos. Sci.*, **52,** 551–573.