ARE THE SUBGRID MIXING SCHEMES IN MM5 ADEQUATE FOR CLOUD-SCALE SIMULATIONS?

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1. INTRODUCTION

Since the hydrostatic Penn State – NCAR mesoscale model series (from MM1 to MM4) was designed and tested primarily for mesoscale resolution (grid spacing > 10 km), there may be assumptions in the nonhydrostatic model (MM5) that do not hold well at cloud-scale resolution (grid spacing ~1-4 km). For example, the subgrid-scale turbulence parameterization may not be suitable for cloud-scale simulations because it is one-dimensional (vertical) and neglects important terms from the three-dimensional turbulence equations. In section 2, the assumptions currently made in MM5 will be compared to assumptions from other cloud models. Then, results from two different turbulence schemes will be presented in sections 3 and 4.

2. TURBULENCE CLOSURE

Consider the Reynolds-averaged Navier-Stokes equation, written in tensor notation (see Stull 1989 for a derivation):

$$\frac{\partial u_i}{\partial t} = -u_j \frac{\partial u_i}{\partial x_j} - \frac{1}{\rho}\frac{\partial p}{\partial x_i} + \delta_{i3} g - \frac{\partial}{\partial x_j}\left(\overline{u_i' u_j'}\right) \qquad (1)$$

where u, p, ρ, and g are, respectively, wind components, pressure, density, and gravity. The Coriolis terms and molecular viscosity have been excluded from (1). Lowercase variables are the “mean” values within a grid box, and primed variables are the unresolved, fluctuating (i.e., turbulent) motions within the grid box. The last term on the right side of (1) represents the flux divergence of momentum due to unresolved (subgrid-scale) motions. Similar terms arise from the other model equations, e.g., the turbulent flux term for potential temperature is :

$$\frac{\partial \theta}{\partial t} = -\frac{\partial}{\partial x_j}\left(\overline{u_j' \theta'}\right). \qquad (2)$$

Note that the turbulent flux divergence terms are actually three terms, e.g., for zonal momentum:

$$\frac{\partial u}{\partial t} = -\frac{\partial \overline{u'u'}}{\partial x} - \frac{\partial \overline{u'v'}}{\partial y} - \frac{\partial \overline{u'w'}}{\partial z}. \qquad (3)$$

These terms are usually parameterized in atmospheric models using “K-theory” (Stull 1989):

$$\frac{\partial u}{\partial t} = \frac{\partial}{\partial x}\left(K_1 \frac{\partial u}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_2 \frac{\partial u}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_3 \frac{\partial u}{\partial z}\right) \qquad (4)$$

where K is an eddy mixing coefficient, which is proportional to subgrid-scale turbulence activity.

2.1 *Assumptions in MM5*

In mesoscale models (such as MM5) it is traditional to ignore the first two terms on the right hand side of (4) for two reasons: 1) horizontal grid spacing is typically one order of magnitude larger that vertical grid spacing, and 2) horizontal gradients of variables within the model (using mesoscale grid spacing) are usually much smaller than vertical gradients. Since the third term in (4) is almost always several orders of magnitude larger than the first two terms with mesoscale grid spacing, the first two terms are neglected to save computations.

At cloud-scale resolution, however, the first two terms on the right hand side of (4) can actually be larger than the third term, and should not be neglected. Not only are the vertical and horizontal grid spacings similar in magnitude, but horizontal gradients become intense at cloud-scale. For example, consider the sides of a cumulonimbus cloud: vertical gradients of wind and temperature may be small, while the horizontal gradients can be large.

Another problem with the application of turbulence closure designed for mesoscale models at cloud-scale resolution is related to the parameterization of the mixing coefficients (the “*K*” terms). Consider the specification for *K* above the boundary layer in the Blackadar PBL code:

$$K = l^2 S^{\frac{1}{2}} \frac{R_{ic} - R_i}{R_{ic}}, \qquad (5)$$

$$\text{where,} \quad S = \frac{\partial u}{\partial z}^2 + \frac{\partial v}{\partial z}^2, \qquad (6)$$

$$R_i = \frac{g}{\theta S}\frac{\partial \theta}{\partial z}, \qquad (7)$$

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