Development of an Atmospheric Model Based on a Generalized Vertical Coordinate

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Introduction

There are great conceptual advantages in the use of an isentropic vertical coordinate in atmospheric models. Design of such a model, however, requires overcoming computational problems due to intersection of coordinate surfaces with the earth's surface. Under this project, we have completed the development of a model based on a generalized vertical coordinate, $\zeta = F(\theta, p, p_s)$, in which an isentropic coordinate can be combined with a terrain-following σ-coordinate creating a smooth transition between the two.

One of the key issues in developing such a model is to satisfy the consistency between the predictions of pressure and potential temperature. In our model, the consistency is satisfied by the use of an equation that determines the vertical mass flux. A procedure to properly choose $\zeta = F(\theta, p, p_s)$ is also developed, which guarantees that ζ is a monotonic function of height even when unstable stratification occurs. The design of the generalized vertical coordinate model is presented by Konor and Arakawa (1997).

There are two versions of the model constructed in parallel: one is the middle-latitude β-plane version and the other is the global version. Both of these versions include moisture prediction, relaxed large-scale condensation and relaxed moist-convective adjustment schemes. A well-mixed planetary boundary layer (PBL) is also added.

In this paper, we will briefly describe the model and discuss the rationale behind its key formulations. We then will discuss simulations obtained by using the two versions and we will present a summary of the completed tasks and our future plans.

Description of the Model

a. The vertical grid

The basic prognostic variables of the generalized vertical coordinate model for the free atmosphere are the horizontal velocity, pressure and potential temperature (Arakawa, Konor and Mechoso 1994; Konor and Arakawa 1996). The pressure ρ is predicted by the mass continuity equation combined with the hydrostatic equation, while the potential temperature θ is predicted by the thermodynamic energy equation. When $\zeta = p$, the prognostic equation for p is automatically satisfied. When $\zeta = \theta$, on the other hand, the prognostic equation for θ is automatically satisfied under adiabatic processes. In the lowest layer of the model, which is designated for planetary boundary layer, the vertically mixed horizontal velocity v_M and potential temperature θ_M are predicted. The mixed layer depth z_B is also predicted by mass continuity equation applied to the PBL.

The vertical grid of the model is chosen in view of the convenience for maintaining the consistency described above (see Figure 1). In the grid above the PBL, the horizontal velocity v is predicted for each of the model layers. At the levels separating these layers, both p and θ are predicted and the vertical mass flux is diagnosed. When $\zeta = \theta$ or σ, the grid becomes the Charney-Phillips grid, which has important advantages over the Lorenz grid (Arakawa and Konor 1994 and 1996). We predict the water vapor mixing ratio q at the same levels as θ.

b. The vertical mass flux equation

The consistency between the predictions of the pressure and the potential temperature is maintained by requiring

$$0 = \left(\frac{\partial}{\partial_t}\right)_\zeta F(\theta, p, p_s) \tag{1}$$

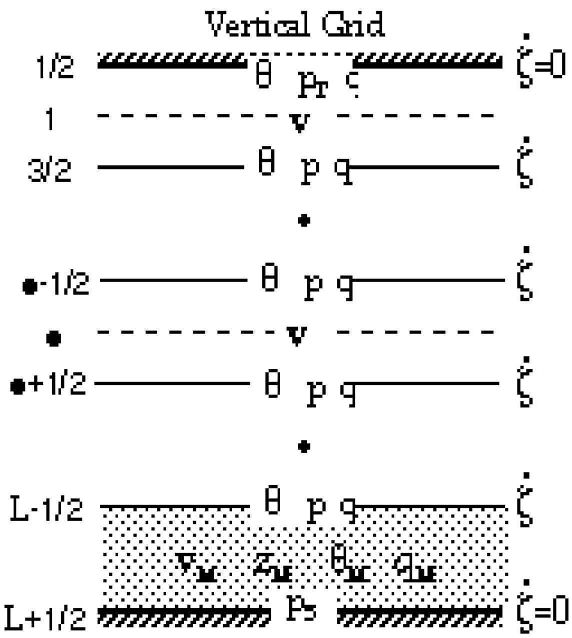

Figure 1. The vertical grid of the model.

Using the thermodynamic equation, the pressure tendency equation and the surface pressure tendency equation in (1), the vertical mass flux equation can be obtained.

For the time discrete case, the vertical mass flux equation is solved through a two-step procedure. In the first step, deviation of $\zeta = F(\theta, p, p_s)$ from its original value is determined solely by considering the horizontal advection of the potential temperature and diabatic heating in the thermodynamic equation and the convergence of horizontal mass fluxes in the continuity equation. In the second step, using an iteration procedure, the vertical mass flux is determined to compensate this deviation of ζ through the vertical advection of the potential temperature and the vertical convergence of the vertical mass flux. Doing so guarantees that ζ of a coordinate surface remains unchanged.

c. The choice of $\zeta = F(\theta, p, p_s)$

The primary purpose for using this coordinate is to combine the advantages of the isentropic coordinate away from the surface with the advantages of the standard σ-coordinate near the surface. Assuming that $\sigma = \sigma(p, p_s)$ monotonically increases with height, a hybrid σ-θ vertical coordinate must satisfy the following requirements:

$$\partial\zeta/\partial\sigma > 0 \qquad (2)$$

with ζ = const. and $\zeta = \theta$ at the lower and upper boundaries, respectively. These requirements can be satisfied by defining

$$\zeta \equiv f(\sigma) + g(\sigma)\theta \qquad (3)$$

with $g(\sigma) = 0$ at the lower boundary, and $g(\sigma) = 1$ and $f(\sigma) = 0$ at the upper boundary, and

$$\frac{\partial f}{\partial \sigma} + \frac{\partial g}{\partial \sigma}\,\theta_{min} + \left(\frac{\partial \theta}{\partial \sigma}\right)_{min} g = 0 \qquad (4)$$

Here g and $dg/d\sigma$ are assumed to be positive and min denotes prescribed lower bound. Now we can define ζ using (3) by first choosing a proper $g(\sigma)$ in (4) and then integrating that equation with respect to σ to obtain $f(\sigma)$. We are currently using $g(\sigma) \equiv g_o(1 - e^{-\alpha\sigma})$, with $\sigma \equiv (p_s - p)/(p_s - p_r)$, where g_o and α are constants and p_t is the constant pressure at the upper boundary. ζ obtained following the above procedure is always a monotonic function of height even when unstable stratification occurs.

Numerical Simulations with the Model

The performance of the generalized vertical coordinate model has been tested by simulating the nonlinear evolution of midlatitude disturbances on a β-plane. We have performed several simulations using different vertical and horizontal resolutions and physical parameters. In these simulations, no moist processes are included; instead a weak Newtonian heating is included to restore the thermal field to the zonally-symmetric initial basic state. The initial conditions consist of a zonally uniform geostrophically balanced basic state and a small-amplitude random perturbation of potential temperature and pressure superimposed on the basic state. An example from these simulations is presented in Konor and Arakawa (1997). Analyses of the simulated fields reveal that the model captures the details of surface and upper-level frontogenesis without serious computational difficulties (Konor, Mechoso and Arakawa 1994). We are currently testing the performance of the global version including moisture prediction, relaxed large-scale condensation and moist-convective adjustment schemes. This version also includes a parameterized PBL.

A Summary of the Completed and Future Tasks

The development of a model based on a generalized vertical coordinate is under way. The "dynamics" portion of the model has been completed and successfully tested (see Konor and Arakawa 1997). The global version of this model is now under development. Significant progress has been made towards a global version of the model with comprehensive physical processes. The latest version of the model includes moisture prediction, large-scale condensation and moist-convective adjustment schemes. To parameterize the PBL processes, a well-mixed layer is added to the model near the surface. We are currently working on details of PBL parameterization, which is based on the prognostic turbulence kinetic energy and variances. The final decision on the cumulus parameterization scheme has not been made yet. Among the possibilities, we are considering an empirical cumulus parameterization and a relaxed Arakawa-Schubert cumulus parameterization. Shortwave and longwave radiation schemes will be included in the model.

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