Development of a New Nonhydrostatic Model ASUCA at JMA

Junichi Ishida[1], Chiashi Muroi[1], Kohei Kawano[1], Yuji Kitamura[2]

[1] *Numerical Prediction Division, Japan Meteorological Agency,* [2] *Meteorological Research Institute*

j_ishida@naps.kishou.go.jp, cmuroi@naps.kishou.go.jp, kkawano@naps.kishou.go.jp, kitamura@mri-jma.go.jp

1 Introduction

The Japan Meteorological Agency (JMA) operates a nonhydrostatic regional model (NHM) with a horizontal resolution of 5 km. In recent years, new nonhydrostatic equations which conserve mass and some highly efficient numerical methods in fluid dynamics have been widely used in numerical weather prediction models. This has motivated us to develop a new dynamical core.

This new core is intended to achieve higher accuracy and improved computational stability. The core and program code are designed to be efficient for massively parallel machines. The new dynamical core is named ASUCA.

2 Outline of ASUCA

ASUCA employs generalized coordinates $(\hat{x}^1, \hat{x}^2, \hat{x}^3)$. Using the Einstein summation convention, its flux-form nonhydrostatic equations are written as follows:

$$\frac{\partial}{\partial t}\left(\frac{\rho u^i}{J}\right) + \frac{\partial}{\partial \hat{x}^j}\left(\frac{\rho u^i \hat{u}^j}{J}\right) + \frac{\partial}{\partial \hat{x}^n}\left(\frac{1}{J}\frac{\partial \hat{x}^n}{\partial x^i} p\right) - \frac{\rho g^i}{J} = \frac{F^i}{J},$$

$$\frac{\partial}{\partial t}\left(\frac{\rho}{J}\right) + \frac{\partial}{\partial \hat{x}^i}\left(\frac{\rho \hat{u}^i}{J}\right) = \frac{F_\rho}{J},$$

$$\frac{\partial}{\partial t}\left(\frac{\rho \theta_m}{J}\right) + \frac{\partial}{\partial \hat{x}^i}\left(\frac{\rho \theta_m \hat{u}^i}{J}\right) = \frac{F_{\rho\theta_m}}{J},$$

$$\frac{\partial}{\partial t}\left(\frac{\rho q_x}{J}\right) + \frac{\partial}{\partial \hat{x}^i}\left(\frac{\rho q_x \hat{u}_x^i}{J}\right) = \frac{F_{\rho q_x}}{J},$$

$$p = R_d \pi \left(\rho \theta_m\right),$$

where u, v, w and $\hat{u}, \hat{v}, \hat{w}$ represent the velocity components in Cartesian coordinates and generalized coordinates, respectively, J is the Jacobian of coordinate transformation, π is the Exner function, ρ is the total mass density, and q_x is the ratio of the density of water substance x to the total mass density (for example, q_v for water vapor, q_c for cloud water and so on). In order to use the same state equation in the dry and moist system, $\theta_m = \theta(\rho_d/\rho + \epsilon\rho_v/\rho)$ is introduced, where ϵ is the ratio of R_v to R_d. The velocity $\hat{u}_x^i$ in the equation for water substances may be different from the velocity of the atmosphere if terminal fall velocity exists. The right hand side of each equation F contains not only the Coriolis force, diffusion and diabatic effects but also terms arising from the density change due to precipitation.

The equations are discretized using the finite volume method (FVM). The flux limiter function proposed by Koren (1993) is employed for monotonicity to avoid numerical oscillations. A third-order Runge-Kutta scheme is adopted for the time integration of the system. The terms responsible for sound waves and gravity waves are treated using a split-explicit time integration scheme. For the short time step, a second-order Runge-Kutta scheme is employed. Another time-splitting method is also used to treat the vertical advection of water substances with a high terminal velocity (such as rain or graupel). Since it is only limited by the vertical CFL condition, a short time step interval is determined in each column.

The Deardorff model (Deardorff, 1980) is implemented to represent the effects of turbulent motions that cannot be resolved in the numerical model. In this model, eddy flux is parameterized in terms of eddy viscosity and eddy thermal diffusivity, and these coefficients are determined as a function of the mixing length l and the turbulent kinetic energy (TKE) E, which is regarded as a prognostic variable. The TKE equation is described as

$$\frac{\partial}{\partial t}\left(\frac{\rho E}{J}\right) + \frac{\partial}{\partial \hat{x}^j}\left(\frac{\rho E \hat{u}^j}{J}\right) = P + D - \epsilon.$$

Here, P, D and ϵ denote the TKE production, diffusion and dissipation terms, and are parameterized as

$$P = \frac{\rho}{J}\left[K_m\left(\frac{\partial \hat{x}^k}{\partial x^j}\frac{\partial u^i}{\partial \hat{x}^k} + \frac{\partial \hat{x}^k}{\partial x^i}\frac{\partial u^j}{\partial \hat{x}^k}\right) - \frac{2}{3}\delta_i^j E\right]\frac{\partial \hat{x}^l}{\partial x^j}\frac{\partial u^i}{\partial \hat{x}^l} - \frac{g}{\theta_v}\frac{\rho}{J}K_h\frac{\partial \hat{x}^k}{\partial x^3}\frac{\partial \theta_v}{\partial \hat{x}^k},$$

$$D = \frac{\partial}{\partial \hat{x}^l}\left(\frac{2K_m}{J}\frac{\partial \hat{x}^l}{\partial x^i}\frac{\partial \hat{x}^k}{\partial x^i}\frac{\partial \rho E}{\partial \hat{x}^k}\right),$$

$$\epsilon = \frac{C_\epsilon \rho E^{3/2}}{lJ}.$$

K_m and K_h represent the eddy viscosity and eddy thermal diffusivity coefficients, respectively. It should be noted that the prognostic equation for $\rho E/J$ instead of E is solved in ASUCA so that the advection term in the TKE equation can be treated as the flux-form in the generalized coordinates. The mixing length l is diagnosed using the formula proposed by Sun and Cheng (1986). The vertical diffusion and the TKE dissipation terms are evaluated with the implicit scheme in order to avoid computational instability.

3 Experiment results

A numerical experiment for nonhydrostatic scale inertia gravity waves, originally proposed by Skamarock and Klemp (1994), was carried out. The configurations used were identical to those in their paper with the exception of the time step of ASUCA, which was 60 s. The left and right parts of Fig. 1 show the numerical solutions obtained using ASUCA and the analytical solution, respectively. The numerical result is quite similar to the analytical solution.

The results of another numerical experiments for non-linear density current in which the result obtained by Straka et al. (1993) is usually used as a benchmark are shown in Fig. 2. The time steps are 1 s for $\Delta x = 50$ m and 2 s for $\Delta x = 100$ m. Both results are comparable to those of the benchmark.

4 Conclusions

We have developed a new dynamical core and turbulent model. A number of idealized experiments were conducted, and the results indicate a high level of performance. The computational efficiency of ASUCA is now being tested both on a GPU (Shimokawabe et al., 2010) and on JMA's super computer system.

The next target of our development is to test the dynamical core extended to the moist system and to develop physics processes for operational purposes. Though the NHM has a lot of physics schemes, which have been well tested operationally, we plan to evaluate them carefully and employ only useful schemes for ASUCA.

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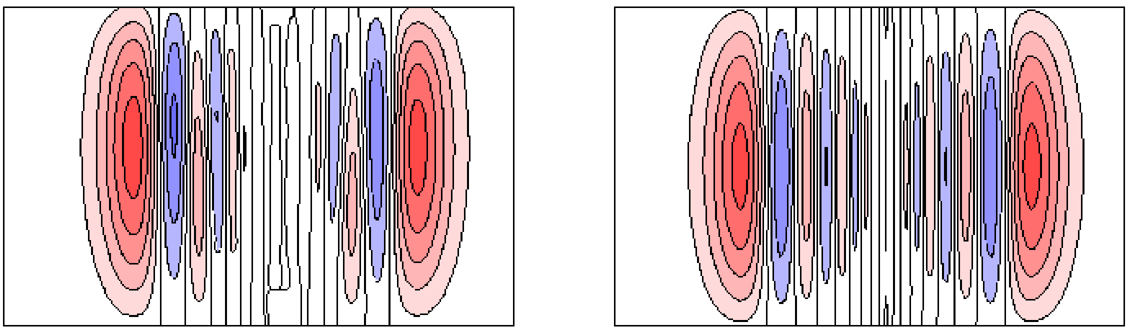

Figure 1: Inertia gravity test by Skamarock and Klemp (1994): Perturbation of θ at $t = 3000$ s of the numerical solution by ASUCA (left) and the analytical solution(right).

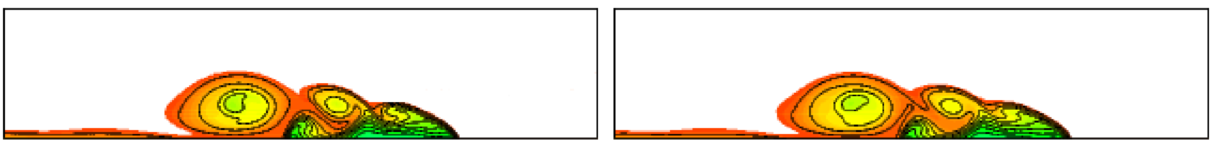

Figure 2: Non-linear density current test by Straka et al. (1993): Contours of θ at $t = 15$ min. The region is the same as that in Fig. 1 for Straka et al. (1993). The figures show the results obtained using ASUCA with $\Delta x = 50$ m (left) and $\Delta x = 100$ m (right).