Direct evaluation of the buoyancy and consideration of moisture diffusion in the continuity equation in the JMA Nonhydrostatic Model

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1. Introduction

The Japan Meteorological Agency (JMA) has been developing an operational nonhydrostatic model for regional NWP. This model (JMA-NHM) is based on the Meteorological Research Institute/Numerical Prediction Division unified nonhydrostatic model (http://www.mri-jma.go.jp/Dep/fo/mrinpd/INDEXE.htm). Among the three dynamical cores of JMA-NHM, the split-explicit time integration scheme (HE-VI scheme) is used for operation, considering the computational efficiency on the distributed memory parallel computer. Saito (2002) introduced a time splitting scheme of gravity waves where the computations of the buoyancy terms and vertical advection of the reference potential temperature are performed in the short time step in the HE-VI scheme. Saito (2003) introduced a time splitting scheme of advection terms where the higher-order advection terms are evaluated at the center of the leap-frog time step and the lower-order components are adjusted at each short time step. These schemes have significantly improved the computational stability of JMA-NHM.

In this report, we describe recent developments for JMA-NHM, which contribute to the mass conservation.

2. Direct evaluation of buoyancy

JMA-NHM defines the density as the sum of the masses of moist air and the water substances per unit volume as

$$\rho \equiv \rho_d + \rho_v + \rho_c + \rho_r + \rho_i + \rho_s + \rho_g = \rho_a + \rho_c + \rho_r + \rho_i + \rho_s + \rho_g, \qquad (1)$$

where subscripts *c, r, i, s, g* stand for the cloud water, rain, cloud ice, snow, and graupel, respectively. ρ_d is the density of dry air and ρ_v, that of water vapor. The buoyancy is defined as

$$BUOY \equiv \sigma \frac{\rho G^{\frac{1}{2}} \theta_m'}{\theta_m} g + (1-\sigma)(\overline{\rho} - \rho) g G^{\frac{1}{2}}. \qquad (2)$$

Here, σ is a switching parameter, which takes zero for direct computation of the buoyancy from the density perturbation and unity for conventional computation by the temperature perturbation. Using σ, vertical momentum equations can be expressed as

$$\frac{\partial W}{\partial t} + \frac{1}{mG^{\frac{1}{2}}} \frac{\partial P}{\partial z^*} + \sigma \frac{P}{mC_m{}^2} g = \frac{1}{m} BUOY - ADVW + RW. \qquad (3)$$

When σ =0, the pressure perturbation term (third term in the left-hand side) varnishes. The semi-implicit (HI-VI) scheme of JMA-NHM can use both σ=0 and σ=1, while σ=1 is assumed in the HE-VI scheme. In case of σ =1, the pressure perturbation term remains in the upper and lower boundary conditions for the vertically implicit pressure equation. In the Lorenz-type vertically staggered coordinate, it is difficult to determine this term at the upper and lower boundaries properly, and this problem yields a positive bias of mean pressure in the JMA-NHM.

In order to solve above problem, we modified the HE-VI scheme of JMA-NHM so that the buoyancy term can be evaluated by the density perturbation directly. In case of σ=0, the pressure perturbation term disappears in the vertical momentum equation (3), however, we have to teat the pressure perturbation implicitly for stable computation. The upper and lower boundary conditions of the vertically implicit pressure equation are as follows:

$$\delta_\tau W + \frac{1}{mG^{\frac{1}{2}}} \frac{\partial P^\beta}{\partial z^*} + \frac{g}{mC_m{}^2} P^\beta = \frac{1}{m} BUOY - (ADVW - RW) + (1-\sigma) \frac{g}{mC_m{}^2} P, \qquad (4)$$

where the terms with super-script β are treated implicitly. Above equation is formally similar to that for σ=1, while the additional last term of the right-hand side offsets the pressure perturbation term and the determination of pressure at upper and lower boundaries becomes less problematic. To split gravity waves, the density must be diagnosed at each short time step.

Figure 1 shows the domain-averaged mean sea level pressure of JMA-NHM whose initial time is 06 UTC 1 March 2003. Pressure of JMA-NHM with σ=1 increases after the start-up and is about 1.2 hPa higher than RSM, the outer model which supplies the lateral boundary conditions. On the other hand, pressure of JMA-NHM with σ=0 well follows that of RSM.

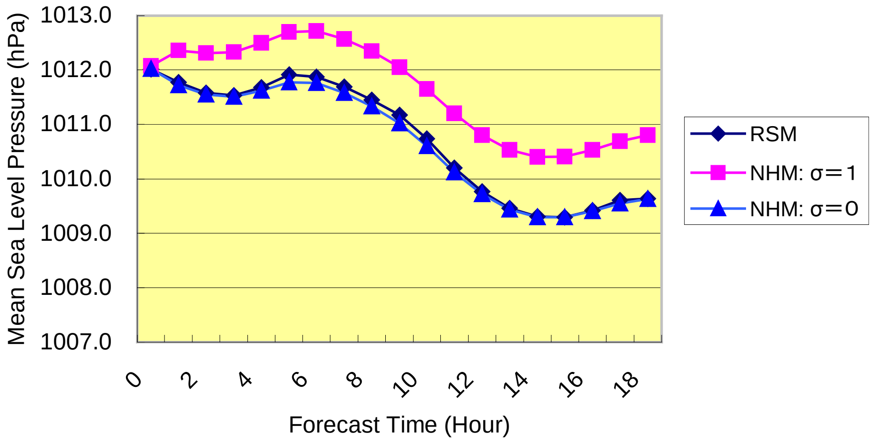

Fig. 1. Time sequence of the mean sea level pressure of JMA-NHM and RSM. Domain-averaged values for area of the JMA Mesoscale Model are shown. Initial condition for JMA-NHM is Meso 4D-Var analysis at 06 UTC 1 March 2003.

3. Consideration of moisture diffusion in the continuity equation

Since the density is defined by Eq. (1), JMA-NHM considers the fall-out of precipitable water substances in the continuity equation as

$$\frac{\partial \rho}{\partial t}+\frac{\partial \rho u}{\partial x}+\frac{\partial \rho v}{\partial y}+\frac{\partial \rho w}{\partial z}=\frac{\partial}{\partial z}(\rho_a V_r q_r+\rho_a V_s q_s+\rho_a V_g q_g). \qquad (5)$$

Here, V is the mass-weighted bulk terminal velocity for precipitable water substances and q the mixing ratio. Volume integrating above equation, we obtain a relation among the time tendency of the domain-averaged surface pressure, the mass flux through the lateral boundaries and the total precipitation rate at surface. JMA-NHM dynamically adjusts the mass flux through the lateral boundaries, monitoring the total surface precipitation. In this method, however, magnitude of the adjustment increases with the increase of the model domain. To solve this problem, we evaluate moisture diffusion in the continuity equation as

$$\frac{\partial \rho}{\partial t}+\frac{\partial \rho u}{\partial x}+\frac{\partial \rho v}{\partial y}+\frac{\partial \rho w}{\partial z}=\frac{\partial}{\partial z}(\rho_a V_r q_r+\rho_a V_s q_s+\rho_a V_g q_g)+\rho K \nabla^2 q_v. \qquad (6)$$

Using above equation, the total surface evaporation offsets the total surface precipitation, thus the magnitude of the adjustment for mass flux at lateral boundaries decreases.

References.

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