Forward-time-weighted semi-implicit adjustment with NDSL dynamics in RSM

Ying-Ju Chen[1,3] **Hann-Ming Henry Juang**[2,3] **Jen-Her Chen**[1]

Meteorological Information Center, Central Weather Bureau[1]

Environmental Modeling Center, National Centers for Environmental Prediction[2]

Department of Atmospheric Sciences, National Central University[3]

Abstract

The forward-time-weighted semi-implicit adjustment can help stabilize the Regional Spectral Model (RSM) with non-iteration dimensional-split semi-Lagrangian (NDSL) scheme. The NDSL scheme was implemented into the dynamical core of RSM in 2019. With NDSL dynamical core, the integration time step can be enlarged 3 to 4 times compared to the Eulerian scheme. Though the time step is no longer constrained by CFL condition, the gravity wave will make the model more unstable with the enlarged time step. To further slow down the gravity wave, we implied forward-time-weighted coefficient 0.7 to the semi-implicit scheme. In the experimental simulation, we found that this forward-time-weighted semi-implicit adjustment can stabilize the model very effectively compared to the purely increasing of the horizontal diffusion.

Keywords: forward-time-weighted semi-implicit, semi-implicit, NDSL, RSM

1. Introduction

In 2017, NCEP RSM (Regional Spectral Model) with 2-D decomposition version and MSM (Mesoscale Spectral Model), nonhydrostatic version of RSM, was introduced to CWB and was nested into CWBGFS (Central Weather Bureau Global Forecast System) for regional dynamical downscaling (Juang and Kanamitsu, 1994; Juang et al., 1997; Juang, 2000; Han and Juang, 2004). The goal of this nested model is to become a united model sharing the same model structure and physics package as CWBGFS for consistency of downscaling and low maintenance expenses. Since both models are spectral model, this united model is called Spectral Unified Model (SUM). For current status, RSM was nested into CWBGFS with MPMD (Multi-Program Multi-Data) method to exchanging the data through MPI (Message Passing Interface) efficiently and some physics parameterization from CWBGFS were implemented into RSM.

Then, in 2018, CWBGFS has been updated from Eulerian scheme to semi-Lagragian scheme using NDSL (Non-iteration Dimensional-split Semi-Lagragian) method. By applying this SL method, the timestep would not be constrained by the Courant number and could be enlarged multiple times depending on the accuracy. This SL version of CWBGFS along with a new octahedral grid and some other updates of physics parameterization showed better forecast skills and higher efficiency. Hence, this CWBGFS TCo639L72 become the operational weather forecasting model in CWB in the spring of 2020. Following this improvement of CWBGFS and for the development of SUM, NDSL was also adopted into RSM to replace the original Eulerian scheme.

However, even though NDSL scheme could allow larger integration timestep, we found that some noises may occurred near the jet area, when the timestep was increased over 3 times compared to the Eulerian scheme. To deal with these noises, we have tried to increase the diffusion but limited influences were shown. Since these noises showed up only when the timestep was increased over 3 times, modifying the semi-implicit integration scheme to include the uncentering coefficient to further stabilize the model was considered. This uncentered forward-time-weighted semi-implicit scheme (also called decentering in other studies) was used in Juang (2000) for nonhydrostatic model (MSM) and it helped stabilize the model with a larger timestep. Simmons and Temperton (1997) showed that this uncentered scheme with uncentering coefficient 0.1 had an effect on further slightly slowing of phase speeds and more damping compared to the centered scheme.

In this paper, the uncentered forward-time-weighted semi-implicit scheme was implemented into RSM and the results of this uncentered scheme were compared with the one using larger horizontal diffusion. The experiments were run with RSM NDSL version and the timestep was set to 3 times larger than the Eulerian version.

2. Forward-time-weighted semi-implicit adjustment

Semi-implicit time scheme was pioneered by Kwizak and Robert (1971) and Robert et al. (1972) and has become widely used in the atmospheric model. This numerical technique was used to deal with the high frequency gravity waves by slowing down the waves. Since gravity waves have little impact on meteorological phenomena yet their high speed may cause instability in the model, the terms related to the gravity waves could be treated implicit and the other terms remain explicit.

The semi-implicit integration of RSM was described in the APPENDIX B of Juang and Kanamitsu (1994). For derivation for the uncentered scheme, the equations from their APPENDIX B were shown here again. The equations of the perturbation of the semi-implicit associated linear terms of 3 variables: logarithm of surface pressure $Q' = \ln(p_s')$, divergence $D^{*'} = \frac{\partial u^{*\prime}}{\partial x} + \frac{\partial v^{*\prime}}{\partial y}$, and temperature T', in terms of sine-cosine series are written as

$$\delta_t Q'_{\text{<cc>}} + S\overline{D^{*\prime}_{j\text{<cc>}}}^{t} = Z'^{n}_{\text{<cc>}},$$

$$\delta_t T_{\text{<cc>}}{}' + B\overline{D^{*\prime}_{j\text{<cc>}}}^{t} = Y'^{n}_{\text{<cc>}},$$

$$\delta_t D^{*}_{\text{<cc>}}{}' + \boldsymbol{A}\nabla^2\overline{T'_{j\text{<cc>}}}^{t} + RT_0\nabla^2\overline{Q'_{\text{<cc>}}}^{t} = X'^{n}_{\text{<cc>}}, \qquad (1)$$

where

$$X'^{n}_{\text{<cc>}} = \left(\frac{\partial D^{*\prime}}{\partial t} + \boldsymbol{A}\nabla^2\boldsymbol{T}'_{\boldsymbol{j}\,\text{<cc>}} + RT_0\nabla^2 Q_{\text{<cc>}}{}'\right)^{n}_{\text{<cc>}},$$

$$Y'^{n}_{\text{<cc>}} = \left(\frac{\partial T'}{\partial t} + BD^{*\prime}_{j\,\text{<cc>}}\right)^{n}_{\text{<cc>}},$$

$$Z'^{n}_{\text{<cc>}} = \left(\frac{\partial Q'}{\partial t} + SD^{*\prime}_{j}\right)^{n}_{\text{<cc>}},$$

$$\delta_t a = \frac{(a^{n+1} - a^{n-1})}{2\Delta t},$$

$$\bar{a}^{t} = \frac{a^{n+1} + a^{n-1}}{2},$$

Here, a can be substituted by $Q, D^{*},$ or T; n means the nth time step; and the other symbols are the same as those in the APPENDIX B of Juang and Kanamitsu (1994). By letting

$$\bar{\bar{a}}^{t} = \frac{a^{n+1} - 2a^{n} + a^{n-1}}{2} = \bar{a}^{t} - a^{n},$$

the discretization of $\delta_t a$ becomes

$$\delta_t a = \frac{\bar{\bar{a}}^{t}}{\Delta t} - \frac{a^{n-1} - a^{n}}{\Delta t}.$$

Then, the terms of the equations can be further reduced as

$$\delta_t Q'_{\text{<cc>}} + S\overline{\overline{D^{*\prime}_{j\text{<cc>}}}}^{t} = \left(\frac{\partial Q'}{\partial t}\right)^{n}_{\text{<cc>}},$$

$$\delta_t T'_{\text{<cc>}} + B\overline{\overline{D^{*\prime}_{j\text{<cc>}}}}^{t} = \left(\frac{\partial T'}{\partial t}\right)^{n}_{\text{<cc>}},$$

$$\delta_t D^{*\prime}{}_{\text{<cc>}} + \boldsymbol{A}\nabla^2\overline{\overline{T'_{j\text{<cc>}}}}^{t} + RT_0\nabla^2\overline{\overline{Q'_{\text{<cc>}}}}^{t} = \left(\frac{\partial D^{*\prime}}{\partial t}\right)^{n}_{\text{<cc>}}. \qquad (2)$$

By solving $\overline{\overline{D^{*\prime}_{j\text{<cc>}}}}^{t}$ from

$$[1 + \lambda^2(AB + RT_0S)\Delta t^2]\overline{\overline{D^{*\prime}_{j\text{<cc>}}}}^{t} = D^{*\prime}_{j\text{<cc>}}{}^{n+1} - D^{*\prime}_{j\text{<cc>}}{}^{n} + \Delta t\left(\lambda^2 A\frac{\partial T'}{\partial t}\Delta t + T'^{n-1}_{\text{<cc>}} - T'^{n}_{\text{<cc>}} + \lambda^2 RT_0\frac{\partial Q'}{\partial t}\Delta t + Q'^{n-1}_{\text{<cc>}} - Q'^{n}_{\text{<cc>}} + \left(\frac{\partial D^{*\prime}}{\partial t}\right)^{n}_{\text{<cc>}}\right), \qquad (3)$$

$\delta_t D^{*\prime}, \delta_t Q', and\ \delta_t T'$ can latter be solved as well as $D^{*\prime n+1}, Q'^{n+1}, and\ T'^{n+1}$. To derive the uncentered scheme, $\bar{\bar{a}}^{t}$ can be rewritten as

$$\bar{\bar{a}}^{t} = \frac{(1+\alpha)a^{n+1} - 2a^{n} + (1-\alpha)a^{n-1}}{2},$$

and by replacing Δt as $(1+\alpha)\Delta t$, the above derivation remains the same. In the code, $2\tilde{\alpha} = (1+\alpha)$ is used. Since $0 < \alpha \leq 1$, then $0.5 < \tilde{\alpha} \leq 1.0$. The larger $\tilde{\alpha}$ is, the more damping and slower phase speed of high frequency gravity wave are. $\tilde{\alpha}$ is then called the forward-weighted coefficient in the rest of this paper.

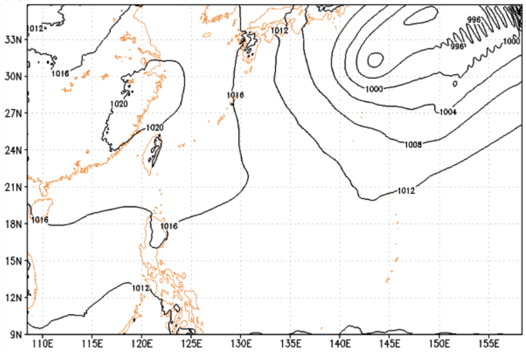
3. Simulation with different $\tilde{\alpha}$ and diffusion coefficients

While NDSL was implemented into RSM, some experiments with high speed jet area in the simulation domain often showed noises near the jet region and some of these ecperiments even crushed when the instability become serious. To solve this problem, stronger horizontal diffusion and the uncentered forward-weighted semi-implicit scheme were tested.

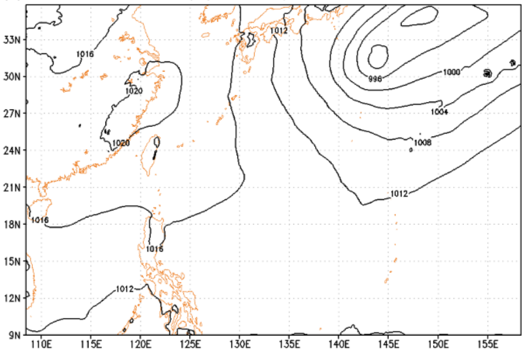
Here, a real case with initial time as 00 UTC 2020 April 9 was chosen, and the domain was set from $[108.477^0E{\sim}158.373^0E, 8.984^0N{\sim}35.827^0N]$. The grid spacing was 8 km, and the timestep was 90 s (3 times of the timestep of the Eulerian version). Compared to the experiment with 12 times larger horizontal diffusion and centered ($\tilde{\alpha} = 0.5$) semi-implicit scheme (Fig. 1 (a)), the results of experiment with 1 times horizontal diffusion (same as Eulerian version) and uncentered forward-weighted semi-implicit scheme ($\tilde{\alpha} = 0.7$) were more stable and less noises near the jet area (Fig. 1 (c)).

Also, two other forward-weighted coefficients $\tilde{\alpha}$ were tested. Fig. 1 (b)~(d) shows the comparison between $\tilde{\alpha} = 0.65$, $\tilde{\alpha} = 0.7$, and $\tilde{\alpha} = 0.8$ at the 144 simulation hours. While the results with $\tilde{\alpha} = 0.8$ have less noises than the two others, it smoothed out more details in the weather systems (not shown). On the other hand, the setting of $\tilde{\alpha} = 0.65$ preserved more details but it blew up after 246 hours, while the other two simulation could survive through the whole 996 simulation hours. Hence, $\tilde{\alpha} = 0.7$ seems to be a better choice among these settings. Other cases like tropical cyclone with different intensity and fronts have been tested with $\tilde{\alpha} = 0.7$, and the results showed that $\tilde{\alpha} = 0.7$ is sufficient in this RSM setting (not shown).

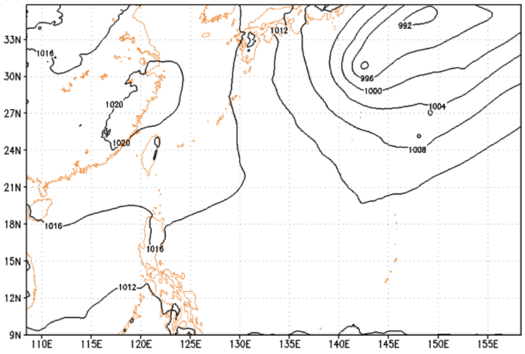
(a) centered scheme (alpha=0.5), 12 times horizontal diffusion



(b)uncentered scheme (alpha=0.65), 1 times horizontal diffusion



(c) uncentered scheme (alpha=0.7), 1 times horizontal diffusion



(d) uncentered scheme (alpha=0.8), 1 times horizontal diffusion

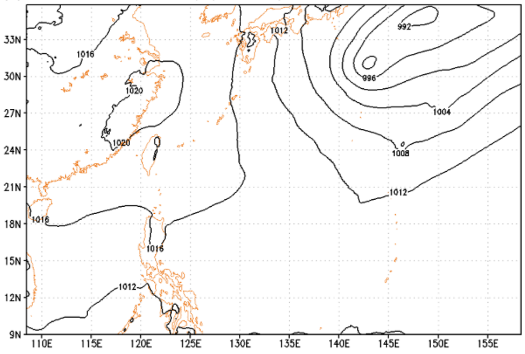


Fig. 1. Mean sea level pressure (hPa) of 4 experiments at 114 simulation hours. (a) is the centered scheme with 12 times horizontal diffusion larger than the one used in the Eulerian scheme. (b) is the uncentered forward-weighted semi-implicit scheme with $\tilde{\alpha} = 0.65$ and the same horizontal diffusion as the Eulerian scheme. (c) is $\tilde{\alpha} = 0.7$ and (d) is $\tilde{\alpha} = 0.8$ with the same horizontal diffusions as the Eulerian scheme.

4. Conclusions

While NDSL scheme with larger timestep could be used in RSM to increase the integration efficiency, some noises happened near the high-speed area. These noises could harm the results of the simulation or even crushed the model. In this paper, the uncentered forward-weighted semi-implicit scheme was implemented into RSM to solve this problem. Through a real case experiment on 00 UTC 2020 April 9, a larger horizontal diffusion with centered semi-implicit scheme was compared with 3 other uncentered scheme using the original horizontal diffusion as the Eulerian scheme. The results showed that the uncentered forward-weighted coefficients from 0.65 to 0.8 all reduce the noises significantly. However, 0.65 may not be sufficient for the whole 996 hours simulation, while 0.8 seems to be too smooth (not shown in this paper). Therefore, 0.7 was chosen to help stabilize the model in this kind of RSM 8 km setting.

This implement of uncentered semi-implicit scheme is to help stabilize RSM with NDSL when the larger timestep is used. Some other numerical methods along with this implement are undertesting for the development of NDSL dynamical core of RSM.

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