An Implementation of Spectral Nudging Technique to the WRF Model

[1)]Dong-Hyun Cha, [1)]Dong-Kyou Lee, and [2)]Ying-Hwa Kuo

[1)]Atmospheric Sciences Program, School of Earth and Environmental Sciences
Seoul National University, Seoul , KOREA
[2)]University Corporation for Atmospheric Research, and National Center for Atmospheric Research,
Boulder, Colorado, USA

1. Introduction

One of the most substantial issues in regional climate modeling is the synoptic-scale climate drift induced by the formulation of the lateral boundary condition (LBC) during the long-term integration of a regional climate model over an open system. In regional climate simulations for East Asia, internal forcing can be generated by characteristics of the East Asian region such as complicated topography and land-surface conditions, and land/ocean contrast as well as strong seasonal monsoon circulations and convective processes. Therefore, the climate drift might result from large deviations between regional model solution and large-scale driving field due to the various scales of internal variability in the regional simulations over East Asia. In order to reduce the deviations between model solution and large-scale forcing, most regional climate models employ the relaxation method originally proposed by Davies and Turner (1977) for lateral boundary condition. This includes the application of a Newtonian term (or diffusion term) which drives the model solution toward the large-scale driving fields over the buffer zone near the lateral boundary. The relaxation method has been modified and tested in a number of regional climate model studies such as Liang et al.(2001).

Recently, the spectral nudging technique (SNT) as an alternate method for the provision of LBC was proposed by Von Storch et al. (2000). Forcing in the spectral nudging technique is stipulated not only at the lateral boundaries but also in the model interior. This is maintained by adding nudging terms to the model equations of horizontal winds in the spectral domain with maximum efficiency in large scales and no effect in small scales. The nudging in the SNT is largely confined to the upper levels of a RCM, and the atmosphere in the lower troposphere is fairly free to evolve internal variability in a RCM. SNT is similar to the methods used by Kida et al. (1991). The SNT is not only to keep the solution of a regional model be feasible to large-scale driving forces but also to allow the evolution of regional details during the model integration.

The Weather Research and Forecast (WRF) model adopts only the traditional relaxation method for LBC. Leung et al. (2005) is developing a regional climate model based on the WRF model, which uses a conventional LBC. The objectives of this study are to implement the spectral nudging technique to the WRF model for long-term regional climate simulations. The case in this study is the extreme flood event that occurred over Central China for June and July, 1998.

Corresponding author address: Prof. Dong-Kyou Lee, Program in Atmospheric Sciences, School of Earth and Environmental Sciences, Seoul National University, Seoul 151-747, KOREA.
E-mail : dklee@snu.ac.kr

2. Implementation of SNT and Experiments

The spectral nudging in this study can be applied to the horizontal wind components for long-wave spectral regimes over the entire model domain as expressed by

$$\alpha_R\,(L_G \cap L_R) = [1-\eta(\sigma)]\alpha^*{}_R(L_G \cap L_R) + \eta(\sigma)\alpha_G(L_G \cap L_R)\,, \quad (1)$$

where L_G and L_R are the long-wave spectral regimes of global and regional models, respectively, and α_G, α_R, and $\alpha^*{}_R$ are variables of large-scale driving fields. Although no objective way is known to identify the spectral intervals, ($L_G \cap L_R$) is assumed to be the long-wave spectral regime corresponding to about 1000-1200 km in a regional climate model with 30-60 km horizontal resolution. The nudging coefficient, η, is a function of height given by

$$\eta(\sigma) = \alpha\ (1-\sigma)^2\,, \qquad (2)$$

where α is 0.05 and σ is the vertical coordinate. The spectral nudging of horizontal wind is applied to all terms in the governing equations which include the nudged variables. To do this, a module for the nudging is added to the WRF model, which separates the model solution and large-scale driving field by a length scale, and combines them using weighting coefficients.

The domain of 160X130 grid points covers most of East Asia. Simulations are performed using a horizontal grid spacing of 30 km and 31 vertical sigma levels (50 hPa model top) with and without the SNT (WRF_NOSP and WRF_SP, respectively). The 6-hourly NCEP/NCAR reanalysis 2 is used for driving forcing data. The model is integrated for three months (MJJ) starting from May 1, 1998 with boundary conditions updated every 6 hours. The boundary relaxation in a buffer zone has a linear functional form over 10 grid points. Sea surface temperature, vegetation fraction, and albedo are updated every 6 hours. Land surface, surface-layer and boundary-layer processes are represented by the Noah land surface model, the Monin-Obukhov surface scheme, and the YSU PBL scheme, respectively. Explicit precipitation processes use the WSM 3 class (simple ice) scheme, convection uses the Kain-Fritsch scheme, and radiation is represented by the rapid radiative transfer model and the Dudhia short-wave scheme.

3. Simulation Results

A record-breaking abnormal flood occurred over East Asia during the summer of 1998. More than 150 % of the normal rainfall which was observed over most of East Asia resulted in a number of casualties and tremendous damage in East Asian countries.

Figure 1 shows the seasonal mean precipitation over East Asia during the summer (MJJ) of 1998 in observation and simulations. In the summer of 1998, the extreme floods over southern China (105-116^{o}E, 22-25^{o}N) and the Yangtze River Basin (YRB) region (105-120^{o}E, 28-30^{o}N) were observed in June and July. The extreme flood events over the YRB region and southern China are captured well in the experiments with and without the SNT. It is noted that the precipitation amount in the WRF_NOSP is relatively large compared with those in observation and the WRF_SP. The overestimated precipitation over southern China and central China in the WRF_NOSP is likely to be associated with the simulation of the monsoon circulation from late June to middle of July that shifts southward compared to the reanalysis. In the WRF_SP, the simulated precipitation over central and southern China is in good agreement with observation, since the monsoon circulation is reasonably simulated by the effect of the SNT.

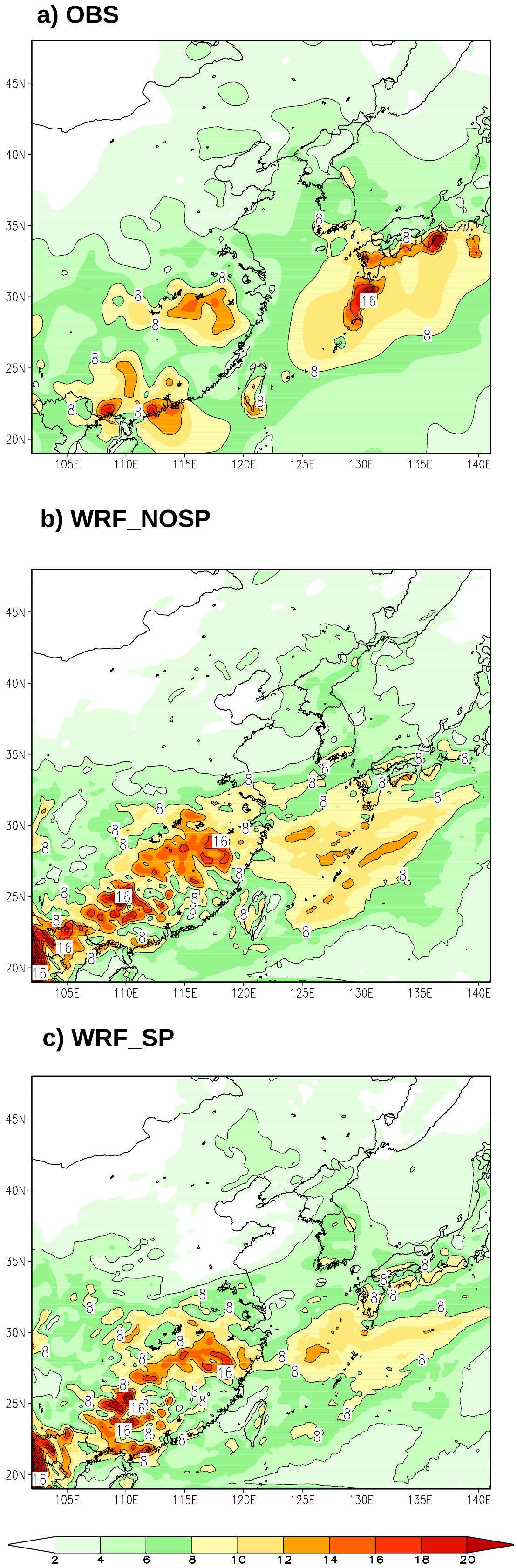

Figure 1. Seasonal mean (MJJ) precipitation (mm day^{-1}).

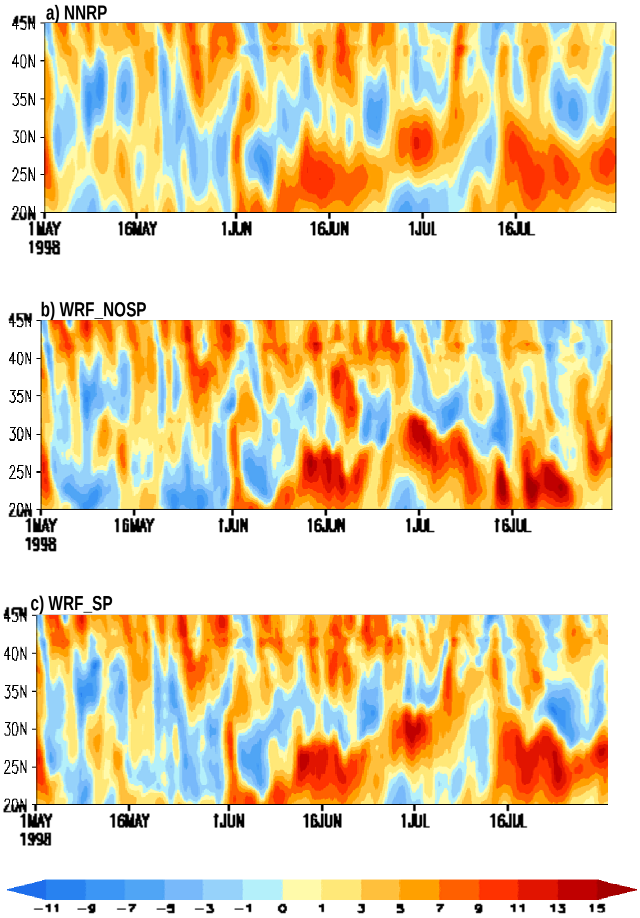

Figure 2. Time-latitude cross sections of 850 hPa zonal wind (m s^{-1}) averaged between 110°E and 120°E

We focus on the temporal evolution of the 1998 East Asian Summer Monsoon (EASM) by examining the time-latitude distribution of the 850 hPa meridional wind. In the reanalysis, the intensity of low-level wind over southern China (~20°N) is increased in early June and shifts northward to the Yangtze River basin until early July (Figure 2). The second northward shift of the East Asian summer monsoon (EASM) also starts over southern China in early July. In the WRF_SP, strong low-level wind over southern China (20-25°N) propagates northward to about 30°N until the end of June while in the WRF_NOSP, the EASM front tends to propagate southward after early July, that propagates northward about 40°N during early July in the reanalysis. That is, the northward propagation of the EASM front after late July in 1998 is not well captured in the WRF_NOSP. The double propagations of the EASM front during the summer of 1998 are also reasonably captured in the WRF_SP. Similarly, the temporal evolution of the upper level wind in the WRF_NOSP is quite different from that of

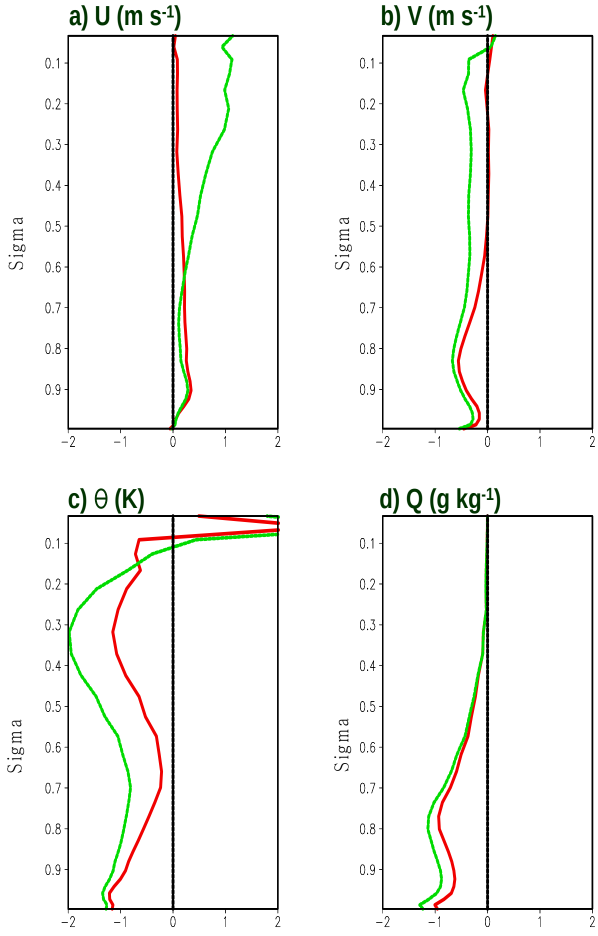

Figure 3. Vertical profiles of the seasonal mean biases of (a, b) horizontal wind components, (c) potential temperature, and (d) water vapor mixing ratio averaged over the model domain. Green and red lines indicate the WRF_NOSP and WRF_SP experiments, respectively.

the reanalysis after late June, while the simulated upper level wind in the WRF_SP is in good agreement with the reanalysis (not shown).

Figure 3 shows the vertical profiles of biases in horizontal wind components (u, v), potential temperature (θ), and water vapor mixing ratio (q) in simulation of the WRF_NOSP and WRF_SP from the reanalysis averaged over the model domain except for the buffer zone. The significant improvements in the WRF_SP are found in horizontal wind components, in particular, above 0.5 sigma level. The differences in vertical distributions of the low level variables between both experiments are not large compared to those of the upper levels, since the SNT does not significantly affect the low levels due to the application of small nudging coefficients. In the profiles of potential temperature in the WRF_SP, cold bias is significantly reduced, and dry bias is slightly reduced in the comparison with the WRF_NOSP. Although the nudging is applied only for the horizontal wind components, the dry and cold biases in the simulation are significantly decreased by the effect of the SNT.

4. Conclusion

The WRF_NOSP has the differences in the temporal evolution of the East Asian monsoon circulation from the reanalysis. In particular, the differences in the monsoon circulations significantly increase from about two months of the model integration, when the extreme floods occurred over the Yangtze River basin. In the WRF_SP, the differences are significantly reduced, and the simulated precipitation is improved in the experiment using the SNT. Also, the SNT results in the improvement in vertical distributions of the model variables.

Although the WRF-SP simulates better precipitation than the WRF_NOSP, further sensitivity experiments should be done to find any involved physical processes. The trade-off experiments between the cut-off wavelengths and the model domain also need to be investigated to better understand the proper application of the SNT to the WRF model.

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