Orography Blending in the Lateral Boundary of a Regional Model

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ABSTRACT

A simple method to employ an orography blending technique near the lateral boundary of the regional model is proposed. The method blends the orography of the regional model on the lateral boundary with that of the global or coarser resolution regional model. This method is tested in the NCEP Regional Spectral Model. A long-range prediction experiment of one month’s duration is conducted in the East Asian region. It is found that the proposed method provides regional model forecasts consistent with the global model forecasts without a discernible systematic bias. It is likely that modifying the regional model orography following the values of global model or analysis data is more efficient than elaborating the numerics of a lateral boundary scheme to eliminate systematic error.

1. Background

An important issue in long-term integrations using a limited-area model is the prevention of long-term drift between the solutions of the coarse and nesting domains. The National Centers for Environmental Prediction (NCEP) Regional Spectral Model (RSM) considers only the perturbation from the base field, which comes from a global model. The global model is the NCEP Medium-Range Forecast model (MRF) used in daily forecasts, and will subsequently be referred to as the global spectral model (GSM). Although the main purpose of the RSM is to produce daily weather forecasts, it is also suitable for long-range integration where boundary forcing is crucial. This is because the model has the advantage of lateral boundary treatments and perturbation method. Therefore, the model has been applied fairly successfully for regional climate studies over different geography regions for periods longer than a month [e.g., Juang and Kanamitsu (1993)].

Although the mass field of the RSM should be consistent with that of the GSM, we have noticed that RSM solutions sometimes deviate from those predicted by the GSM, as was the case when the model was used to simulate the East Asian monsoon. This defect seems to be due to the very steep orography near the western sides of the lateral boundary of the integration domain. Bias was not discernible when the model was applied to the domains over the United States and India. It was therefore considered likely that better representation of the RSM orography would help to achieve results consistent with the GSM.

For the reasons mentioned, a blending of the RSM orography with that of the GSM near the lateral boundary was proposed, so that the RSM includes not only longer meteorological waves near the boundary, but also, smaller waves generated by the higher resolution RSM topography, inside the domain. This method is tested for a month-long integration over the East Asian region. The orography blending method and experimental design are described in section 2. In section 3, the impact of the modified orography is compared to the original design in Juang and Kanamitsu (1994) and the applicability of this method to other regional models is discussed.

2. Methodology and experimental design

a. A brief description of the RSM

The NCEP RSM is a primitive equation model using the sigma-vertical coordinate. A detailed description of the model is given by Juang and Kanamitsu (1994) (hereafter JK94). While only a brief description of the model is given in this paper, a more detailed discussion can be found in Juang et al. (1997). The RSM uses sine-cosine series as horizontal basis functions for representation of the perturbation fields. The $x$ component of the wind perturbation, $u$, is represented by sine series in the $x$ direction and cosine series in the $y$ direction, while the $y$ component, $v$, is represented by cosine series in the $x$ direction and sine series in the $y$ direction. All the other variables are represented by cosine series in both directions. The version of the RSM used in this study...
employs the same "physics package" as the GSM (Hong and Pan 1996). Both models include long- and shortwave radiation, cloud–radiation interaction, planetary boundary layer processes, deep and shallow convection, large-scale condensation, gravity wave drag, enhanced topography, simple hydrology, and vertical and horizontal diffusion.

Computation of the perturbation variables and the lateral boundary treatment are fully described in JK94. A further improvement of the lateral boundary condition is discussed in Juang et al. (1997). The GSM outputs on the Gaussian grid are typically available every 6 or 12 h and are horizontally interpolated to yield values on the RSM grid. These values are used as base fields for the RSM during the model integration. Perturbations are obtained by subtracting the base fields from the RSM full values. Implicit lateral boundary relaxation of the RSM is the only numerical technique used to relax the lateral boundary RSM values to the GSM results. To reduce the noise from the lateral boundaries, the lateral boundary relaxation is applied to the total tendency. The weighting function for perturbation relaxation in JK94 is defined as

\[ \alpha = 1 - \left( \frac{|I - IM|}{NI} + \frac{|J - JM|}{NJ} \right)^{15}, \]  
\[ (1) \]

where \( I \) and \( J \) are the grid indices in the \( x \) and \( y \) direction, \( IM, JM, NI, \) and \( NJ \) are the indices of the central grid points, and \( NI \) and \( NJ \) are the number of half grid points in each direction. This relaxation causes the tendency of the perturbation to be 0 at the lateral boundaries. The dotted line in Fig. 1 designates the weighting for global tendency \((1 - \alpha)\).

b. Methodology

1) JK94 method

There is no unique blending technique for orography used in the original design of the RSM. Instead, after the initial perturbations of all fields, including orography, are obtained, the values are blended near the boundary with the same weighing function used for relaxation in Eq. (1). With this treatment, the RSM orography follows that of the GSM at the lateral boundary, but the GSM portion decreases very sharply inside the boundary, as shown in Fig. 1. This method is referred to subsequently as the JK94 method.

2) HJ98 method

The method proposed here is to blend the orography of the RSM before constructing the perturbation to create a more natural balance than when all fields are blended arbitrarily as in JK94. Modifications of regional mountains were made near the boundary to make them agree closely with the mountains used in the global model. In this way the RSM preserves longer meteorological waves near the boundary as well as smaller waves generated by the higher-resolution RSM topography inside the domain.

The modified orography of the RSM is obtained using the following formula:

\[ Z_{rsim} = \omega Z_{gsm} + (1 - \omega)Z^*_{rsm}, \]
\[ (2) \]

where

\[ \omega = \max\left[ \frac{1 + \sin\pi(x - 0.5)}{2}, \frac{1 + \sin\pi(y - 0.5)}{2} \right]^{0.5}, \]
\[ (3) \]

\[ x = \min\left[ \frac{\max(|I - IM|) - (1 - \varepsilon)IM + 1, 0}{\varepsilon IM}, 1 \right], \]
\[ (4) \]

\[ y = \min\left[ \frac{\max(|J - JM|) - (1 - \varepsilon)JM + 1, 0}{\varepsilon JM}, 1 \right]. \]
\[ (5) \]

In Eqs. (2)–(5), \( I, J, IM, \) and \( JM \) are the same as in Eq. (1). The blended orography, \( Z_{rsim} \), is derived from both \( Z^*_{rsm} \), the regional orography taken from the navy 10′ resolution orography file archived at the National Centers for Atmospheric Research (NCAR), and \( Z_{gsm} \), the regional orography interpolated from the GSM orography. Further, \( \omega \) is the weight assigned to the GSM orography and \( \varepsilon \) is the fraction of the regional domain that is affected by mountain blending. (We used 20%.) Figure 1 shows the weight \( \omega \) derived from Eq. (3), together with that used for the perturbation blending at the initial time in the JK94 method \([1 - \alpha in (1)]\). In Fig. 1, it is apparent that the new weight given to the GSM orography gradually decreases inside the boundary as compared to the rapid decrease in the JK94 method. Figure 2 compares \( Z_{rsim}, Z^*_{rsm}, \) and \( Z_{rsim} \), together with the orography modified by the JK94 method for a region
covering East Asia where experiments were performed in this study.

The resolution of the RSM is approximately 25 km, with 129 latitudinal points, 86 longitudinal points in Cartesian coordinates, and 28 sigma layers. The RSM is one-way nested within the GSM, which is integrated using the same vertical resolution and T62 truncation (global triangular truncation at wavenumber 62). In Fig. 2c it can be seen that the modified orography follows the GSM orography near the boundary where the slight differences inside the domain between Figs. 2b, 2c, and 2d are due to the application of a spectral filter after the modification is done. Of course, the function in Eq. (3) is arbitrary, however, the weighting factor in this equation, which gradually decreases the weight assigned to the GSM portion, was found to be very important to achieve success. This investigation will focus on the impact of different orography modifications between Fig. 2c and Fig. 2d, as explained in the following section.

c. Experimental design

Two experiments will be discussed below. The first is the original method of JK94 that makes the perturbation 0 near the boundary at the initial time, and the second, HJ98, uses the modified orography following Eqs. (2)–(5) without modifying the perturbation. The reported experiments differ not only in the treatment of orography, but also in the blending of the perturbation near the boundary. However, we found that preserving the perturbation blending at the initial time in the HJ98 experiment did not affect the results. This is because the perturbation is already made 0 near the boundary when using blended orography. On the other hand, blending the perturbation at the initial time in the JK94 experiment does not affect the monthly averaged climate made in this study. Consequently, the differences found between the JK94 and HJ98 experiments can be attributed to the impact of the different modification of orography near the lateral boundary between Fig. 2c and Fig. 2d.
The model integration spanned one month starting at 0000 UTC 1 July 1987, which corresponds to the period of the summer monsoon over the Korean peninsula. Initial conditions were obtained from the NCEP–NCAR reanalysis data (Kalnay et al. 1996). Sea surface temperatures were kept constant while the lateral boundary and base field were obtained by temporal interpolation of the 6-h global model forecast data.

3. Results and discussion

Figure 3 shows the evolution of domain averaged sea level pressure from the two RSM experiments together with the corresponding GSM result. It is apparent that the domain-averaged sea level pressure of the RSM evolves consistently with the global model forecast when blended orography is introduced, whereas the RSM forecast using the JK94 method produces an increase of sea level pressure with time. Recognizing that sea level pressure is a measure of mass, we may conclude that the RSM with the orography blending method provides a mass field that is consistent with the GSM.¹

From a comparison of the horizontal distribution of sea level pressure (not shown), some small-scale noise appeared at the western boundary in the JK94 experiment even at the 24-h forecast; however, this noise did not contaminate the solutions over the interior of the regional domain for at least a 3-day forecast period. This implies that the original technique used in JK94 performs adequately for short-range forecasts, even when steep orography appears at the lateral boundary. Indeed, the model produced a synoptic system moving too rapidly eastward even at the 24-h forecast time when the treatment in JK94 was not taken into account (when orography in Fig. 2b is used), but showed the same evolution of systematic error as in the JK94 experiment after the 7-day forecast. In contrast to the JK94 experiment, the HJ98 experiment produced very similar sea level pressure distribution to that from the GSM without the noise appearing in the JK94 experiment. Therefore, the monotonically increasing mass found in the JK94 experiment after 10 days seems to be due to internally generated undesirable waves at the eastern flank of the Tibetan Plateau.

The success of the HJ98 experiment can be interpreted by comparing the relaxation amounts of the perturbation near the boundary. Compared to the magnitude of the dynamically induced perturbation near the boundary in the JK94 method, the HJ98 experiment generates relatively small perturbations because of smaller differences in terrain heights between the RSM and GSM. This results in less reduction of the perturbation by the relaxation technique described in section 2a. On the other hand, relatively large perturbations generated in the JK94 method are also strongly reduced near the boundary by the numerics. Consequently, it is considered that strong relaxation by arbitrary function is not as efficient in removing the internally generated undesirable waves in regional models as the method that suppresses the generation of these waves by model dynamics.

From a comparison of monthly averaged fields, such as 500-hPa temperature and geopotential heights, obtained from the GSM and two RSM experiments (not shown), the HJ98 experiment showed little systematic error, whereas the JK94 experiment revealed a distinct cold bias accompanying an intensified trough to the west of the Korean peninsula. Consequently, the JK94 experiment showed enhanced precipitation activity, particularly over the monsoon frontal region. The domain-averaged precipitation rate was 20 and 27 mm month⁻¹ for the HJ98 and JK94 experiments, respectively. In view of the fact that the HJ98 experiment did not show a distinct systematic error as in Fig. 3, it may be concluded that the 35% increase of precipitation amount from the JK94 method may be a measure of systematic error arising from mass inconsistency.

The new method has been tested in different regions and provides forecasts that are consistent with the global forecasts while generating the regional detail. The method was implemented in a self-nested RSM analogous to the nesting method of a global model. It is found that the model is able to provide reasonable results in a small domain without a discernible systematic bias. Meanwhile, the changes in the relaxation coefficients and buffer area of the boundary conditions improved the
solution in part, but not enough to solve the problem when the orography blending method was not employed. In other words, without blended orography, regional solutions are relatively sensitive to the choice of coefficients, buffer area, and numerics of the lateral boundary conditions whereas this sensitivity is greatly reduced when blended orography is employed. Therefore it is likely that blending the regional model orography with that used in the global model provides a more efficient way of eliminating systematic error than increasing the complexity of the lateral boundary scheme numerics.

It is believed that other regional modeling groups have examined this issue, in particular in the nested grid system. As an example, the MM5 (The Pennsylvania State University–National Center for Atmospheric Research Mesoscale Model version 5) adjusts terrain heights along the boundary of nested grids so that they are consistent with their mother domain (Guo and Chen 1993). In MM5, there are no specific terrain modifications when the model is driven by analysis data (Guo 1997, personal communication). However, our results imply that terrain modifications are important even when the model is driven by analysis data. Our findings also suggest that the weighting factor formulation of global orography in Eq. (3) and Fig. 1 is crucial to achieve success. Although the formula is arbitrary, the weighting function is constructed so that it allows the regional model to gradually absorb the long waves from the global model.

In addition to the orography blending method, the success of regional mass conservation achieved in this study should be attributed to the perturbation technique of the RSM along with the same model frame as in the global. The perturbation design in the RSM guarantees a solution that is convergent with global model behavior. Nevertheless, we expect the method should reduce a possible systematic error in other regional models by alleviating arbitrary forcing due to the dynamical uncertainty in the lateral boundary when steep orography appears. As an example, a mesoscale model (Miller and Kim 1996) adopted the method appearing in Hong and Juang (1995). Kim (1996, personal communication), using the method proposed in this study, obtained considerable improvements in the regional climate simulation over East Asia forced by NCEP–NCAR reanalysis data. Additionally, smooth transitions between coarse grid (about 60 km) and fine grid (about 20 km) in a twofold one-way nested grid system were achieved.

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