Performance of Long-Term Integrations of the Japan Meteorological Agency Nonhydrostatic Model Using the Spectral Boundary Coupling Method

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ABSTRACT

The spectral boundary coupling (SBC) method, which is an approach used to couple a limited-area model with a large-scale model, was introduced into a nonhydrostatic model. To investigate whether the SBC method works well in a long-term integration of a high-resolution nonhydrostatic model, two numerical experiments were conducted with a model having a horizontal grid interval of 5 km. In one experiment, the SBC method was employed, while it was not in the other experiment. The time integration in both experiments was over a 40-day period. The nonhydrostatic model was nested into objectively analyzed fields, instead of the forecasts from an extended-area model.

Predicted patterns of sea level pressure and precipitation were compared with objective analyses, and data provided by the Global Precipitation Climatology Project (GPCP), respectively. The predicted rainfall amounts and surface temperature over the Japanese islands were statistically evaluated, making use of the analyzed rainfall and surface data observed by the Japan Meteorological Agency (JMA). All results examined in the present study exhibited better performances with use of the SBC method than those without the SBC method. It was found that the SBC method was highly useful in long-term simulations by a high-resolution nonhydrostatic model.

1. Introduction

Climate changes are recognized as critical factors that can seriously affect human life. For several decades, possible climate changes on global scales have been investigated and discussed. Although global-scale climate changes are of universal importance, climate changes also have small-scale aspects that are strongly connected with serious disasters and directly affect living conditions over a limited area. It is likely that the regional-scale climate undergoes drastic changes, even when global-scale climate changes slightly. Therefore, detailed information of the climate change over a limited area (e.g., occurrences of severe phenomena such as heavy rainfall and wind gusts, changes in the hydrological cycle, drains on water resources, frequencies of abnormally warm–cold weather) is of great importance.

General circulation models (GCMs) use a coarse horizontal resolution of a few hundred kilometers for climate simulations. While a GCM with a grid interval of a few hundred kilometers can resolve synoptic-scale disturbances, mesoscale disturbances, which are equally important to the regional climate, cannot be resolved. Therefore, numerical models with a 20–100-km grid-spacing covering only a limited area of interest have been used to simulation regional climate (e.g., Giorgi et al. 1994; Jones et al. 1995, 1997; Hong et al. 1999; Kanae et al. 2001; Nobre et al. 2001; Hong and Kalnay 2002; Mabuchi et al. 2002, etc.). Such regional climate models (RCMs), however, are still insufficient for examining regional climate, since horizontal scales of severe phenomena accompanied by strong vertical motions are smaller than 20–100 km and most mesoscale models can only accurately resolve scales greater than about several times the grid spacing due to numerical diffusion adversely impacting smaller scales. Moreover, hydro-

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static balance, which is generally assumed in most GCMs or RCMs, cannot be used in the simulations of severe phenomena with a horizontal grid of less than 10 km (e.g., Kato 1997). Accordingly, a nonhydrostatic model with a high resolution of several kilometers is presently used to conduct a detailed investigation of regional climate.

The Meteorological Research Institute (MRI) and the Numerical Prediction Division, Japan Meteorological Agency (JMA), have jointly developed a nonhydrostatic model (JMA-NHM). The JMA-NHM is presently used for short-term predictions (less than 1 day), and good model performances have been confirmed, especially for the forecast of heavy rainfall (Saito et al. 2001). Some improvements, however, are necessary when the JMA-NHM is applied to a long-time integration of the climate model (e.g., updated SST, function of restart, etc.). One of those improvements, a sophisticated coupling method of a limited-area model to a GCM, has been introduced into the JMA-NHM.

There are several approaches available for coupling a limited-area model with a GCM. Traditionally, a method termed the lateral boundary coupling (LBC) has often been used. The LBC method is a conventional nesting method, in which an inner high-resolution model is joined with a one-way transfer of information from the outer low-resolution model at the lateral boundary. In the LBC method, numerical treatment near the boundary of a limited-area model is generally required in order to remove spurious solutions, as well as numerical noise. According to Anthes et al. (1989), this can be accomplished by introducing Newtonian damping near the lateral boundary. In the present paper, the LBC method employs a boundary coupling technique that includes a boundary relaxation method near the lateral boundary. Although the LBC method adjusts an inner fine mesh model to an outer coarse mesh model only near the lateral boundary, other information from the outer model has no direct effect within the inner model. Therefore, it is likely that large differences will occur between the two models, unless the lateral boundary is precisely treated (Anthes et al. 1989).

Kida et al. (1991) proposed another coupling approach termed the spectral boundary coupling (SBC) method. The SBC method is a nesting technique employed in wavenumber space. In practice, the SBC method replaces the large-scale field (the long-wave part) of the inner fine mesh model with the corresponding large-scale field supplied externally from the outer coarse mesh model. Accordingly, the SBC method would inhibit the discrepancies that arise between the phases and positions of large-scale disturbances in the two models over the entire domain of interest, and a long-term integration can be conducted smoothly.

While the concept of the LBC method is based on the idea that the regional model is used to solve an initial-boundary-value problem, the concept of the SBC method is based on the idea that regional modeling is used to predict the small-scale response to large-scale conditions (downscaling), and that the large-scale field cannot be well reproduced within a limited area (Kida et al. 1991; Chen et al. 1999).

The SBC method is employed in wavenumber space, while the LBC method works in real space. Therefore, the SBC method can be simultaneously used with the LBC method. Sasaki et al. (1995, 2000) utilized objective analyses instead of a GCM as the outer model, and found that limited-area models with horizontal resolutions of 40 and 127 km reproduced well the objectively analyzed fields with a higher accuracy when the SBC method was employed together with the LBC method, rather than when only the LBC method was used. The models assume hydrostatic balance, and the dynamical and physical frameworks of the two models are similar to those of the model used for objective analyses by the JMA. It is believed that the similarity is favorable for suppressing numerical noise, when the long-wave part is replaced in the use of the SBC method.

On the other hand, a nonhydrostatic model does not assume hydrostatic balance, and employs elements of cloud microphysics schemes including both warm rain and ice in the model (no convective parameterization is used). Namely, the dynamical and physical frameworks of the nonhydrostatic model are quite different from those of the above-mentioned models. Therefore, the nonhydrostatic model might be subject to numerical noise, when the long-wave part is replaced in the SBC method.

Moreover, a nonhydrostatic model usually employs a much finer resolution. Higher resolution implies that more space can be controlled by a limited-area model in wavenumber space. Mesoscale disturbances are affected not only by the large-scale motions (downward cascading), but also by local-scale motions (upward cascading). For example, a synoptic disturbance and each convective cell are both responsible for the development of a mesoscale convective system. A high-resolution model with a horizontal grid interval of a few kilometers is able to resolve local-scale motions. If the inner high-resolution model has a strong bias upon the development of local-scale motions, or the interaction between local-scale and mesoscale motions, the mesoscale disturbances would not be well reproduced. Namely, high-resolution model performances are not necessarily improved, even if a strong constraint is
placed on the large-scale fields by the SBC method. Therefore, it is necessary to examine whether the SBC method also works well in a high-resolution nonhydrostatic model.

The main purpose of the present study is to show whether the performance of a long-term simulation with the high-resolution JMA-NHM is improved by the SBC method. To evaluate the performance, the JMA-NHM is nested into objective analyses instead of a GCM.

The idea is that the SBC is basically similar to the “spectral nudging” technique used to add nudging terms only to the long-wave components in the spectral domain (Waldron et al. 1996; von Storch et al. 2000). It is also similar to the “perturbation method” used to predict only perturbations from the results of a coarse grid model (Juang and Kanamitsu 1994; Juang et al. 1997; Cocke and LaRow 2000). That is, following the downscaling concept, a regional model is forced to satisfy large-scale conditions supplied externally from an outer coarse mesh model over the entire domain of interest. The similar methods however have not been applied to such a high-resolution nonhydrostatic model as that used in the present study. Therefore, the present investigation should offer useful information on the use of these similar methods.

Small-scale features (e.g., orography, land use contrasts, etc.) would have large upscale impacts on the large-scale flow, and regional climate models are recently being used to study upward cascading. It is, therefore, not desirable to force the large scales of the inner domain to the large scales of the outer domain like the SBC method, but rather to force the large scales of the outer domain to the large scales of the inner domain through two-way communication. The two-way coupling method, however, consumes too much computer resources to simulate regional climate. Accordingly, the one-way coupling technique of the SBC method, the spectral nudging technique, or the perturbation method, is one of the realistic solutions.

Brief descriptions of the model, the experimental designs, and the SBC method are given in section 2. The results of the present numerical experiments are shown in section 3. The sensitivity of some arbitrary parameters in the SBC method is examined in section 4. Conclusions are summarized in section 5.

2. Model description and experimental designs

a. Model description

The nonhydrostatic model used in the present study is the JMA-NHM, as described before. For the basic equations, the fully compressible equations in terrain-following coordinates on a Lambert conformal projection map are employed. The model treats sound waves implicitly in the vertical direction and explicitly in the horizontal direction (the HE–VI scheme). Terms related to the sound mode are integrated with a short time step. Other terms, which include the advection term, the friction term, and physical processes, are integrated with long time steps. A modified second-order centered-difference advection scheme and a leapfrog time differential scheme are also used. Further information on the JMA-NHM can be found in Saito et al. (2001).

The prognostic variables are the horizontal mass fluxes \((u, v)\), the vertical mass flux \((w)\), potential temperature \((\Theta)\), pressure \((p)\), turbulent kinetic energy \((e)\), the mixing ratios of water substances (water vapor, cloud water, rainwater, cloud ice, snow, and graupel), and the number densities of the condensates. The ground temperature is predicted by a four-layer soil model (Segami et al. 1989). The atmospheric radiation scheme is based on Sugi et al. (1990), where cloud amounts are calculated using relative humidity, although water substances are prognostic variables. Calculations of the surface fluxes are based on Monin–Obukov similarity theory. The level-2.5 closure model (Deardorff 1972, 1980) is applied to represent the vertical turbulent diffusion.

b. Experimental designs

In East Asia, the summer monsoon starts from the south in May and, extending to the north, ends in July. The monsoon circulation forms a wide rain/cloud zone with a quasi-stationary front oriented in the east–west direction (from continental China to the Japanese islands), and a large amount of rainfall occurs in this season (Ninomiya and Murakami 1987; Tao and Chen 1987). The monsoon rainfall season over East Asia is termed the baiu season in Japan. From the point of view of water resources or natural disasters, it is especially important to examine how the position of the frontal zone, and the intensity of the precipitation over the frontal zone, are altered when greenhouse gas concentrations (e.g., \(\text{CO}_2\), \(\text{CH}_4\), \(\text{O}_3\), \(\text{N}_2\text{O}\), and others) steadily increase. The future goal is to predict regional climate changes during the baiu season around East Asia resulting from the increase in greenhouse gas concentrations, making use of the high-resolution JMA-NHM. Consequently, the model domain in the present study covers East Asia, and the simulation period extends across the baiu season.

The horizontal grid size is 5 km, and the domain covers an area of 4000 km \(\times\) 3000 km (Fig. 1). The model has 48 layers in the stretched vertical, with the
The finest grid spacing (20 m) near the surface, and the coarsest grid spacing (920 m) at the model top. Rayleigh damping is imposed near the upper boundary. Although a horizontal grid of 5 km cannot fully resolve convective updrafts, the JMA-NHM with a horizontal grid of 5 km has successfully reproduced many heavy rainfall events, making use of only the cloud microphysical scheme developed by Murakami (1990) (e.g., Kato 1998; Kato and Goda 2001). Therefore, no convective parameterization is used in the present study.

The sea surface temperature (SST) objectively analyzed by JMA is used instead of that predicted by an ocean model. The JMA’s SST analysis is conducted once a day, at a horizontal resolution of 1°. Accordingly, the SST analysis is linearly interpolated onto the grids of the JMA-NHM at each model time step.

The regional objective analysis by the JMA (RANAL) is utilized for the initial field, and for the boundary conditions in the LBC method and the SBC method. So the experiments conducted in the present study are simulations, not forecasts. Operationally, the RANAL is provided four times a day (at 0000, 0600, 1200, and 1800 UTC), and covers East Asia with a resolution of 20 km in the east–west and north–south directions. Accordingly, the RANAL is also linearly interpolated in time and space, as is the SST analysis.

Two numerical experiments are conducted to evaluate the SBC method. In one experiment, only the conventional LBC method is employed, while in the other experiment, the LBC and SBC methods are simultaneously used. Hereafter, the former is conveniently called the LBC experiment, and the latter the SBC experiment. In both experiments, the time integration starts at 0000 UTC on 21 May 2003, and ends at 0000 UTC on 30 June (40 days).

### c. Brief description of the SBC method

The procedure governing the SBC method and some specified constants controlling the SBC method are briefly described in this section. More details can be found in Kida et al. (1991) or Sasaki et al. (1995).

To develop a spectral limited-area model, Tatsumi (1986) introduced the concept of an additional base, and defined the modified Fourier sine bases denoted with an *:

\[
\sin^* kx = \cos(-kx)(k = -1, 0), \\
\sin^* kx = \sin(kx)(k = 1, 2, 3, \ldots),
\]

for \( 0 \leq x \leq \pi \),

where \( k \) is the wavenumber. The modified Fourier sine bases are applied to the expanded horizontal field of a limited-area model. The additional base \( (k = -1, 0) \) and sine bases with low wavenumbers \( (k = -1, 2, 3, \ldots) \) can be interpreted as the large-scale field in the sector of the limited-area model.

First, the limited-area model fields and the corresponding fields of the outer extended-area model are individually horizontally expanded in the double-modified Fourier sine series after a given time. Second, only the long-wave parts of the two models in wave-
number space are transformed back to real space. After these procedures, the large-scale fields of the limited-area model \( F_{\text{large}}(x,y) \) and outer extended-area model \( G_{\text{large}}(x,y) \) are obtained as follows:

\[
F_{\text{large}}(x,y) = \sum_{k=-L_x/2}^{L_x/2-1} \sum_{l=-L_y/2}^{L_y/2-1} F_{kl} \sin^* \left( \frac{x}{Lx} \right) \sin^* \left( \frac{y}{Ly} \right),
\]

\[
G_{\text{large}}(x,y) = \sum_{k=-L_x/2}^{L_x/2-1} \sum_{l=-L_y/2}^{L_y/2-1} G_{kl} \sin^* \left( \frac{x}{Lx} \right) \sin^* \left( \frac{y}{Ly} \right),
\]

where \( 0 \leq \pi(x/Lx), \pi(y/Ly) \leq \pi \).

Here, \( k \) and \( l \) are the boundary wavenumbers in the \( x \) and \( y \) directions, respectively. The boundary wavenumber divides the large-scale and small-scale fields. The \( L_x \) and \( L_y \) are the distances of the region in the \( x \) and \( y \) directions where the SBC method is employed.

Third, the large-scale fields of the limited-area model \( F_{\text{large}}(x,y) \) are subtracted from the total field of the limited-area model \( F_{\text{LAM}}(x,y) \). As a result, the grid data that belong to the short-wave part in wavenumber space \( F_{\text{small}}(x,y) \) can be obtained as

\[
F_{\text{small}}(x,y) = F_{\text{LAM}}(x,y) - F_{\text{large}}(x,y).
\]

The long-wave part of the outer extended-area model and the short-wave part of the limited-area model are finally coupled as

\[
F_{\text{coupled}}(x,y) = F_{\text{small}}(x,y) + G_{\text{large}}(x,y),
\]

and the time integration is continued. These cycles are repeated until the end of the time integration.

While the SBC method replaces the large-scale field of the inner fine mesh model with the corresponding large-scale field supplied externally from the outer extended-area model, nudging terms are added in the spectral nudging technique. The procedure of the spectral nudging technique can be briefly expressed as

\[
F_{\text{coupled}}(x,y) = F_{\text{small}}(x,y) + (1 - \alpha)F_{\text{large}}(x,y) + \alpha G_{\text{large}}(x,y),
\]

where \( \alpha \) is the nudging coefficient, and if \( \alpha \) equals 1, the spectral nudging technique is the same as the SBC method.

In the present study, \( k_x = 6, l_x = 6, L_x = 3780 \) km, and \( L_y = 2780 \) km are used. It should be noted that the distances \( L_x \) and \( L_y \) are not those of the entire model domain \( (4000 \) and \( 3000 \) km). The LBC method is employed near the lateral boundary (within 150 km of the nearest boundary) and the values of the limited-area model within the marginal area are forced toward those of the outer extended-area model through Newtonian damping. On the other hand, the values of the coupled field \( F_{\text{coupled}}(x,y) \) do not necessarily approach those of the outer extended-area model after using the SBC method. Therefore, if the SBC method is used over the entire model domain, the discrepancy between the SBC and LBC methods in the marginal area will produce numerical noise. For the time interval of the SBC method, 20 min is adopted. The RANAL is provided every 6 h and linearly interpolated in time. If the time interval of the SBC method equals that of the model dynamics or physics \( (12 \) s), the SBC method is equivalent to the spectral nudging method (Waldron et al. 1996; von Storch et al. 2000) in which the nudging coefficient is 1. The SBC method is applied to the horizontal mass fluxes \( (u, v) \) and the potential temperature \( (\theta) \), and is confined to heights above 5 km, so that the flow at lower levels is free to adjust to local conditions.

3. Results

a. Sea level pressure

Figure 2 shows the analyzed and predicted patterns of sea level pressure. On day 11 of the integration (0000 UTC 31 May), a depression is predicted, located close to the analyzed position in the SBC experiment (Figs. 2a-1 and 2b-1) while the depression is predicted well south of the analyzed position in the LBC experiment (Fig. 2c-1). On days 21 and 31, predicted depressions are also located closer to the analyzed positions in the SBC experiment than in the LBC experiment (Figs. 2a-2, 2a-3, 2b-2, 2b-3, 2c-2, and 2c-3). On days 31 and 41, anticyclones over the Pacific Ocean are much stronger in the LBC experiment than those in the SBC experiment and analysis (Figs. 2a-3, 2a-4, 2b-3, 2b-4, 2c-3, and 2c-4).

To statistically evaluate the simulated sea level pressure differences in the values averaged over the model domain and correlation coefficients between the analyzed and predicted patterns are calculated (Figs. 3 and 4, respectively). While the bias of domain-averaged sea level pressure frequency exceeds a value of 1.5 hPa in the LBC experiment, it does not exceed a value of 1.3 hPa in the SBC experiment (Fig. 3). The averaged value of the model bias during the entire integration period is about 1.53 hPa in the LBC experiment, which is about twice as large as that in the SBC experiment \( (0.78 \) hPa).

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1 Both the SBC and LBC methods are employed over an area that covers 110–150 km from the nearest boundary. The Newtonian damping efficiency in the marginal area is a linear function of the distance from the nearest boundary, and one can assume that the damping efficiency is such that numerical noise will not develop excessively in the area located 110–150 km from the nearest boundary.
In Fig. 4, higher correlation coefficients are found in the SBC experiment, which implies that SBC patterns more similar to the analyses are reproduced, compared to those in the LBC experiment. All these statistical results support the higher accuracy of the sea level pressure predicted in the SBC experiment.

**b. Precipitation**

The Global Precipitation Climatology Project (GPCP) is an element of the Global Energy and Water Cycle Experiment (GEWEX) of the World Climate Research Program (WCRP). The GPCP has compiled a 2.5° × 2.5° pentad dataset starting in 1979 by merging infrared and microwave satellite estimates of precipitation with rain gauge data from more than 6000 stations.

Figure 5 represents rainfall patterns accumulated over 10 days. In both experiments, predicted peaks in the precipitation are weaker than those in the analyses by the GPCP, except for the period 10–19 June of the LBC experiment (Fig. 5c-2). Overall, the SBC experiment reproduces patterns similar to those of the GPCP. In the LBC experiment, heavy rainfall regions shift northward during 20–29 June, and a false maximum is found in northern Japan (Fig. 5c-3). Moreover, the peaks found in China in the GPCP analyses and the SBC experiment (Figs. 5a-3 and 5b-3) are not reproduced in the LBC experiment. It is thought that the shift to the north in the LBC experiment results from the stronger anticyclones over the Pacific Ocean (Figs. 2c-3 and 2c-4).
To statistically evaluate surface precipitation around Japan, the area of Japan is divided into five subregions (SW, KS, CJ, EJ, and NJ in Fig. 6). The total rainfall amounts over all grid points within each subregion predicted by the JMA-NHM are compared with Radar-AMeDAS analyzed rainfall over the same regions. The Automated Meteorological Data Acquisition System (AMeDAS) automatically observed several meteorological elements (e.g., wind speed, wind direction, temperature, or rainfall amount) every 10 min. About 1300 AMeDAS stations are located over Japan, and the mean distance between the stations is about 17 km. The Radar-AMeDAS analyzed rainfall is the hourly total precipitation estimated by ground-based C-band radar, calibrated with the AMeDAS rain gauge data. The resolution of the data is about 2.5 km.

Figure 7a shows integrated rainfall amounts over Japan and the subregions (Fig. 6) for 33 days (from 28 May to 29 June). To remove the influence of the initial fields, the precipitation amounts during the first 7 days are not included in these statistics. In the LBC experiment, the rainfall amounts are overestimated in all regions, except for those in SW. For the SBC experiment, the rainfall amounts are closer to the Radar-AMeDAS analyzed rainfall than those from the LBC, except for those in the EJ region.

Figure 7b represents correlation coefficients between the time series of rainfall amounts predicted by the JMA-NHM, and those estimated from the Radar-AMeDAS analyzed rainfall over Japan and the subregions (Fig. 6). In this analysis, the first 7 days data are also excluded, and daily total amounts are utilized in order to remove the influence of diurnal variations. The precipitation predicted in the SBC experiment is highly correlated with the Radar-AMeDAS analyzed rainfall, and no values of the correlations are lower than 0.7 (Fig. 7b). Although the EJ region rainfall amount in the LBC experiment is closer to the Radar-AMeDAS analyzed rainfall than that in the SBC experiment (Fig. 7a), the correlation coefficient of the EJ region rainfall in the LBC experiment (0.38) is half the value of that in the SBC experiment (about 0.78). This implies that the phase of the disturbance is remarkably improved by the SBC method. Therefore, it can be concluded that the SBC method results in a fair model prediction in the EJ region.

Considerably large differences in the correlation coefficients between the two experiments are also found in the CJ, EJ, and NJ regions. The strong anticyclones over the Pacific Ocean in the LBC experiment (Figs. 2c-3 and 2c-4) deflect disturbances northward (not shown). The precipitation associated with these deviated disturbances would induce lower values of the correlation coefficient in the CJ, EJ, and NJ regions (e.g., Fig. 5c-3).

Figure 7c represents the ratios of the amount of heavy rainfall (intensity greater than 10 mm h\(^{-1}\)) to the 33-day total rainfall amounts (from 28 May to 29 June) of the integration over Japan and the subregions (Fig. 6). In the SBC experiment, the ratios of heavy precipitation are similar to those of the Radar-AMeDAS analyzed rainfall, except in the KS region. On the other hand, in the LBC experiment, the ratios are much larger than those of the Radar-AMeDAS analyzed rainfall in all regions.

The large contribution of heavy rainfall in the LBC
The experiment is not a special feature found only around the Japanese islands, but is also found in the ratios over the entire model domain, which indicates that heavy rainfall is overestimated when the SBC method is not used. The domain-averaged temperature around the 300-hPa level decreases by about 1 K on the first day of the LBC experiment, and the temperature in the LBC experiment is colder by about 1 K than that in the SBC experiment on average (not shown). The cold bias around the 300-hPa level results in reduced stability in the upper troposphere, because the domain-averaged surface temperature is not so different in between the LBC and SBC experiments, and deeper convection can easily develop in the LBC experiment.

c. Surface temperature

In this section, the surface temperature predicted by the JMA-NHM is compared with that observed at each AMeDAS station (Fig. 8). First, the correlation coefficient between the daily mean value of the surface temperature predicted by the JMA-NHM and that observed by the AMeDAS is calculated at each AMeDAS station. The predicted temperature is linearly interpolated to the AMeDAS stations. Second, the correlation coefficients are averaged over all stations within Japan and the subregions (Fig. 6). To remove the influence of the initial fields and diurnal variations, the data during the first 7 days are excluded, and daily mean values are used.

Over all regions, the mean correlation coefficients are larger in the SBC experiment than are those in the LBC experiment (Fig. 8). This result implies that the SBC simulation well reproduces the surface temperature trends. The differences between the temperature coefficients in the SBC and LBC experiments are not as remarkable as those of precipitation (Fig. 7b). This is probably a consequence of the importance of boundary layer processes and radiative processes in determining
the surface temperature relative to the influence of large-scale motions.

4. Discussion

There are some arbitrary parameters in the SBC method, such as the time interval, the boundary wave-numbers that divide the large-scale and small-scale fields, and the lowest height above which the SBC method is applied. It would be useful to examine the sensitivity of these parameters.

a. Time interval in the SBC method

The time interval in the SBC method is 20 min in the present study. When a shorter time interval is employed, the Fourier transform and the inverse Fourier transform are more frequently needed, such as in a spectral model. Consequently, the SBC method consumes considerably more computer resources. On the other hand, a longer interval is capable of keeping computational costs down. The discrepancy between the inner limited-area model and the outer extended-area model however would become so large that numerical noise will develop. Actually, when a time interval of 6 h...
is used, a domain-averaged vertical wind exceeding 10 cm s$^{-1}$ often develops after the SBC method is applied (not shown). Therefore, the time interval should be chosen taking computer resources and the discrepancy between the two models into consideration. In the present study, the optimal time interval of the SBC method is 20 min (100 time steps).

b. Wavenumber and height in the SBC method

To examine the effects of the boundary wavenumber ($K_{bd}$) and the height in the SBC method ($Z_b$), several sensitivity experiments were conducted (Table 1). In all sensitivity experiments, the integration period was 25 days (0000 UTC 21 May–0000 UTC 15 June 2003), and the boundary wavenumber in the east–west direction is the same as that in the north–south direction. In the sensitivity tests, the values of $K_{bd}$ are changed from 0 to 12 by an interval of 3 (experiments K0, K3, K6, K9, and K12), and the $Z_b$ is changed from 2.5 to 7.5 km by an interval of 2.5 km (experiments Z25, Z50, and Z75). It should be noted that the K0 experiment is a subset of the LBC experiment. The K6 and Z50 experiments are the same experiments, and subsets of the SBC experiment.

Correlation coefficients between the analyzed and simulated sea level pressure patterns averaged during the integration period (25 days) are shown in Fig. 9. The smallest value is found in the K0 experiment. Although the SBC method greatly improves the predicted patterns of sea level pressure, higher correlation coefficients are not necessarily observed in the experiments with the higher $K_{bd}$ values. Namely, the accuracy of the predicted sea level pressure is not highly sensitive to $K_{bd}$. On the other hand, the correlation coefficients decrease with increases in $Z_b$ and are more sensitive to $Z_b$ than $K_{bd}$.

Correlation coefficients between the time series of the total rainfall amounts predicted by the JMA-NHM, and those estimated from the Radar-AMeDAS analyzed rainfall over Japan and the subregions (Fig. 6), are calculated in each sensitivity test in the same manner as in Fig. 7b. In Fig. 10a, the smallest value of the coefficients is also found in the K0 experiment, and the correlation coefficients are neither highly sensitive to $K_{bd}$ nor $Z_b$, except in the K0 experiment.

Figure 10b represents the ratios of heavy rainfall with intensities greater than certain thresholds (10, 20, and 30 mm h$^{-1}$) to the total rainfall amounts over Japan for 18 days (from 28 May to 15 June) of the integration period of the K0 experiment. In the K0 experiment, the ratios of the heavy precipitation are overestimated, as was found in Fig. 7c. While considerable improvements by the SBC method are found, the predictions of heavy rainfall are not sensitive to the value of $K_{bd}$.

**Table 1.** The names and parameters employed in the sensitivity tests. The boundary wavenumber $K_{bd}$ divides the large- and small-scale fields. In all sensitivity tests, the boundary wavenumber in the east–west direction is the same as that in the north–south direction. The lowest height above which the SBC method is applied is $Z_b$.

<table>
<thead>
<tr>
<th>Expt</th>
<th>$K_{bd}$</th>
<th>$Z_b$ (km)</th>
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<tbody>
<tr>
<td>K0</td>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td>K3</td>
<td>3</td>
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<td>K12</td>
<td>12</td>
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<tr>
<td>Z25</td>
<td>6</td>
<td>2.5</td>
</tr>
<tr>
<td>Z50</td>
<td>6</td>
<td>5</td>
</tr>
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</table>

**FIG. 8.** Mean correlation coefficients of surface temperature over all AMeDAS stations within Japan and the subregions (see Fig. 6). The correlation coefficients were calculated at each AMeDAS station from the time series of surface temperature predicted by the JMA-NHM and that observed by the AMeDAS. The vertical lines represent the ranges within one standard deviation.

**FIG. 9.** Correlation coefficient between the analyzed and simulated sea level pressure patterns averaged over the integration period (25 days). The plotted values are for the sensitivity experiments as listed in Table 1.
In the Z75 experiment, large contributions from heavy rainfall are found (Fig. 10b). The ratios of the heavy rainfall dramatically change between the Z75 and Z50 experiments, while those in the Z50 and Z25 experiments are almost the same. The large difference between the Z75 and Z50 experiments could result from the cold bias around the 300-hPa level, which is remarkably found in the Z75 and Z0 (LBC) experiments, as pointed out in section 3b (not shown).

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5. Summary

The spectral boundary coupling (SBC) method used when coupling an RCM with a GCM, as proposed by Kida et al. (1991), was introduced into the JMA-NHM. The performance of long-term integrations by the JMA-NHM with a horizontal grid spacing of 5 km was examined in order to evaluate the SBC method. Two numerical experiments were conducted in the present study. In one experiment, only the conventional lateral boundary coupling (LBC) method was employed (the LBC experiment), while in the other, the LBC and SBC methods were simultaneously used (the SBC experiment). The time integration in both experiments started at 0000 UTC on 21 May 2003, and ended at 0000 UTC on 30 June (40 days). The regional objective analyses by the JMA (RANAL) were utilized for the initial and boundary conditions in the LBC and SBC methods, instead of the forecasts produced by a GCM.

In the SBC experiment, patterns of predicted sea level pressure were more similar to the RANAL, and the model bias was lower than that in the LBC experiment. The SBC experiment also reproduced well the precipitation patterns from the GPCP. Statistical verifications of predicted precipitation and surface temperature around Japan were conducted. Rainfall amounts accumulated for 33 days in the SBC experiment agreed with the Radar-AMeDAS analyzed rainfall. Moreover, correlation coefficients of the daily rainfall amounts and surface temperature were larger in the SBC experiment than in the LBC experiment. All these statistics demonstrate better performance in the SBC experiment, with the result that the SBC method (i.e. “spectral nudging technique”) or the “perturbation method is highly useful for long-term simulations by a high-resolution regional climate model.

Miguez-Macho et al. (2004) stated that the spectral nudging of long wavelengths is necessary to eliminate the dependence of results on the position of the domain of a regional climate model. In the SBC experiment, the model can reproduce a much more similar pattern of atmospheric fields, which implies large-scale structure can be introduced efficiently by the SBC scheme regardless of the model domain or its position in physical space. Therefore, the SBC method is also expected to eliminate the dependence of results on the position of the domain of a regional climate model.

Anthes et al. (1989) pointed out that objective measures of error over a domain size 3600 × 4800 km$^2$ show little growth beyond about 36 h, and that on these time and space scales, the quality of the lateral boundary conditions is more important than the physical parameterization. The SBC method also constrains the boundary of a limited-area model in wavenumber space. Therefore, the difference between the LBC and SBC methods would be more important than the model physics in the long-term simulation beyond several days. Moreover, even if physical parameterizations are perfect, large-scale errors would be inevitable in long-term simulations by a regional climate model using the LBC method only, because there is no lateral boundary condition satisfying the well posedness. The problem of
the ill posedness in the LBC method will become more important to upscaling research using a regional climate model.

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REFERENCES


