A Scale Interaction Study on East Asian Cyclogenesis Using a General Circulation Model Coupled with an Interactively Nested Regional Model

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ABSTRACT
This study newly developed the interactively nested climate model (INCL) using a general circulation model (GCM) interactively nested with a regional atmospheric model (RAM). One interactive experiment with finer RAM topography and another with coarser topography, as well as offline versions of each experiment, were performed to investigate the effects of subsynoptic-scale eddies and subsynoptic-scale mountains in northeast Asia on the larger-scale climate, using the GCM with T42 atmosphere and the RAM with 40-km mesh size in the INCL system. The subsynoptic-scale eddy effect restrictively increased synoptic-scale eddy activity within the RAM domain. In contrast, subsynoptic-scale mountains had the effect of robust anticyclonic circulation around the Sea of Japan and effectively forced larger-scale circulation. The effect was positively fed back to the mean field and amplified the anticyclonic circulation accompanied by suppressed storm activity in northeast Asia. The results suggest that subsynoptic-scale mountains affect not only subsynoptic-scale eddies but also the global climate.

1. Introduction
The atmosphere consists of a variety of planetary-\([O(10^4 \text{ km})]\), synoptic-\([O(10^3 \text{ km})]\), subsynoptic-\([O(10^2 \text{ km})]\), meso-\([O(10 \text{ km})]\), and microscale \([O(1 \text{ km})]\) phenomena,\(^1\) the mutual interactions of which play a substantial role in the atmospheric general circulation. The extratropical quasigeostrophic theory advanced in the 1980s explained the relationship between zonal-mean flow and zonally varying eddies using the Eliassen–Palm flux theory (Edmon et al. 1980). Extension of the Eliassen–Palm flux theory to three dimensions has contributed to an understanding of the interaction between time-mean flow and temporally varying eddies (Hoskins et al. 1983; Takaya and Nakamura 2001). Recently, Nakamura et al. (2004) provided a comprehensive overview of the relationship of the planetary-scale jet stream, synoptic-scale eddy activity, and sea surface temperature (SST) fronts. Based on these theoretical foundations, the interaction between planetary- and synoptic-scale phenomena has been thoroughly investigated for the extratropical atmosphere.

Even with dominating baroclinic instability, the mid-latitude atmosphere contains phenomena smaller than the synoptic scale that possibly influence planetary-scale or synoptic-scale phenomena. Cyclones are generally of synoptic scale, which can be resolvable in conventional general circulation models (GCMs). The subsynoptic-scale structure of a cyclone may be related to the rapid growth or geographical distribution of storm generation. This may be one reason why a GCM with a T106 (triangular truncation at total wavenumber 106) atmosphere rather than T42 atmosphere tends to produce larger storm activity (Inatsu and Kimoto 2005) or more heavy-rainfall days (Kimoto et al. 2005). Interestingly, a

\(^1\) The horizontal scale of atmospheric motions were formerly classified into macro \(\alpha\)-, macro \(\beta\)-, meso \(\alpha\)-, meso \(\beta\)-, meso \(\gamma\)-, and microscales (Orlanski 1975). The planetary, synoptic, and subsynoptic scales referred to in this paper correspond to macro \(\alpha\)-, macro \(\beta\)-, and meso \(\alpha\)-scales, respectively.

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GCM study by Inatsu and Hoskins (2004) showed that only removing the South African Plateau significantly reduced the climatological storm-track activity in the Southern Hemisphere. That study implied that mountains or plateaus with a 1000-km horizontal scale play an important role in storm generation and storm-track activity in downstream areas.

Focusing on northeast Asia, there are various surface conditions of subsynoptic scale. Figure 1 shows the Japanese Archipelago, the Sea of Japan, and a series of subsynoptic-scale mountains and valleys from Mongolia to North Korea such as the Altai, Sayan, and Hangayn Mountains, the Mongolian Plateau, the Daxing’anling Mountain Range, the Donbei Plain, and the Changpai Mountain Range. Chen et al. (1991), using the Beijing Meteorological Center’s historical surface maps for 1958–87, found that the areas of most active cyclogenesis were the lee sides of mountain complexes in northeast Asia, the East China Sea, and the Sea of Japan. Updating their analysis with 1.25° × 1.25° mesh 40-yr European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA-40) and using a new cyclone-detecting technique, Adachi and Kimura (2007) revealed that cyclones were frequently generated in spatially limited regions. Yoshida and Asuma (2004), using high-resolution data to partially resolve subsynoptic-scale cyclones, classified three types of preferred cyclone tracks around Japan: the Okhotsk–Japan type, Pacific Ocean–land type, and Pacific Ocean–ocean type. In particular, cyclones that pass along the south coast of Japan, known as Japanese south-coastal cyclones, feature a subsynoptic-scale structure in the incipient stage but often rapidly develop because of stimulation by large amounts of water vapor supplied from the warm ocean of the Kuroshio Current (Takano 2002; Nuss and Kamikawa 1991). In the field of cyclogenesis and tracking study, investigation of the effects of subsynoptic-scale eddies and subsynoptic-scale mountains on larger-scale climate are possible next research steps. However, it has been quite difficult to study these relationships because of the immense computational resources needed to perform several-year integrations using a climate model with a high resolution of less than 50-km mesh size. Such an unrealistically heavy computational burden has previously been an obstacle to scale-interaction studies of this kind.

An interactively nested climate model (INCL) system, newly developed in this study, will solve the problem discussed above. In this system, a regional atmospheric model (RAM) with a higher resolution for a specific limited area is nested into a GCM with a conventional resolution for the global domain, and the exchange of information between the two models is realized in an interactive manner. The INCL system is a kind of two-way nesting climate model, like that of Lorenz and Jacob (2005), who first attempted to use a two-way nesting model for a climate problem. As an example of how the INCL system works, we consider the effect of subsynoptic-scale mountains in northeast Asia on the global climate. If we used a desired-resolution GCM, such as a T213 GCM, we could easily solve the problem by comparing an experiment with T213 surface elevation everywhere.

Unlike our INCL system, they nested a RAM with 0.5° × 0.5° mesh size into an atmosphere-only GCM and used the same cloud parameterization in the two models.
and another experiment with T42 surface around northeast Asia and T213 surface elsewhere. With the INCL system, in contrast, the RAM would be nested from northeast Asia to the northwest Pacific, and we would perform two INCL experiments: one with finer RAM topography and the other with coarser topography. The difference in the GCM output between the two INCL experiments would show the effect of the subsynoptic-scale topography not only on the regional weather in northeast Asia but also on the global climate. Compared with the high-resolution GCM, the INCL system should greatly reduce the computational burden because the INCL system calculates only a limited area with fine resolution and calculates other areas with coarse resolution. We could therefore calculate the above example using a conventional supercomputer.

The purpose of this paper is to investigate the following two effects on larger-scale climate using the INCL system and focusing on northeast Asia: the effect of subsynoptic-scale mountains, which may generate cyclones, on larger-scale climate as discussed above; and the effect of subsynoptic-scale eddies that are resolvable in a 40-km mesh-size RAM nested into the GCM. In this paper, we describe two interactive INCL experiments, each with a different resolution for RAM topography, as well as noninteractive versions of these experiments. Each INCL experiment produces both GCM and RAM outputs. We then analyze each experiment's output to investigate the mountain and eddy effects. The details are described in section 2, together with brief documentation of the newly developed INCL system. Analysis methods such as cyclone tracking are described in section 3, supplemented with appendix B. Section 4 describes the effects of subsynoptic-scale mountains and subsynoptic-scale eddies. Although we do not deal with the general possibility that the INCL could reduce biases in the GCM used, we add a short comment on the comparison of the INCL results with observations in section 4. Section 5 discusses possible applications of the INCL system to other multiscale interaction problems. Section 6 concludes the paper.

2. Models and experiments

a. Models

The INCL system, a kind of two-way nesting climate model, contains an atmosphere–ocean GCM, called the Model for Interdisciplinary Research on Climate 3.2, (MIROC3.2); a RAM, called the Japan Meteorology Agency/Meteorological Research Institute (JMA/MRI) nonhydrostatic model (NHM); and a coupler for transferring data between the two models. The GCM has been jointly developed by Center for Climate System Research (CCSR) of the University of Tokyo, National Institute for Environmental Studies (NIES) of Japan, and the Frontier Research Center for Global Change (FRCGC) of the Japan Agency of Marine-Earth Science and Technology (JAMSTEC). The RAM has been developed jointly by the JMA and MRI. The coupler was newly developed in this study.

MIROC3.2, one wing of the INCL system, calculates the whole domain of the global atmosphere and oceans and has five submodels for atmosphere, ocean, sea ice, land surface, and river with a flux coupler connecting the five submodels. The resolutions are T42 with 20 vertical sigma levels for the atmosphere and land submodels and 1.4° longitude by 0.9° latitude with 44 levels for the ocean and sea ice submodels. The dynamical package of the atmosphere and ocean submodels is based on three-dimensional primitive equations. In the atmospheric submodel, the prognostic variables are zonal and meridional winds, air temperature, specific humidity, and surface pressure. The atmospheric and ocean physical packages parameterizes cumulus cloud convection (Pan and Randall 1998), large-scale condensation, vertical turbulent mixing, radiative transfer, gravity wave drag, and oceanic turbulence and convection. The other submodels solve for processes of snow, soil, and canopy water, runoff, river flow, and sea ice. No flux adjustment is applied in the atmosphere–ocean coupling. See the report of the K-1 model developers (Hasumi and Emori 2004) for more details.

The JMA/MRI NHM, the other wing of the INCL system, calculates a limited domain of the atmosphere and is based on the nonhydrostatic formulation. The horizontal mesh size is set to 40 km, about one-fifth of the GCM zonal mesh size in the midlatitudes, where the GCM mesh size is about 200 km in the zonal direction and about 280 km in the meridional direction. The RAM has 38 vertical levels in a terrain-following coordinate. The prognostic variables of the RAM are three-dimensional wind vectors, potential temperature, and densities of dry air, water vapor, cloud water, cloud ice, snow, and graupel. The RAM also has state-of-the-art physical packages, though different from those of the GCM, such as cloud microphysics parameterization, atmospheric radiative transfer, turbulent mixing, boundary layer processes, and surface flux estimations. The Kain–Fritsch convective parameterization scheme (Kain and Fritsch 1993) complements the precipitation amounts and is widely used for NHMs with mesh size greater than 10 km. See Saito et al. (2006) for this version of the JMA/MRI NHM.

The INCL system includes data-transferring subroutine codes that connect the GCM integration with the RAM one. In a usual downscaling, a RAM only obtains
information from GCM outputs or observation data as its lateral boundary conditions. In the INCL system, we implement not only such a one-way nesting but also an interactive nesting, in which the RAM not only takes the GCM outputs as the boundary conditions but also returns the aggregation of the finer-mesh RAM result to the GCM within a RAM nested area. Technically a main program controls both the GCM and RAM in the INCL system using a parallel programming technique called single program and multiple data.

The INCL experiment is basically a cycle of the following four procedures. First the GCM is integrated from a particular time \( t_0 \) to the time \( t_0 + \Delta t \); one GCM time step \( \Delta t \) is 20 min. Second, the RAM obtains the GCM data at \( t_0 \) as the lateral boundary conditions. Third, the RAM is integrated from \( t_0 \) to \( t_0 + \Delta t \) with 30 RAM time steps; one RAM time step is 40 s. The RAM prepares Rayleigh-type damping sponge layers that are imposed in 24 grids from the outer edge of the RAM domain. The RAM prognostic variables are hence enforced by the data interpolated from the GCM prognostic and diagnostic variables (see appendix A for details of the interpolation). In the RAM, the SSTs are prescribed using the smoother atmospheric GCM outputs, and the land surface temperatures are predicted. At the end of the third procedure, the GCM and RAM provide different time increments from \( t_0 \) to \( t_0 + \Delta t \) of their common prognostic variables such as zonal and meridional winds, air temperature, and specific humidity. The GCM time increments of zonal and meridional winds, air temperature, and specific humidity are then modified; however, we did not implement this procedure for surface pressure because surface pressure is greatly influenced by surface height. This is one of the points that we should improve in the INCL system, although we think that it may not be a crucial issue in this paper. Finally, the GCM time increment of a particular prognostic variable \( \Delta f \) is modified as

\[
\Delta f = \alpha \Delta f_{\text{RAM}} + (1 - \alpha) \Delta f_{\text{GCM}},
\]

where \( \Delta f_{\text{RAM}} \) and \( \Delta f_{\text{GCM}} \) are time increments of variable \( f \) by the GCM and RAM, respectively; and \( \alpha \) is an interactive nesting index as a function of space in the nested area and uniformly equals zero outside the nested region. If we set \( \alpha = 0 \) everywhere, the INCL system realizes a conventional one-way downscaling and provides GCM and RAM outputs in a single computation. This is called offline integration. An interactive integration in this paper uses \( \alpha \) as in Fig. 2b after a spinup offline integration in the initial 5 days. In most of the interacting region, we adopt a value of \( \alpha = 0.5 \). Use of the full interactive value of \( \alpha = 1 \) everywhere often creates some computational instability in the GCM, perhaps because it might be too strong a forcing in only a limited region.

b. Experiments

Table 1 shows the four experiments. In all the experiments, the RAM calculated the limited domain with 194 \times 110 grids focused on the area from northeast Asia to the northwest Pacific (contoured or shaded areas in Figs. 1 and 2a) to separately show the effects of subsynoptic-scale eddies and subsynoptic-scale mountains in northeast Asia on larger-scale climate. The conventional downscaling is referred to here as the OF

<table>
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<tr>
<th>Nesting</th>
<th>Land surface boundary of the RAM</th>
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<tr>
<td>IF Interactive Fine with 40-km mesh size</td>
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<tr>
<td>IS Interactive Smooth with 200-km mesh size</td>
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<tr>
<td>OF Offline Fine with 40-km mesh size</td>
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<tr>
<td>OS Offline Smooth with 200-km mesh size</td>
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experiment, in which the finer mesh-size RAM with finer surface elevations (Fig. 1) was, in a conventional sense, nested into the coarser mesh-size GCM with coarser boundary conditions (Fig. 2a). The other offline INCL experiment is called OS, in which the finer mesh-size RAM with coarser surface elevations completely the same as in the GCM (Fig. 2a) was nested into the coarser mesh-size GCM. The interactively nested versions of the OF and OS experiments are named IF and IS, respectively. All the experiments output both GCM and RAM results. Hereafter, the RAM output of the IS experiment is abbreviated as IS RAM, for example. Note that OF GCM is completely the same as OS GCM and a single control GCM, whereas OF RAM is different from OS RAM. In this paper we will only focus on the results of the RAM and the results of the atmospheric submodel of the GCM; the ocean submodel is included for the convenience of future studies.

In all INCL experiments, 10 ensemble time integrations started from 22 November and ended 105 days later. The initial condition for each of the ensemble integrations was different and was constructed by a 10-yr control GCM experiment. Based on the results for December–January–February (DJF), in section 4 we will mainly focus on the 10-DJF climatology including cyclone statistics. Without any assurance to conserve total energy and total water content, the INCL experiment would possibly suffer from climate drifts for a long-term integration. Here we did not have to pay much attention to this potential problem because the experiments were only 105 days long.

Section 4b will concentrate on the effect of subsynoptic-scale eddies. We will first compare OS RAM with OS GCM. The former can resolve the subsynoptic-scale eddies, whereas the latter mostly misses them. This comparison is expected to reveal, within the limited nested domain, the difference in subsynoptic-scale eddy characteristics between the GCM and RAM. It is important to note that the difference between OS GCM and OS RAM includes the effects not only of subsynoptic-scale eddies but also of the different parameterizations between the two models. We expect that the model parameterization difference may not be large because the RAM atmosphere is forced by the GCM in the upper, lower, and sidewall boundaries, and because the phenomena of interest here are principally dynamically driven. Because some additional sensitivity experiments are needed to solve this problem, we decided to leave this problem for future study and here interpret the difference between OS RAM and OS GCM as the subsynoptic-scale eddy effect only. The comparison between IS GCM with OS GCM will also reveal the effect on global climate of subsynoptic-scale eddies in the nested domain because the IS GCM reflects OS RAM, in which subsynoptic-scale eddies are resolvable.

Section 4c will emphasize the effect of subsynoptic-scale mountains in northeast Asia. We will first compare OF RAM with OS RAM. The difference between OF and OS is only the resolution of surface elevations in the RAM. This comparison will clarify the effect of subsynoptic-scale mountains within the nested domain. As noted in the introduction, comparison of IF GCM with IS GCM clarifies the global interactive effect. Moreover,
comparison of IF RAM with IS RAM displays a feedback effect of the GCM–RAM coupling.

3. Storm track detection

Cyclone track density will be calculated to reveal subsynoptic-scale eddies in section 4. The tracking algorithm, only using the gridded sea level pressure (SLP) data, is quite simple but sufficient for our purpose. See appendix B for details of the algorithm. Figure 3 shows the cyclone track density in the northwest Pacific based on ERA-40 data from 1979 to 1997. The tracking is calculated within the area shown by the rectangle in Fig. 3. Three to six cyclones pass the central North Pacific in one winter season on average, and a density maximum is located just east of Japan (35°N, 150°E). The density distribution clearly shows two cyclogenesis regions: the Sea of Japan and the mouth of the Yangtze River to the south of Japan. A secondary maximum is located in the Sichuan Basin, but this is perhaps a false result. The cyclone tracks tend to move northeastward to Alaska and the northeast Pacific. Comparing the results with those of Hoskins and Hodges (2002), who used a highly sophisticated tracking algorithm, the track density is qualitatively similar. Our simple tracking result is also consistent with other tracking results such as those of Yoshida and Asuma (2004) and Adachi and Kimura (2007).

Overall middle and lower-tropospheric storm-track activity can also be represented using the variance of high-pass-filtered meridional wind at 500 hPa and the covariance of high-pass-filtered temperature and meridional wind at 850 hPa, respectively. The high-pass filter we used is a 14-point numerical filter that can extract fluctuations with periods between 2 and 8 days.

4. Results

a. Conventional GCM climatology

Figure 4 shows the DJF climatology in OS GCM, which is exactly the same as a conventional GCM experiment. The GCM produces strong stationary troughs...
over the Sea of Okhotsk and eastern Canada and stationary ridges in Alaska and northern Europe (contours in Fig. 4a). Consistent with the stationary troughs and ridges, the midtropospheric storm activity represented by high-pass-filtered meridional wind variance at 500 hPa (shadings in Fig. 4b) has maxima in the central North Pacific and central North Atlantic, just downstream of a maximum of lower-tropospheric storm activity represented by high-pass-filtered meridional heat flux at 850 hPa (contours in Fig. 4b). Focusing on northeast Asia, the heat flux has a secondary maximum in northeast China that corresponds to a preferable storm generation area (cf. Chen et al. 1991; Yoshida and Asuma 2004). The 500-hPa high-pass eddy momentum flux (shadings in Fig. 4a) shows that baroclinic eddies contribute to transporting zonal momentum from the subtropical jet (STJ) to the subpolar front in the North Pacific and North Atlantic. The overall climatology of planetary-scale and synoptic-scale eddy activity in DJF is considered to be similar to the observed activity, and thus for our study purpose, the OS GCM can be regarded as the reference.

b. Subsynoptic-scale eddy effect

The subsynoptic-scale eddy effect, as stated in section 2, can be shown by the comparison between OS GCM and OS RAM or the comparison between IS GCM and OS GCM. The former comparison, in the conventional downscaling context, reveals the effect in the RAM-limited domain, whereas the latter includes the subsynoptic-scale eddy effect on the larger-scale climate by using the newly developed INCL system with the interactive mode.

Figure 5 shows the RAM–GCM difference in the OS experiment. Using smooth topography as in the GCM (Fig. 2a) and the sidewall boundary conditions given from the GCM output, the RAM has substantially the same setting as the GCM. Except for a bogus horizontal wind response around the Tibetan Plateau, presumably due to an insufficient model-to-model connection (Figs. 5a,b), the RAM zonal wind is weaker in the STJ region and is slightly stronger around 50°N, 130°E (Fig. 5a). There is little difference in meridional wind, indicative of little change in position of the stationary trough in the nested region (Fig. 5b). The RAM significantly amplifies the synoptic-scale eddy activity in the center of the nested domain. Comparing RAM with GCM, the high-pass eddy activity in the midtroposphere increases by about 20%3 (Fig. 5c); the high-pass eddy heat flux in the lower troposphere is specifically emphasized from Taiwan to Japan and slightly deemphasized from North Korea to the Sea of Okhotsk (Fig. 5d). Such eddy activity amplification might mainly be caused by the fact

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3 Some caution is necessary in comparing Fig. 4b and Figs. 5c,d. Rigorously, the eddy covariance at a constant height is quantitatively different from that at a constant pressure near that height. However, the difference can be neglected in this discussion.
that the RAM with 40-km mesh size can resolve most subsynoptic-scale cyclones. Note also that the enhancement of storm activity, taking zonal momentum from the STJ (not shown), brings the wind response around Japan as in Figs. 5a,b. Moreover, in the comparison of the cyclone track density distribution (section 3 and appendix B) between OS GCM and OS RAM (Fig. 6), OS RAM has twice as many cyclone tracks to the southeast of Japan and emphasizes the cyclone track running from northeast China to the Sea of Japan.

Because IS GCM reflects the RAM characteristics of subsynoptic-scale eddy activity, IS GCM is expected to produce more cyclones in the western Pacific. This implies that the interactive experiment possibly emphasizes explosively developing cyclones. Figure 7a shows the frequency distribution of the maximum deepening rate of the SLP for explosive cyclones in the IS and OS GCMs in the limited area of 25°–65°N, 100°E–180°E, following Yoshida and Asuma (2004). An explosive cyclone is defined as a cyclone with a maximum deepening rate of more than 1 bergeron, or 24-hPa pressure depression in 24 h (Sanders and Gyakum 1980). Whereas OS GCM counts 145 explosive and 249 nonexplosive cyclones, IS GCM counts 171 explosive and 228 nonexplosive cyclones (Table 2). The statistics show that the interactive experiment produced approximately 20% more explosive cyclones in the western Pacific area. This difference is apparent in the explosive cyclones in the area south of 40°N (Fig. 7b). The IS GCM counts 165 cyclones there, and OS GCM counts 150. However, IS GCM shows 76 explosive cyclones, whereas OS GCM shows only 52 (Table 3). Half of the total tracks have been counted as the Pacific Ocean–ocean type cyclones that formed and developed over the Pacific Ocean (Yoshida and Asuma 2004). Assuming that this type corresponded to the explosive cyclones south

![Figure 6](https://example.com/figure6.png)

**Fig. 6.** The DJF climatology of the cyclone-track density for (a) OS GCM and (b) OS RAM. The contour interval is 1 track season$^{-1}$. The density is calculated within the same area as in Fig. 3 for OS GCM and within the RAM domain shown in Fig. 1 for OS RAM.
of 40°N in this discussion, the interactive model would apparently produce many more cyclones categorized as this type.

Figure 8 shows the GCM difference between IS and OS experiments. Because the interactive integration feeds the RAM result back to the GCM, IS GCM emphasizes the eddy activity in the western Pacific in the lower and midtroposphere (cf. Figs. 5c,d). The difference is highly statistically significant, but the synoptic-scale eddy activity difference is confined around the nested domain. The IS GCM greatly emphasizes cyclone track density along the Kuroshio Current (Fig. 9), reflecting the RAM result directly. This suggests that the subsynoptic-scale eddy effect in northeast Asia may change the synoptic-scale eddy activity at least there. The enhanced eddy activity seems to transport zonal momentum poleward in northeast Asia and then likely induces an anticyclonic circulation anomaly in the central Pacific. The signal, however, is statistically insignificant and does not propagate farther. Except for a significant anticyclonic circulation around Greenland, there is little difference in the geopotential height field between IS GCM and OS GCM (Fig. 8a). Therefore, the subsynoptic-scale effect has little feedback.

Summarizing the model result comparison, the subsynoptic-scale eddy effect in northeast Asia increases the regional synoptic-scale eddy activity around the nested domain. In the interactive experiment, the eddy-induced circulation that stems from the RAM response is too weak to generate any significant and globally propagating signals in the GCM. Hence, little feedback occurs in the interactive experiment.

c. Subsynoptic-scale mountains effect

The subsynoptic-scale mountains effect can be shown in the comparison between OF RAM and OS RAM and the comparison between IF GCM and IS GCM. The former, one of the conventional downscaling applications, can reveal the effect within the limited RAM domain, whereas the latter includes the effect to the global climate and its feedback to the RAM domain. The feedback effect is displayed in the comparison between IF RAM and IS RAM.

The difference between OF RAM and OS RAM shown in Fig. 10 is robust time-mean circulation with high statistical significance at the center of the RAM domain. The circulation difference is eventually caused by subsynoptic-scale mountains in northeast Asia. From additional experiments, we suspect that the Changpai and Sikhote-Alin Mountains effectively block and meander time-mean northwesterlies and excite the cyclonic circulation around the Sea of Japan (not shown; the mechanism of this local response will be reported elsewhere). On the other hand, subsynoptic-scale topography in northeast Asia does not generate significant

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<th>Area of 25°–65°N, 100°E–180°</th>
<th>OS GCM</th>
<th>IS GCM</th>
<th>IF GCM</th>
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<tr>
<td>Nonexplosive cyclones</td>
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<td>226</td>
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<tr>
<td>Explosive cyclones</td>
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changes in midtropospheric synoptic-scale eddy activity. An insignificant enhancement of eddy activity in the midtroposphere can be found in the south of the storm-track axis (cf. Fig. 10c). Only small-scale characteristics in near-surface meridional heat flux can be found in Fig. 10d.

Figure 11 shows the difference between IF GCM and IS GCM. Strongly reflecting the offline RAM mean-flow response to the subsynoptic-scale topography in northeast Asia, the interactive GCM shows a clear (though marginally significant) cyclonic circulation difference in the central Pacific (Fig. 11a). The mechanical RAM forcing not only influences the atmosphere around the nested domain, but may also excite a global pattern.

Related to the anticyclonic circulation response around
the polar region, the time-mean westerly wind is weakened in Siberia. Corresponding to this, all the eddy statistics in northeast Asia show a significant reduction in the GCM. In spite of the eddy heat flux reduction, the cyclone density increases slightly to the south of Japan (Fig. 12). The explosive cyclone statistics reveal that IF GCM produces about 5% more cyclones and about 10% more explosive cyclones (Table 2), and the tracks south of the storm-track axis contribute to this increase (Table 3).

The feedback to the RAM is apparent in the difference between IF RAM and IS RAM shown in Fig. 13. Comparing with the offline case, we found that the difference of horizontal wind is almost doubled with expanding areas of statistical significance (Figs. 13a,b). Following the mean circulation response, the eddy activity is completely reduced in the whole RAM domain (Figs. 13c,d), whereas there is little difference in the offline case. We hence interpret that, in the context of the mean circulation, a positive feedback works in the interactive experiments.

Summarizing the above results, the effect of subsynoptic-scale mountains changes not only the eddy statistics, but also the time-mean circulation in the offline RAM. In the interactive experiments, the RAM mean-flow forcing effectively excites the global GCM response and in turn amplifies the mean-flow response in the RAM. We can recognize this result as a positive feedback in the context of the mean flow working in the interactive model. The change of eddy statistics follows the mean-flow response.

d. Total effect and comparison with observations

Figure 14 presents the total effect of subsynoptic-scale eddies and mountains in northeast Asia. The mean-flow response shows the anticyclonic circulation in the high latitudes (Fig. 14a) and weaker westerly wind in the midlatitudes (not shown), which partially resembles the Arctic Oscillation (Thompson and Wallace 2000). Following the mean-flow response, the total effect shows the reduction of storm-track activity in the midlatitudes (Fig. 14b). Comparing Figs. 8, 11, and 14, the subsynoptic-scale mountains in northeast Asia mainly contribute to the total effect. Hence, the total nested impact mainly stems from the local response of the mean-wind field (Fig. 10). Although the subsynoptic-scale eddy effect induces the synoptic-scale eddy response only in the nested area (Fig. 8), the subsynoptic-scale mountain effect effectively induces the response extending to the atmosphere in the whole extratropics. The regional model pushes the GCM to a stronger STJ and weaker polar front jet (PFJ) in the nested region, and as a result of large-scale eddy–mean flow interaction, this forcing changes the zonal wind globally.

We now briefly discuss the comparison of the interactive experiment results with observations. The original MIROC3.2 GCM suffered from biases of the northward shift of the zonal-mean wind (not shown). The bias of zonal-mean wind is relatively large at 15°–30° and 40°–55°N (Fig. 15a). Results of IF GCM show a stronger STJ and a weaker PFJ, consistent with the decrease in storm-track activity (Fig. 14b). Except for the polar region, the zonal wind bias seems to be improved in IF GCM. However, the better zonal wind simulation is accompanied by worsened storm-track activity simulation because the original MIROC3.2 can reproduce quantitatively reasonable storm-track activity in the midlatitudes (Fig. 15b). On the other hand, the interactive experiment ameliorated the explosive cyclone statistics in the nested area (IF GCM simulated only approximately 10% fewer explosive cyclones, whereas OF simulated approximately...
30% fewer explosive cyclones). Whether the partial high-resolution simulation performed in this study works to reduce a particular bias in the GCM depends on the relative importance of the nested area on the bias. The partial improvement shown here implies that other regions might be key to the storm-track activity bias. At this time, we can only hope that the interactive simulation may have the potential to reduce the GCM biases from which MIROC3.2 suffers, even though this study, the first use of the INCL system, cannot show a clear successful result on the bias-reduction problem. This point will be further expanded in the discussion.

5. Discussion

We have performed two interactive and two offline INCL experiments to investigate the effect of subsynoptic-scale eddies and subsynoptic-scale topography around northeast Asia on the larger-scale climate. As stated in the introduction, the merit of the INCL system is its reduction of computational cost. Using immense computational resources to run a high-resolution (e.g., T213 atmosphere) GCM, we could investigate the problem presented in this paper without the INCL system as follows: we would run the GCM with T42 atmosphere and T42-resolution topography (experiment A), the GCM with T213 atmosphere and T42-resolution topography (experiment B), and the GCM with T213 atmosphere and T213-resolution topography only for northeast Asia, with T42-resolution topography elsewhere (experiment C). The comparison between experiments A and B would reveal the subsynoptic-scale eddies, whereas that between experiments B and C would reveal the subsynoptic-scale orography. Practically, experiments B and C need a high-spec computer. The INCL system was therefore useful for the purpose of this paper.

The effect of the midlatitude SST front along the Kuroshio Current could be investigated using the INCL system. The Kuroshio Current and its extension, pushing against the colder Oyashio Current counterpart, make a very fine oceanic front with a very large meridional gradient of SSTs. Xie et al. (2002) suggested that this sharp SST front played a significant role in an initial development of subsynoptic-scale eddies along the front. Even in a planetary-scale context, some studies have reported that the sharp SST gradient modulated storm-track activity [Inatsu and Hoskins (2004) and Nakamura and Shimpo (2004) for Southern Hemisphere storm tracks, and Inatsu et al. (2003) for an idealized context]. Hence, the INCL system is expected to reveal the effect of the fine SST gradient on the larger-scale climate. The current version of the INCL system, however, could not be used to investigate the high-resolution effect of SSTs because the lower boundary condition of the RAM is directly taken from the coarser atmospheric submodel. We will target this problem and improve the system in the near future.

Ideally, we hope that the INCL system reduces GCM biases, but this problem is very difficult and beyond the scope of the present paper. Since we did not take any prudent implementations on the conservation of the conserved quantities such as total energy and total...
water vapor, the GCM in INCL interactive experiments did not have any assurance of conservation, though the single GCM met the conservations of total energy and total water vapor. In the interactive experiments, therefore, it would be likely that the nested RAM would force GCM without any consideration of global climate balance. As one of the worst examples, one could think that, if much warmer midlatitude climate simulated by RAM forced GCM, the jet stream might be unrealistically shifted far poleward only in the nested longitudes. Generally, since such an additional false energy source/sink must cause an additional false circulation or additional biases, it is indispensable to assure the energy conservation in the model system when one argues a problem on the GCM bias reduction. We will implement energy- and moisture-conserved RAM–GCM coupling in the INCL system in the near future, in order that we can arrange some experiments to think of the feasibility of the GCM bias reduction by using INCL.

Pessimistically, even the forthcoming energy- and moisture-conserved INCL might not realize the bias reduction, perhaps because a bias reduction in a particular

![Fig. 11. As in Fig. 7, but for the difference between IF GCM and IS GCM.](image)
nested region might produce new another bias out of the nested region to meet the conservation constraints. We are now thinking of an example in which a GCM calculates a biased storm-track activity in region A but an unbiased precipitation in region B located in the downstream of region A. If the INCL’s nested region is set to region A, the storm-track activity bias might be reduced but the precipitation bias in region B might be produced because it is related to the storm-track activity in the upstream region A. More pessimistically, even a single high-resolution GCM actually captures high-frequency and small-scale phenomena, but depending on tuning of parameterizations it does not always reproduce more realistic climatology and low-frequency variability compared to a low-resolution GCM. However, the interactively nested experiment by Lorenz and Jacob (2005) successfully reduced the tropospheric temperature bias from which most conventional GCMs suffer. This suggests the potential of the INCL system to contribute to the bias-reduction problem, if a particular region is known a priori to be an important area for the bias directly or indirectly. Actually, the nested area studied by Lorenz and Jacob (2005) was the Maritime Continent, where very small-scale sea-breeze circulation creates significant diabatic heating responsible for the global climate (Neale and Slingo 2003). Another encouraging study was provided by Xie et al. (2006), who investigated the wind-side precipitation of a very narrow range of Burmese mountains during the summertime Indian monsoon season and found that the diabatic heating by such mesoscale rainfall is positively fed back to the strength of monsoon wind. In the INCL system, there is some possibility that such positive feedback could be shown using the finer-resolution RAM nested into the GCM.

Considering the interactively nested model problems outlined in the above discussion and optimistically believing that the INCL strategy will be able to contribute to the GCM bias reduction problem more or less, whether the INCL contributes to bias reduction seems to depend on whether the RAM can capture a phenomenon that most conventional GCMs partly or completely miss. Considering the RAM characteristics, the possible causes of the difference between the GCM and RAM can be appear to be differences in (i) the resolution of the lower boundary condition such as mountain height, land–sea contrast, islands, and SSTs; (ii) the mesh size of the models; or (iii) the model physics. The pioneering work by Lorenz and Jacob (2005) and the extension of that work by Xie et al. (2006) may fall into category (i). At present, we cannot propose any works that fall into categories (ii) and (iii) because modeling studies are often strongly model dependent.

6. Conclusions

We have investigated the effects of subsynoptic-scale eddies and subsynoptic-scale mountains around northeast Asia on the larger-scale climate using an interactively nested climate model system, the INCL, in which a RAM is nested into a GCM, and both the models are integrated in a single main program that exchanges information between the models. In this study, we performed two interactive INCL experiments with finer or smoother surface elevations in the RAM, together with offline version of these experiments. The RAM–GCM difference of the offline experiment with the smooth surface shows increased storm activity but weak eddy-induced circulation as the subsynoptic-scale eddy effect. However, the GCM difference between interactive and
offline experiments shows that the effect on the global climate does not generate statistically significant circulation out of the RAM domain. The subsynoptic-scale eddy effect only contributes to the synoptic-scale activity around the nested area.

Comparing the experiment with the finer RAM land surface boundary and that with the coarser one, the subsynoptic-scale mountains of northeast Asia excite robust cyclonic circulation around the Sea of Japan. In the interactive experiment, the GCM takes the RAM information as a forcing and effectively excites the global pattern. Taking the GCM response as the sidewall boundary conditions, the RAM in the interactive experiments amplifies the cyclonic circulation around the Sea of Japan and suppresses storm activity in northeast Asia. These results suggest that a positive feedback does work for the mean flow in the interactive experiments.

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APPENDIX A

GCM–RAM Interpolation

The third procedure of the INCL simulation, for any \( \alpha \) distribution [see Eq. (1)], needs a spatial interpolation from GCM to RAM for the RAM lateral boundary conditions. To fit the finer RAM grid, three-dimensional winds, temperature, specific humidity, surface pressure, and SLP of the GCM data are interpolated horizontally and vertically. For a technical reason, we first take a vertical interpolation from sigma GCM levels to the

![Diagram](https://example.com/diagram.png)

**Fig. 13.** As in Fig. 5, but for the difference between IF RAM and IS RAM.
terrain-following RAM levels based on the same surface height as the GCM (Fig. 2a). Second, horizontal interpolation using a simple parabolic fitting is done from the GCM’s T42 grid to the RAM’s Lambert conformal 40-km mesh-size grid. Third, though this procedure was skipped in OS and IS (section 2b), another vertical interpolation is conducted from the RAM level based on the GCM surface height (Fig. 2a) to the RAM level based on the RAM surface height (Fig. 1). At a grid where the GCM surface is higher than a particular RAM level, a value at the lowermost GCM level is substituted for a value at the RAM level. The surface pressure is modified from the GCM surface to the RAM surface using the hypsometric formula.

APPENDIX B

Simple Tracking Algorithm

Our simple tracking algorithm first needs to pick out the gridded local minimum of the gridded SLP data. The gridded local minimum point satisfies that the SLP at a specific grid point is lower than all the SLPs at the eight neighboring points. We next use nine gridded data surrounding the gridded local minimum (inclusive of itself) and fit the data into a parabolic surface to estimate the local minimum point near the gridded minimum and its SLP value. If the data are arranged in the equally spaced grid with \( \Delta x \) for a longitudinal grid space and \( \Delta y \) for a latitudinal grid space, the parabolic surface could be estimated as

\[
g(x, y) = C_{20} x^2 + C_{11} xy + C_{02} y^2 + C_{10} x + C_{01} y + P_{00},
\]

(B1)

where \( P_{ij} = P(i\Delta x, j\Delta y) \), the origin of \((x, y)\) is the gridded local minimum point,

\[
C_{20} = \frac{P_{1,0} - 2P_{0,0} + P_{-1,0}}{2\Delta x^2},
\]

\[
C_{02} = \frac{P_{0,1} - 2P_{0,0} + P_{0,-1}}{2\Delta y^2},
\]

\[
C_{10} = \frac{P_{1,0} - P_{-1,0}}{2\Delta x},
\]

\[
C_{10} = \frac{P_{0,1} - P_{0,-1}}{2\Delta y}, \quad \text{and}
\]

\[
C_{11} = \frac{P_{1,1} - P_{1,-1} + P_{-1,-1} - P_{-1,1}}{\Delta x \Delta y}.
\]

\[B1\] The GCM output is originally arranged in a grid that is slightly different from an equally spaced grid, but this difference can be neglected. The RAM output is quite different from the gridded data; thus, we first interpolate these data to an equally spaced grid with 0.5° mesh.
The minimum point and the minimum value can be estimated using the \( g/\partial x = g/\partial y = 0 \) conditions. The model outputs (and also ERA-40 data) are 6-hourly, and thus the minimum SLP point and its value can be estimated every 6 h. The tracking algorithm connects a minimum point at a specific time \( t_0 \) to the minimum point at the time 6 h later \( t_1 \). With most typical extratropical cyclones moving eastward, the neighbor-point-identification method is modified with the assumption that a cyclone would have a minimum velocity of approximately 10 m s\(^{-1}\) on average (200-km eastward in 6 h). The SLP minimum point at \( t_1 \) is then sought from the inner region of the circle with its radius of 300 km and center 200 km eastward from the minimum point at \( t_0 \). We only choose cyclone tracks having a lifetime of more than 2 days. This procedure determines the track line for each cyclone.

The final step of the tracking algorithm is to calculate the track density. A track line is generally a zigzag because we connected the minimum points every 6 h. The track density calculation is performed for grid points with distance from the track line segment of less than \( l_r = 300 \) km. For a grid point of \( R_i \), for example, with a distance \( d_j < l_r \) from the line segments of a track number \( i \), we set the weighting \( w_{ij} = 1 - (d_j/l_r) \). The track density of point \( R_j \) (here, the unit is track per season) is calculated as

\[
D(R_j) = \frac{\sum_{i=1}^{N} w_{ij}}{T},
\]

where \( N \) is the total number of tracks and \( T \) is the number of seasons (\( T = 10 \) for all the experiments here).

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