Sensitivity of the regional climate of East/Southeast Asia to convective parameterizations in the RegCM3 modelling system. Part 1: Focus on the Korean peninsula

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ABSTRACT: This study investigates the capability of the regional climate model, RegCM3, to simulate fine-scale regional climate over a narrow peninsula or archipelago. The model is run in one-way double-nested mode with one mother domain and two nested domains. The mother domain encompasses the eastern and southern regions of Asia and adjacent oceans with a grid spacing of 60 km. The first nested domain focuses on the Korean peninsula and the second one covers the Philippine archipelago with a grid spacing of 20 km. The simulation spans a period of 5 years and 1 month, from November 2000 to December 2004. The sensitivity of the two convection schemes, namely, the Grell scheme (Grell) and the MIT-Emanuel scheme (EMU), is studied.

Model results obtained with both the Grell and EMU show reasonable performance in capturing the seasonal variation and the spatial characteristics of the East Asian monsoon. However, the Grell simulation appears to have persistent cold and dry biases in the summer season. There is a definite improvement in these model deficiencies by the implementation of EMU. Although the temperature fields in the Grell and EMU simulations are essentially the same in terms of the spatial distribution, the EMU simulation is quantitatively in better agreement with the observed estimates, indicating a substantial reduction in the cold bias. Further, in comparison with the Grell simulation, the EMU simulation shows an improvement in the timing and amplitude of the rain band propagating northward. The spatial distributions of precipitation also have good quality, capturing the localized maxima over Korea. The frequency distributions of daily temperature and precipitation simulated by EMU are closer to observations than those of the Grell simulation. It is found that the convective precipitation derived from different convection parameterizations is a major contributor to the performance of the model in summer. Copyright © 2008 Royal Meteorological Society

KEY WORDS RegCM3 nesting system; convection scheme sensitivity; Korean peninsula

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1. Introduction
The climate over Korea and the Philippines is strongly governed by the monsoon system that is characterized by the seasonal wind reversal primarily due to the continent–maritime temperature contrast (Kang et al., 2005). However, both the regions lie in different climatic regimes. Korea experiences the East Asian monsoon which covers the mid-latitude region (from approximately 34° N to 38.5° N) and the Southeast Asian monsoon influences the climate of the Philippines which is located in both tropical and subtropical regions (from approximately 4.7° N to 22.5° N). The main features and energy sources associated with these monsoons are different due to the contrast in the geography and location of both these regions (Kripalani and Kulkarni, 2001). One of the most distinct characteristics of the East Asian monsoon is the early summer rainfall, i.e. Meiyu in China, Baiu in Japan, and Changma in Korea, which is associated with a narrow rain band with a quasi-stationary monsoon front that develops along the northwestern boundary of the subtropical high (Lee and Suh, 2000; Kitoh and Uchiyama, 2006). On the other hand, the monsoon over the Philippines is characterized by the moisture flow which mostly comes from the tropical ocean (Francisco et al., 2006). Basically, it is an oceanic monsoon that is supported by monsoonal disturbances, with a minor role played by the north–south heat contrast (Kripalani and Kulkarni, 1998).

In the last few decades, considerable research has been conducted to simulate the Asian monsoon features using various regional climate models (RCMs) (Hirakuchi and Giorgi, 1995; Giorgi et al., 1999; Kato et al., 1999; Lee and Suh, 2000; Leung et al., 2004; Kang et al., 2005). Most RCM studies have been carried out over the continental regions of Asia. Studies that focus on a narrow peninsula or archipelago such as, Korea and the Philippines are relatively few. In spite of the rapid
improvement in computing facilities, the typical range of the horizontal resolution in regional climate modelling over Asia still remains approximately 50–60 km (Lee et al., 2004). At this resolution, the basic characteristics of the East Asian monsoon climate can be captured, however the physiographical features of both regions characterized by complicated mountain systems surrounded by an ocean are described inadequately (Im et al., 2006). One method to enhance the resolution of RCMs over selected sub-domains of particular interest is to use multiple nesting. Due to the complex physiography of Korea and the Philippines, a high-resolution RCM with a nesting system can be a particularly useful tool in capturing fine-scale features with sufficient accuracy.

As reported in a special issue of Theoretical and Applied Climatology (TAC) (Giorgi et al., 2006), Im et al. (2006) and Francisco et al. (2006) have already examined the basic performance of the Abdus Salam International Centre for Theoretical Physics (ICTP) Regional Climate Model latest version (RegCM3) for reproducing fine-scale regional climate over each region. Im et al. (2006) have developed a one-way double-nested system for the Korean region and validated it against a dense observational network over the Korean territory. Francisco et al. (2006) have investigated the summer monsoon precipitation over the Philippine archipelago and assessed the sensitivity of the model to driving boundary conditions and ocean surface flux schemes. These studies generally indicate that RegCM3 is capable of capturing the main features on a regional scale, although its performance varies depending on the season and the physical parameterization choices, with some persistent biases. Before any general conclusions can be drawn, the RCM performance for this region must be evaluated more systematically. The above-mentioned studies use diverse simulation periods, integration areas, and model configurations, which lead to variations in the performance of the model. Therefore, it is an open question whether similar success can be achieved for both the regions using the same model configuration, considering that factors governing the climate at low latitudes are intrinsically different from those that determine the behaviour of the extratropical climate.

In this study, we design a one-way double-nested system with one mother domain and two nested domains. In our double-nested model, the mother domain encompasses the eastern regions of Asia and adjacent oceans and extends from the tropical to the northern part of Asia covering a relatively large area in the north–south direction with a grid spacing of 60 km. The first nested domain focuses on the Korean peninsula and the second one covers the Philippine archipelago with a grid spacing of 20 km. Considering the meridional linkage between the East Asian and Southeast Asian monsoons, the mother domain is adequate for capturing the northward progression of the monsoon rain band.

The convective parameterization scheme (CPS) is the most important and the sensitive physical process associated with the simulation of the monsoon rainfall (Leung et al., 2004; Dash et al., 2006; Hong and Choi, 2006). Therefore, the sensitivity of the simulated regional climate over these regions to the following two CPSs is also studied: the Grell scheme (Grell) with Fritch-Chappell closure and the Massachusetts Institute of Technology (MIT)-Emanuel scheme (EMU) recently implemented in RegCM3. Im et al. (2006) investigated the sensitivity to the CPS choice and selected the Grell over East Asia including the Korean peninsula. Francisco et al. (2006) have also applied the Grell over the Philippines. However, Singh et al. (2006) have recently reported that the performance of the EMU was better than that of other schemes implemented in RegCM3 for the simulation of both monsoon circulations and precipitation over East Asia. The EMU has recently been implemented within RegCM3, and therefore its performance has not been tested extensively to date. Throughout this sensitivity experiment in our study, we can advance understanding of the relative performance of the CPS by applying it to different climatic regimes (Korea vs. the Philippines) across varying spatial scales (60 km vs. 20 km).

We present our results through this and a companion paper (Im et al. in preparation). In this paper, we first focus on the analysis of the climatological mean aspects of the mother domain simulation and the fine-scale structure of the nested domain simulation covering the Korean peninsula. This study emphasizes the sensitivity of the CPS over our simulated region, addressing the different characteristics revealed by the EMU and Grell simulations. A companion paper (Im et al. in preparation) then focuses on the performance of the inter-annual variability of the mother domain simulation and the fine-scale structure of another nested domain covering the Philippine archipelago.

The following statistics are analysed: monthly and seasonal averages, and the frequency distribution of the daily temperature and precipitation. The mother-domain simulation is validated by comparing it with large-scale analysis fields, while the simulations with the two nested domains are primarily evaluated by comparison with station observations covering the territory of each country.

In Section 2, we present a brief description of the modelling system, experiment design, and the observational data used for the validation. In Section 3, the results of the mother and nested domain simulations are validated and inter-compared. The discussion and conclusion of this study are presented in Section 4.

2. The model, experiment design, and validation strategy

2.1. The regional climate model

The regional climate model used in this study is the latest version of the ICTP Regional Climate Model RegCM3 (updated in June 2006). It is an upgraded version of the model originally developed by Giorgi et al. (1993a,b), and improved as discussed by Giorgi and Mearns (1999) and Pal et al. (2007). The dynamic core
of the RegCM3 is equivalent to the hydrostatic version of the NCAR/Pennsylvania State University mesoscale model MM5 (Grell et al., 1994). The physical parameterizations employed in this simulation include the comprehensive radiative transfer package of the NCAR Community Climate Model, version CCM3 (Kiehl et al., 1996), the non-local boundary layer scheme of Holtslag et al. (1990), and the BATS land surface scheme (Dickinson et al., 1993).

As compared to the previous version described by Giorgi et al. (1993a,b), the latest version of RegCM3 includes a number of new features which are detailed by Pal et al. (2007). The feature that is most relevant to the present study is the one-way nesting capability. In this one-way nesting, the relevant meteorological fields (wind, temperature, water vapour, and surface pressure) from the mother domain simulation with a coarse resolution are interpolated onto the lateral buffer area of a high-resolution nested domain in order to provide lateral boundary conditions for the nested domain simulation. These boundary conditions entail the use of a relaxation and a diffusion term throughout the lateral buffer area (Giorgi et al., 1993b), which consists of 8 grid points in our case.

In the RegCM3 modelling framework, precipitation is derived by the combined process of resolved (grid-scale) precipitation as well as unresolved (sub-grid-scale) precipitation. The resolvable grid-scale precipitation is described using the sub-grid explicit moisture scheme of Pal et al. (2000), which accounts for the sub-grid variability in the clouds by linking the average relative humidity of a grid cell to the cloud fraction and cloud water. The unresolved precipitation is produced by a CPS, which describes the effects of sub-grid-scale convective clouds. In this study, we analyse the simulations by employing two different CPSs.

The first CPS is the mass flux cumulus scheme of Grell (1993) with Fritsch-Chappell type closures, which tends to maintain a balance between the convective and the resolved scale rainfall. The mass flux scheme simply includes the moistening and heating effects of penetrative updrafts and corresponding downdrafts, with no mixing between cloudy air and environmental air except at the cloud top and base. Thus, convective mass fluxes are constant with height and no entrainment or detrainment occurs along the cloud edges. The Grell scheme is activated when a lifted parcel attains moist convection. The convective mass flux is determined by the flux required to stabilize an unstable air column. In a Fritsch-Chappell closure, it is assumed that the buoyancy energy available for convection is dissipated during a specified convective time period (between 30 min and 1 h).

The second CPS is the EMU scheme (Emanuel, 1991; Emanuel and Zivkovic-Rothman, 1999), which has been recently implemented in RegCM3. This scheme assumes that the mixing in clouds is highly episodic and inhomogeneous and considers convective fluxes based on an idealized model of sub-cloud-scale updrafts and downdrafts. Convection is triggered when the level of neutral buoyancy is greater than the cloud-base level. Between these two levels, air is lifted and a fraction of the condensed moisture forms precipitation while the remaining fraction forms a cloud. The cloud is assumed to mix with air from the environment according to a uniform spectrum of mixtures that ascend or descend to their respective levels of neutral buoyancy. The mixing entrainment and detrainment rates are determined by the vertical gradients of buoyancy in the clouds. The fraction of the total cloud base mass flux that mixes with its environment at each level is proportional to the rate of change in the undiluted buoyancy with altitude. In other words, the mass flux at the cloud base is a function of buoyancy, and the air parcel can lose its buoyancy during ascent due to the entrainment of dry air from the environment.

According to the sensitivity studies related to the comparison of CPSs, the simulations using the Grell in regional models tend to underestimate precipitation, probably due to the infrequent triggering of the scheme (Gochis et al., 2002; Ratnam and Kumar, 2005; Im et al., 2006). On the other hand, the EMU usually overestimates the convective precipitation in the tropical oceanic regions with a generally high sea surface temperature (SST) and high water vapour (Chow et al., 2006).

2.2. Experiment design

Figure 1 shows the model domain used in this study. It consists of one mother domain and two nested domains. The mother domain covers the eastern regions of Asia (including the Korean peninsula) and the southern regions of Asia and adjacent oceans (including the Philippine archipelago) at a grid spacing of 60 km. The first nested domain focuses on the Korean peninsula and the second one covers the Philippine archipelago at a grid spacing of 20 km. A comparison between the mother and nested domains shows that the mountain ranges in the nested domain are more realistic than those in the mother domain, which emphasizes the necessity of the double-nesting system. The Korean peninsula in the nested domain effectively represents a mountainous region with the most prominent ranges (reaching elevations of over 1000 m) extending from north to south along the eastern coastal regions. The main topographical features of the two largest islands of the Philippines in the nested domain are reasonable. Many islands with intermediate sizes are also captured.

The regional model can be run with both initial and lateral boundary conditions from either global analysis data or the output of a Global Circulation Model (GCM). In our study, the RegCM3 mother domain simulation is driven at the lateral boundaries by NCEP/NCAR reanalysis II data (wind, temperature, water vapour, and surface pressure) at a resolution of 2.5° (Kalnay et al., 1996). The SST over the oceanic areas is obtained from the National Oceanic and Atmospheric Administration (NOAA) Optimum Interpolation (OI) SST dataset with
Figure 1. Model domain and topography (m) for the mother (60 km grid spacing) and two nested (20 km grid spacing) simulations. The simulation spans continuously over a period of 5 years and 1 month, from 1 November 1999 to 31 December 2004. One month is assigned as the spin-up process; therefore, five full annual cycles are included in our analysis. This spin-up period is sufficient for the dynamical equilibrium between the lateral forcing and the internal physical dynamics of the model. Anthes et al. (1989) found that regional models reach equilibrium in about 2–3 days. The two simulation sets are integrated by implementing the Grell and EMU, all other conditions being identical. We analyse the simulation results by focusing on the summer (June, July, August; JJA) and winter (December, January, February; DJF) seasons.

2.3. Verification strategy

Various reanalysis and observation datasets are used for the validation of the climatological performance of the RegCM3 double-nested system.

We use global reanalysis datasets for the validation of the mother domain simulation. The precipitation results are compared with the Global Precipitation Climatology Project (GPCP) (Huffman et al., 1997), which includes daily data with a resolution of 0.5° × 0.5°. The temperature and wind fields are compared with the NCEP/NCAR reanalysis data.

Figure 2 shows the topography and location of the climate stations throughout the southern Korean peninsula. For the evaluation of the nested domain over Korea, 57 climate stations maintained by the Korea Meteorological Administration (KMA) are used. This dataset allows...
first-order validation of the fine-scale structure of the nested model simulation over the Korean peninsula. Because the resolution of the model is high, it is reasonable to compare an individual station with the closest grid point.

3. Results

3.1. Mother domain simulation

We begin our analysis of the 5-year climatological aspects in the mother domain. It is important to assess whether the driving fields in the mother domain are adequate for the double-nesting method (Im et al., 2006), particularly with regard to the synoptic-scale climate characteristics from East Asia to Southeast Asia.

The seasonal average wind fields at a lower level (850 hPa) simulated by RegCM3 with the Grell and EMU are compared with the NCEP/NCAR reanalysis data (Figure 3). The climate in the Asian region is significantly influenced by the monsoon circulation characterizing seasonal reversal. Generally, both simulations capture not only the large-scale circulation pattern but also certain aspects of monsoon-dominated seasonal evolution.

During the winter season, the northwesterly winds that penetrate into Korea, and the easterly winds in the southern part of the mother domain are pronounced. A predominant northwesterly monsoon flow carries cold air from the polar regions into East Asia. In the lower troposphere, this flow is associated with anti-cyclonic circulation induced by the Siberian High, which determines the development of the winter monsoon (Jhun and Lee, 2004), and induces dry and cold conditions over East Asia. The simulated wind field successfully reproduces the observed maximum strength over 10 m/s and a wave pattern with seasonal reversal direction.

During the summer season, the prevailing large-scale flow is associated with the westward movement of the subtropical Pacific High, which induces a southwesterly flow of moist monsoon air over East Asia (e.g. Giorgi et al., 1999). The model generally reproduces the migration of the warm and wet southwesterly monsoon flow that sweeps the East Asian region well. Although the simulated patterns are similar to those of the reanalysis, the southwesterly flow is too strong over the South China Sea and Japan. The deficiency of the model appears to be a somewhat eastern displacement of the western branch of the subtropical Pacific High and the southwesterly winds are also excessive.

The difference between the Grell and EMU simulation indicates that low-level winds simulated with the EMU are generally stronger anti-cyclonic circulations than those obtained using Grell, with the centre located around the Philippines during winter and around Taiwan during summer. Later, more discussion of this seasonal pattern is presented, to be related with the temperature difference feature.

![Figure 3. Five-year seasonal mean (DJF: upper panels, JJA: lower panels) 850 hPa winds (m/s) for (a,e) Grell simulation, (b,f) EMU simulation, (c,g) NCEP/NCAR reanalysis, and (d,h) difference between EMU and Grell simulations. Here, shading indicates the magnitude of the winds.](image-url)
Figure 4 shows the spatial distribution of the seasonal average surface air temperature obtained by the NCEP/NCAR reanalysis and two simulations for the winter and summer seasons. Overall, the model results are in good agreement with the seasonal characteristics obtained by the reanalysis data. In addition, the simulated results show a fine structure missed by the reanalysis data due to its coarse resolution. In general, RegCM3 consistently shows a cold bias of a few degrees, regardless of the lateral boundary forcing in the experiment using the perfect boundary condition (Im et al., 2006) as well as the GCM boundary condition (Im et al., 2007a). It is noted that the temperature fields simulated with the EMU are reduced with a cold bias throughout the entire integration area, indicating seasonal dependency. From the area-averaged mean, it is found that the results of the simulation with the EMU are quantitatively in good agreement with the reanalysis estimates as compared to that with the Grell.

Based on the difference fields in the EMU and Grell simulation, we find that the spatial features of the difference change seasonally. In spite of the overall warm pattern of the EMU simulation, the maximum locality is evidently different for the two seasons. Moreover, a major increase of temperature is found over the region in response to the intensified low-level circulation (Figure 3(d) and (h)). The intensified advection of heat and moisture accompanying the anomalous anti-cyclonic circulation is likely to induce the increase in temperature and precipitation over the Philippines and southern China.

Moreover, stronger convection in EMU (supplementary Section 3.2) implies increased heating, which is spread through gravity-wave propagation and the associated subsidence (A. Tompkins, personal communication).

Figure 5 shows the same quantities as in Figure 4 except for precipitation. Comparing the precipitation simulated by Grell with GPCP, it can be seen that the Grell simulation overestimates in the winter season and underestimates in the summer season. The results of the simulation with the EMU show that significant winter precipitation occurs along the Kuroshio extension region in the northeast direction from southern China to the east of Japan. In summer, despite a considerable improvement in the quantitative measure as an area-averaged mean, there exist spatial discrepancies between the EMU simulation and GPCP. The precipitation produced by the EMU is excessive over the continental area.

In order to investigate the relative contribution of convective and non-convective portions to the total precipitation in both simulations, we present the spatial distribution of the large-scale precipitation and convective precipitation separately (Figure 6). First, during the winter season, the convective effect over the northern part of the simulated area appears to be negligible. In both simulations, most of the winter precipitation over the Kuroshio extension region is due to large-scale precipitation, and not to convective precipitation. However, in the case of the EMU simulation, an overestimation error over this region is compounded by the additional
Figure 5. Five-year seasonal mean (DJF: upper panels, JJA: lower panels) precipitation (mm/day) for (a,e) Grell simulation, (b,f) EMU simulation, (c,g) NCEP/NCAR reanalysis, and (d,h) difference between EMU and Grell simulations.

Figure 6. Five-year seasonal mean (DJF: upper panels, JJA: lower panels) large-scale precipitation (mm/day) for (a,e) Grell simulations, and (b,f) EMU simulation, and convective precipitation (mm/day) for (c,g) Grell simulation, and (d,h) EMU simulations.
convective precipitation, although its magnitude is less than that of large-scale precipitation. The EMU usually tends to overestimate the convective precipitation in regions with a high SST and water vapour (Chow et al., 2006).

As analysed in other variables, considerable differences are found in the summer season, although most regions are prone to convective precipitation. The summer precipitation obtained by the EMU simulation dominates the effect of the convective precipitation, while the summer precipitation obtained by the Grell simulation balances between large-scale and convective precipitation and follows the spatial pattern of the large-scale precipitation (Figure 5). A comparison of the total summer precipitation between the EMU simulation and the GPCP reveals that overestimation occurs in the EMU simulation mostly due to the excessive convective precipitation. Chow et al. (2006) pointed out the overestimation problem of the EMU and suggested that this limitation could be overcome by applying certain convective suppression criteria to the EMU.

For further explanation of the possible reason for the differences in the convective precipitation simulated by both the CPSs, we calculated the integrated moist static energy (MSE) over the entire mother domain. The MSE is the sum of the sensible, latent, and geopotential energy, and it is expressed as follows:

\[ \text{MSE} = C_p T + L q + g Z \]

(Where, \( C_p \) is the specific heat of air at constant pressure, and \( T \) is the air temperature. \( L \) is the latent heat of evaporation, and \( q \) is the specific humidity. \( g \) is the acceleration due to gravity, and \( Z \) is the height.)

The vertically integrated MSE could be a good descriptor of the state of the atmosphere. Srinivasan and Smith (1996) have shown that the precipitation in the tropics depends on the MSE of the troposphere from 1000 to 400 hPa. Figure 7 shows the spatial distributions of the integrated MSE from 1000 to 400 hPa computed by the NCEP/NCAR reanalysis and both simulations. The spatial distributions of the integrated MSE directly reflect the general characteristics, as shown in the convective precipitation (third and fourth panels in Figure 6). In the winter season, the northern part of the simulated area shows a low MSE, corresponding to an entirely small amount of convective precipitation. On the other hand, during the summer season, most of the regions show a high MSE, and this results in more potential energy to promote the convective activity. An important result can

\[ \text{MSE} = C_p T + L q + g Z \]

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Figure 7. Five-year seasonal mean (DJF: upper panels, JJA: lower panels) integrated moist static energy (kJ/kg) from 1000 to 400 hPa for (a,e) Grell simulation, (b,f) EMU simulation, (c,g) NCEP/NCAR reanalysis, and (e,h) difference between EMU and Grell simulations.
be derived from the different pattern between the EMU and Grell simulations in the summer season, which is similar to the pattern of the total precipitation (fourth and lower panel in Figure 5). In general, the integrated MSE obtained from the EMU simulation is higher than that obtained from the Grell simulation. This implies that the underestimation of precipitation in the Grell simulation is related to the simulation of a low MSE in the summer season. It can be observed that the regions of heavy precipitation correspond to the regions of a higher MSE. Thus, the atmospheric condition simulated by EMU is more favourable for activating the convection during the summer season.

Since the stability and moisture contents along the altitudes determine the initiation of the convective activity, it is worthwhile investigating the vertical structure of the equivalent potential temperature and specific humidity in the atmosphere. Figure 8 shows the vertical error profiles of the equivalent potential temperature and specific humidity area averaged over the mother domain for the winter and summer seasons. Here, the error is calculated by estimating the difference between the NCEP/NCAR reanalysis and the two simulations. The bias pattern along the vertical differs considerably from the winter to the summer season, and the error as well as the difference of both the simulations increases during the summer season. The overall negative biases in the equivalent potential temperature (upper panels in Figure 8) and specific humidity (lower panels in Figure 8) shown by the Grell simulation match the underestimation of the temperature and moisture fields well, particularly in the summer season. The convective stability relative to the observations is assessed by examining the vertical gradient of the difference in the equivalent potential temperature with height (Gochis et al., 2002). In Figure 8, the Grell simulation has a more unstable lower part of atmosphere than the reanalysis, but despite this instability, the air is cooler and drier as indicated by the variation in the specific humidity along the vertical. According to this, the Grell simulation generates a more unstable atmosphere and less rainfall. The possible reasons for the excess instability in the Grell

![Figure 8](image_url)

Figure 8. Vertical profiles of the differences between both simulations and NCEP/NCAR reanalysis in equivalent potential temperature (K: upper panels) and specific humidity (kg/kg: lower panels) area-averaged over the mother domain. Here, open (close) circles represent the Grell (EMU) simulation results.
simulation could be related to the underestimation of the convective activity due to the inappropriate formulation of the trigger function or its associated parameters, causing the underestimation of the convective mass flux (Gochis et al., 2002; Ratnam and Kumar, 2005). In other words, one of main reasons for less precipitation in the Grell simulation might be that the Grell is triggered infrequently as compared to the EMU, which results in a more unstable atmospheric structure. Clearly, in comparison with the vertical profile produced by the Grell simulation, the vertical profile produced by the EMU simulation is more similar to that of the reanalysis.

The above-mentioned characteristics of both the simulations can be reflected in the northward propagation of the monsoon rain band. Figure 9 shows the time-latitude cross-section of the zonal average 5-day rainfall amount along the band, 120–130° E. The development of the monsoon is characterized by the northward propagation of the rain band. The seasonal advance and retreat of the summer monsoon behaves in a stepwise rather than a continuous manner, as indicated by abrupt northward jumps (Yihui and Chan, 2005). It is observed that in comparison with the Grell simulation, the EMU simulation produces a substantial improvement in the timing and amplitude of the rain band.

The first major quasi-stationary monsoon front appears near 30° N. Then, the rainfall maximum rapidly moves northward by the end of July. The EMU simulation realistically reproduces the maximum position and the propagation speed. However, in the Grell simulation, the position of stationary phase from early June to mid June appears to be displaced somewhat southward and the simulation fails to capture the northward propagation. The northward expansion of the rain band is weak or does not even occur, resulting in estimates drier than those of the GPCP. In early September, another maximum takes place in the lower part around 30° N, which should be linked to the rainfall caused by typhoons (Qian et al., 2002). The biggest weakness of the EMU simulation occurs at this time. Despite considerable improvement, the EMU simulation has limitations in realistically capturing the effect of typhoons.

In summary, Figures 3–9 indicate that the model performs reasonably well in reproducing temperature and precipitation patterns as well as large-scale circulations of the East Asian monsoon. The EMU simulation has potential to improve the climatological aspects, showing a reduction in cold and dry biases, which appear to be in line with those found in experiments conducted over other regions (e.g. South American monsoon region) (Seth et al., 2007). This implies that the model’s physics can influence the large-scale circulation and the local processes to determine regional climatic characteristics. Considering the fact that the region of integration where the monsoon-dominated climate has been traditionally very difficult for precipitation simulations (Gao et al., 2006), these EMU simulation results show an encouraging performance in this regard.

In the next section, we turn our attention to the analysis of the fine-scale nested domain simulation over Korea.

3.2. Nested domain simulation – Over the Korean peninsula

In the analysis of our nested domain simulation, we compare the results of the model with those of observations derived from the 57 climate stations in South Korea.

Figure 10 shows the 5-year seasonal mean spatial distribution of the surface air temperature for two seasons (summer and winter). The set of panels on the right side presents the results obtained directly from the 57-station dataset. The set of panels in the middle shows the results of the nested model implemented using the EMU, while the set of panels on the left side presents the results of the Grell simulation. The observed temperature field shows substantial spatial variability with a number of topographically induced fine-scale regional features, possibly related to the data at individual stations. The results of the nested domain simulation reproduce these regional features in the two seasons. The temperature fields over Korea are affected by the two most relevant mountain ranges: the Taebaek Mountains extending from north to south along the eastern coastal regions of Korea, and the Sobaek Mountains located in the southcentral regions of the peninsula. This regional
Figure 10. Five-year seasonal mean (DJF: upper panels, JJA: lower panels) surface air temperature (degree) for (a,d) Grell simulation, (b,e) EMU simulation, and (c,f) station observation. Here, the model results are obtained from the nested domain over the Korean peninsula at a grid spacing of 20 km.

detail is clearly reproduced in the nested domain, where the temperature field effectively reflects the location of the Taebaek and Sobaek Mountains. Both simulations produce essentially the same spatial distributions for the two seasons. However, the cold bias reduction of the EMU simulation is evident, especially in the summer season. These patterns are along the lines of those found in the mother domain simulation.

Figure 11 shows the same quantities as Figure 10 except for precipitation. The observations show a band of large winter precipitation over the northeastern coasts and southwestern parts of Korea. Considering the topography of the Korean peninsula (Figures 1 and 2), the former is associated with the upslope topographic forcing of the northeasterly flow occurring over this region in winter, and the latter is evidently formed in response to the topographic uplift of the westerly flow by the Sobaek chain in southern Korea (Im et al., 2007a). Although both the simulations capture the general pattern reasonably well, the model results tend to overestimate the amount of precipitation, particularly in the Grell simulation.

In the summer season, the observations reveal more complicated features, with three spatial maxima over Korea. Considerable differences are observed between the spatial distribution and quantitative amount of the summer precipitation simulated by the EMU and Grell. The EMU simulation successfully reproduces two spatial maxima, one in the southern coastal regions and the other in the northeastern regions; however, it fails to capture the localized maxima over the northwestern region found in the observations. On the other hand, in the case of the Grell simulation, the precipitation is significantly underestimated and the spatial properties are not reproduced. Further, it is reported that the performance of the EMU simulation is also of good quality compared to other simulations implementing the Grell scheme over the Korean region (Singh et al., 2006; Im et al., 2007b). This indicates that the East Asian summer monsoons are particularly sensitive to the CPS, and the EMU simulation suggests skillful transferability over this region.

In order to further investigate the origin of the difference in the precipitation between the EMU and Grell simulations, we analyse the convective precipitation calculated by the two CPSs. Figure 12 shows the 5-year seasonal mean convective precipitation obtained by the Grell and EMU simulations from the nested domain over Korea. The mechanism of precipitation formation over Korea in the summer season is completely different from that in the winter season. In winter, precipitation is mainly produced by large-scale circulation under strong baroclinic conditions, whereas moist convection plays a major role in determining precipitation during summer (Im et al., 2006). These characteristics are well reflected by the spatial distribution of the convective precipitation for the two seasons. In winter, the convective precipitation ratio appears to be negligible, despite the relatively strong evidence found in the EMU simulation over the southwestern part, where a large band of winter precipitation is formed.

A major discrepancy is observed in the summer season. It is very likely that a maximum portion of the increase in summer precipitation obtained by the EMU simulation occurs as convective precipitation. The positions of
convective precipitation enhancement coincide with those of the localized maxima of the total precipitation. A significant improvement in the EMU simulation comes from the convection process, which is a major contributor to the enhancement of the summer monsoon over Korea in terms of the spatial location and intensity.

In order to provide a more quantitative measure of the performance of the model, we calculated the monthly variation in the area-averaged temperature and precipitation over the Korean peninsula (125.5–130°E, 34–38.5°N) (Figure 13). As expected from the spatial distribution, the strong improvement in both the temperature and precipitation obtained by the EMU simulation is pronounced in the summer season, when the convection effect has been mostly influenced upon by the monsoon climate system. In general, the performance of the EMU simulation is better than that of the Grell simulation, showing a reduction in cold and dry biases during summer.

In an attempt to verify the contribution to resolutions (60 km vs. 20 km) and the effect of CPS (Grell vs. EMU), we comprehensively compared the monthly variation in the convective precipitation obtained by both the EMU and Grell simulations for the mother domain (60 km) and nested domain (20 km) over Korea (Figure 14). The convective precipitation increases with the horizontal resolution. As mentioned previously, the precipitation produced by the EMU simulation is generally greater than that produced by the Grell simulation, particularly in the summer season. Therefore, the nested domain simulation with the EMU shows the maximum precipitation intensity. An important result derived from this figure is that the impact of the enhanced horizontal resolution is not as large as that of the CPS. Convective precipitation derived from different CPSs is the major contributor to the performance of the simulated precipitation in terms of magnitude and location. However, it should be noted
that it is difficult to separate accurately the resolution effects and CPS effects in comparison with the mother and nested domain simulation.

Most commonly, the evaluation of the RCM has concentrated on monthly, seasonal, and even over annual values of meteorological variables. Thus far, intensive examination of the daily temperature and precipitation appropriate for analysing extreme events is relatively limited. In fact, there are more discrepancies between the observed and simulated statistics of the local climate based on daily data as compared to the mean climatology conditions in terms of the seasonal and monthly averages. For further understanding the limitations and advantages of the simulated regional climate information, it is necessary to demonstrate the ability of the regional model to adequately capture the characteristics of the observed daily temperature and precipitation. In this study, we therefore validate the daily statistics of temperature and precipitation against a dense observation network over the Korean territory. More specifically, we compare station data with model data at the grid point closest to the station location, an approach justified by the high resolution of the model.

Figure 15 describes the frequency distribution of the daily mean temperature and precipitation at all station locations over Korea. After counting the daily events included in each interval (e.g. 1 degree for temperature, 10 mm/day for winter precipitation, and 25 mm/day for summer precipitation).
summer precipitation), we calculate the probability in all bin intervals. Each interval is empirically chosen based on the expected properties of the weather variables. It gives a measure of both the central tendency (e.g., mean) and dispersion (e.g., standard deviation or variance) of the daily values. With regard to the temperature distribution in winter, the shape of the simulated distribution is the same as that of the observed one, and in particular, the observed variance is well reproduced. The model has a tendency to shift slightly towards colder values due to the cold bias. However, in summer, both model results show a distribution that is narrower than that of the observations, i.e., a lower variance and higher incidence of mean values. It is noteworthy that the shapes of the winter and summer distributions are quite different. The winter distribution is more symmetrical and wider than the summer distribution.

A comparison of the temperature distribution reveals that there are no significant differences between the winter temperature statistics simulated by the EMU and Grell. The difference observed between both the simulations is quite evident in the summer season. The EMU simulation shows a distinct improvement in the distribution pattern, with a much better dispersion. The EMU simulation modifies the shape of the distribution, of which Grell is narrower and more peaked than that of the observed one because the cold bias reduces. Despite substantial improvement, the main deficiency of the EMU simulation remains, with the asymmetrical structure of the summertime distribution lacking. While the lower tail of the distribution is well simulated, the upper tail is still underestimated.

Moving to the precipitation distribution, the simulated frequency distribution during the winter season matches the observations remarkably well, except for slight overestimation. During the summer season, the low precipitation bias of the Grell simulation represented by the spatial pattern is reflected throughout the entire frequency distribution, i.e., the number of precipitation events is underestimated at all intensities. In particular, the Grell simulation completely fails to capture precipitation events for intensities greater than 300 mm/day. By comparison, dramatic improvement is seen in the summertime frequency distributions. The distribution obtained by the

EMU simulation has a longer tail in the high-intensity range, more similar to the observations. In other words, this suggests that the EMU is capable of producing extreme precipitation episodes. Moreover, at all intensities, the precipitation obtained by the EMU simulation is significantly closer to the observations than the precipitation obtained by the Grell simulation. In this regard, RegCM implementing the EMU exhibits a greater degree of transferability as compared to that implementing the Grell, at least over the integration area used in this study.

In order to better understand the characteristics of the daily precipitation in greater detail, wet spells in terms of the sequences of wet days over various durations are analysed. Successive events of various durations can reveal a significant structure of the frequency and intensity of extremes (Halenka et al., 2006). Figure 16 presents the wet spell distribution for various durations in the winter and summer seasons. Here, a wet spell is calculated as a number of consecutive days using the daily precipitation, and a wet day is defined as a day with precipitation accumulation greater than or equal to 1.0 mm (Im and Kwon, 2007). At least one wet day is referred to as a wet spell. In order to facilitate the comparison, the tail portion of the distribution with a duration of more than four days is presented on a vertical axis with a logarithmic scale. From this type of representation, we can clearly recognize the differences between the observed values and both the simulations throughout the entire duration, particularly in a relatively small number of extreme cases persisting over a long duration.

A comparison between the winter and summer seasons reveals that the shapes of both their distributions are quite different, indicating that wet spells in the summer season have a significantly longer duration than those in the winter season as reflected by the weather regime characteristics of Korea region. As the interval increases, the frequency of wet spells in the summer season decreases more slowly than in the winter season, with a heavier tail.

Both models have reproduced the wet spell characteristics for not only the relative ratio but also the total number of the frequencies across various durations. In general,
the results of the EMU simulation are quantitatively in better agreement with the observation estimates. During the winter season, although the frequency variation across durations shows similarities between the observed and simulated estimates, the total number of precipitation events simulated with the Grell is systematically overestimated. In the summer season, the Grell simulation tends to underestimate the relatively short period of wet spells (one or two days), while the model tends to excessively overestimate the wet spells for durations exceeding 9 days (inset graph). Substantial differences between the EMU and Grell simulations occur in the duration in which the latter shows poor performance, clearly indicating a reduction in the error in the EMU simulation.

4. Summary and discussions

In this study, we explored the ability of the RegCM3 nesting system to reproduce complex temporal and spatial characteristics under different climate regimes. Not only the mean climate, in terms of the seasonal and monthly averages, but also the frequency and intensity of the daily temperature and precipitation were investigated with a focus on the Korean peninsula. In our experiments, the double-nesting system comprised one mother domain covering East Asia and Southeast Asia at a grid spacing of 60 km, and two nested domains covering the Korean peninsula and the Philippine archipelago at a grid spacing of 20 km. In this paper, we first focussed on the analysis of the climatological mean aspects of the mother domain simulation and fine-scale structure of the nested domain simulation covering the Korean peninsula. This study emphasized the basic performance of temperature and precipitation as well as their sensitivity to CPS in the RegCM nesting system. A companion paper (Im et al., in preparation) will present the details of the analysis of the inter-annual variability of the mother domain simulation and fine structure of another nested domain covering the Philippine archipelago.

Generally, both mother domain simulations implementing the Grell and EMU, reasonably reproduced the seasonal evolution of temperature and precipitation as well as large-scale circulation. However, there were considerable differences between the Grell and EMU simulations, indicating the convective sensitivity with seasonal dependence. The EMU simulation could improve the performance of the climatological aspects related to the East Asian monsoon. The temperature fields simulated with the EMU reduced the systematic cold bias shown by the RegCM simulation over this region, regardless of the lateral boundary conditions. A predominant increase in the temperature was observed over the region in response to the intensified low-level circulation, with the centre around the Philippines during winter and around Taiwan during summer. Although the winter precipitation obtained by the EMU showed a large error along the Kuroshio extension, the summer precipitation was in good agreement with the GPCP estimates as compared to the summer precipitation obtained by the Grell simulation. In particular, the EMU simulation realistically reproduced the northward propagation of the rain band in terms of timing and amplitude. One of the main reasons for a lower precipitation intensity in the Grell simulation is explained by the vertical structure of the stability and moisture contents, indicating the overall negative biases. It is an indication that the Grell scheme is triggered infrequently compared to the EMU, which results in a more unstable atmospheric structure. From these results, the mother domain simulation with the EMU indicated skillful transferability as compared to the simulation with the Grell over our study area, where the monsoon-dominated climate has been traditionally very difficult for the simulation of summer precipitation, thereby providing more adequate boundary conditions to the nested domain simulation.

A great spatial detail is found in the nested domain simulation due to better-resolved surface forcing, indicating that high resolution is required over Korea. The broad patterns of improvement achieved by implementing the EMU were along the lines of those found in the mother domain simulation. Reductions in dry and cold biases were evident in the EMU simulation. It is indeed encouraging that the EMU was capable of capturing the localized maxima of summer precipitation, which exhibits highly spatial variability across the region over Korea. This substantial improvement was mainly derived from the enhancement of convective precipitation. Moreover, it was found that the impact of enhanced horizontal resolution was less than that of changing the CPS over our study region. It has already been demonstrated that the enhanced resolution alone is insufficient for providing an obvious improvement in the summer precipitation performance over Korea (Im et al., 2006). This supports the fact that the improvement and optimal selection of physical parameterizations could be critical for determining the reliability of the model performance (Seth et al., 2007).

Detailed aspects of the improvement obtained from the EMU simulation could be derived from the frequency distribution of the daily temperature and precipitation. The difference between both simulations was quite evident in the summer season. With regard to the daily temperature in the summer season, the EMU simulation noticeably improved the shape of the distribution, with significantly better dispersion. At all intensities, the summer daily precipitation obtained by the EMU simulation was much closer to observations than that obtained by the Grell simulation. In addition, the EMU simulation could produce extreme precipitation episodes, showing a longer tail in the higher-intensity range. It also improved the wet spell characteristics for not only the relative ratio of the frequencies across various durations but also the total frequency of various durations.

Despite the substantial improvement of the EMU simulation, some deficiencies still remain. The model fails to capture the typhoon effects and does not reproduce the

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asymmetrical structure of the daily temperature frequency distribution in the summer season.

From the results described above, we propose that the RegCM nesting system implementing the EMU could be applied more effectively over our study region. The companion paper (Im et al., in preparation) will provide a comprehensive evaluation of the transferability of the RegCM one-way double-nested system over different regions (Korea vs. the Philippines), resolutions (60 km vs. 20 km), and CPSs (Grell vs. EMU).

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