Assessing Future Climate Changes in the East Asian Summer and Winter Monsoon Using Regional Spectral Model

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Abstract

This study investigated potential future climate changes over East Asia with a focus on temperature variation and changes in precipitation as well as future changes in the East Asian monsoon system. The current and future climate projection scenarios are downscaled over East Asia using the regional spectral model (RSM). The representative concentration pathways (RCPs) 2.6 and 8.5 scenarios driven by the Hadley Center Global Environmental Model version 2 (HG2) are used to provide large-scale forcing for the RSM downscaling simulations. Simulations were conducted for the current climate from 1980 to 2005 and two types of future climate between 2020 and 2100. Near-future (2025–2050) and far-future (2075–2100) climate simulations are compared with the current (1980–2005) climatology to investigate climatic change over East Asia. The RSM well captures the precipitation and temperature distribution related to the East Asian summer and winter monsoon and mesoscale mountain range with added values, although the wet and cold biases are aggravated in the RSM downscaling. Additionally, short time-scale phenomena such as daily mean temperature and daily precipitation are more accurately reproduced by the RSM than by the HG2. From future climate projection, the increasing temperature trends of each RCP scenario are consistently reproduced in the RSM downscaling; in particular, the result from the RCP 8.5 experiment shows a significantly steeper trend with increasing temperature. Meanwhile, the East Asian monsoon is intensified in the future climate projection by the strengthening North Pacific subtropical high and Okhotsk high in summer and intensified Siberian high in winter. These changes lead to an increase in precipitation for summer and a decrease for winter.

Keywords downscaling; East Asian monsoon; future climate change; regional spectral model

1. Introduction

Climate change is known to significantly impact human activities. Casualties and damage associated with extreme weather events induced by climate
change have significantly increased with the expansion of human activity (Solomon et al. 2007). The Intergovernmental Panel on Climate Change (IPCC) developed several feasible future climate scenarios (IPCC 2000, 2007; Moss et al. 2010). These scenarios, which reflect plausible future climate, have been constructed for explicit use in investigating the potential consequences of anthropogenic climate change and natural climate variability.

In climate research communities, global climate models (GCMs) are used to produce future simulations. Although GCMs can resolve synoptic-scale disturbances, they are unable to adequately resolve anomalous surface forcing due to their coarse spatial resolution (generally > 100 km). Regional climate models (RCMs) are able to provide regional details such as realistic small-scale features embedded within a low-resolution global model. This downscaling approach is used to obtain the geographical distribution and time evolution of small-scale features, given large-scale coarse-resolution analyses, forecasts, or simulations (Hong and Kanamitsu 2014).

Two fundamentally different downscaling methods are available: statistical and dynamical. The statistical approach pioneered by Kim et al. (1984) is based on statistical associations between the observed large-scale parameters and regional-scale observations. The dynamical downscaling pioneered by Giorgi and Bates (1989) is believed to be less dependent on present-day statistics, and it produces more generally applicable, physically based results. Statistical downscaling has been reported to be inferior in producing extreme weather phenomena and physically consistent variables (Lim et al. 2007; Gutmann et al. 2012). By contrast, the dynamical approach is better able to reproduce mesoscale disturbances that play important roles at regional scales, which cannot be resolved in low-resolution GCMs.

Recently, many studies have analyzed regional climate using RCMs forced by GCM scenarios, which contain higher spatial resolutions and comprehensive physical schemes (Leung et al. 2003; Wang et al. 2004; Solomon et al. 2007; Nikulin et al. 2011; Zou and Zhou 2013). Nikulin et al. (2011) projected future climate and assessed projected extremes using RCM forced by multi-GCM. Zou and Zhou (2013) showed results of near-future climate simulation for 2015–2040 using RegCM3 under the representative concentration pathways (RCPs) 8.5 scenario. They found that total and extreme precipitation tended to decrease over southeastern China but tended to increase over northeastern China. Additionally, Chen et al. (2011) investigated regional climate changes in terms of both means and extremes over southeast China using the GCM as well as RCM. Their results with respect to greenhouse gas forcing showed increased temperature associated with increased extreme events.

These studies provided future climate change simulations at the regional scale; however, their independent domain configurations preclude inter-comparison of downscaled results among models. To develop a comparable downscaling protocol for future scenarios, the Coordinated Regional Climate Downscaling Experiment (CORDEX) project has been launched to provide a unified framework for downscaling research (Giorgi et al. 2009). The project is now underway to improve the experimental framework leading in the second phase of CORDEX. This project covers several domains, namely, the entire African, Australian, South American, North American, Central America, and European continents. The Asian continent is divided into four domains, one approached via the South Asia, a second focusing on East Asia, a third targeting central Asia, and last focusing on South-East Asia (See http://www.cordex.org for details). Lee et al. (2013) assessed future climate change for 2006 to 2050 over East Asia using RCM. They concluded that extreme weather conditions will increase and intensify over South Korea in the near future (2025–2050) climate. However, studies comparing downscaled results for East Asia future climate change in the CORDEX to East Asia (CORDEX-EA) domain are still lacking.

The purpose of this study is to identify future climate changes related to the East Asian monsoon in the CORDEX-EA domain using RCM downscaling. Many RCM studies have used prior-generation future scenarios (IPCC 2000) on their own domain configuration, whereas this study adopts recently produced scenarios, namely, RCP (Moss et al. 2010), on a standardized framework as a participant in the CORDEX East Asia Project. In this study, dynamical downscaling is conducted for current (1980–2005) and future (2020–2100) climate using the regional spectral model (RSM; Juang et al. 1997). Current and RCP simulations of the Atmosphere–Ocean-coupled Hadley Center Global Environmental Model version 2 (HadGEM2-AO; Baeck et al. 2013) are used as large-scale forcing conditions. The RSM’s ability to provide regional-scale simulation details within a low-resolution global model is evaluated, and the resultant projected near- and far-future climatology are compared with current climatology. Although Lee et al. (2013) assessed future climate change over...
East Asia using the same CORDEX-EA framework and HadGEM2-AO, this study used different RCM and physics schemes, extending the future projection period to 2100 for far-future climate change under RCP scenarios 2.6 and 8.5. Additionally, we present future projections for the East Asia summer and winter monsoon.

This paper is organized as follows: The model description and experimental setup are given in Section 2. Section 3 provides evaluations of the downscaled results from the RSM for the current climate. A comparison of future and current climates is presented in Section 4. Finally, summary and conclusions appear in Section 5.

2. Model and experimental setup

2.1 Regional climate model

The RSM is applied as a RCM for dynamical downscaling in this study. This model has been extensively used for dynamical downscaling and operational short-range forecasting. The RSM uses a spectral method representing a two-dimensional cosine series for perturbations of pressure, divergence, 2-m temperature, and vapor mixing ratio. A unique aspect of the model is that spectral decomposition is applied to the difference between the full field and the time-involving background global analysis field. The horizontal derivatives that appear in the dynamical forcing terms in the prediction equations are first computed to yield the perturbation spectral coefficients and the base field separately. The derivatives are then summed to obtain total forcing. Linear computations of horizontal diffusion and semi-implicit adjustment are only considered as perturbations; thus, the error due to the reevaluation of the linear forcing from the base fields is eliminated (Juang and Kanamitsu 1994; Juang et al. 1997).

The physics package of the RSM employs the simplified Arakawa–Schubert convection scheme (Hong and Pan 1998) for convective parameterization, a diagnostic microphysics scheme (Hong et al. 1998), a nonlocal boundary layer scheme (Hong and Pan 1996), the National Centers for Environmental Prediction (NCEP)–Oregon State University–U.S. Air Force–National Weather Service Office of Hydrologic Development (NOAH) land surface model (LSM) (Chen and Dudhia 2001; Ek et al. 2003), and shortwave (Chou 1992) and long-wave (Chou et al. 1999) radiation parameterizations. To prevent distortion of large-scale fields, the revised scale selective bias correction method is applied, which has contributed to enhance performance of the precipitation simulation in RCM downscaling (Hong and Chang 2012).

2.2 Experimental Design

Figure 1 shows the RSM model domain and orography. This domain includes East Asia, India, the Western Pacific Ocean, and the northern part of Australia. These regions have been reported to have significant direct and remote effects on the East Asian monsoon system. This configuration of the model domain follows a protocol of CORDEX for East Asia (Giorgi et al. 2009). Climatology analyses are conducted in the analysis zone, whereas skill scores are tabulated for each subregion. Intra-annual variation and more detailed analysis are investigated over the Korea–Japan region in Fig. 1. The number of grid points in Cartesian coordinates is 200 (west–east) by 165 (north–south), with nominal horizontal resolution of 50 km. A 28-level terrain-following (sigma) vertical grid is used. The boundary condition is used from the historical run of the HadGEM2-AO (hereafter, called the “HG2”) simulation of National Institute of Meteorological Research of Korea Meteorological Administration (Baek et al. 2013). The HG2 is composed of an atmospheric GCM with N96 (1.875° × 1.25°) horizontal and 38 vertical levels, 38 km of
top altitude, and an ocean GCM with 1° horizontal and 40 vertical levels.

The RSM experiments are conducted for current (1980–2005) and future (2020–2100) climates with 1-year spin-up period. The RSM is forced by two types of future climate scenarios: the RCP 2.6 and 8.5 scenarios for the IPCC AR5 (IPCC 2013). Analyses for the current (1980–2005) climate are performed to evaluate the RSM’s ability to reproduce precipitation and surface temperature (hereafter called the REF experiment). Near- (2025–2050) and far-future (2075–2100) climate periods using the RCP 2.6 (hereafter called the N_RCP26 and F_RCP26 experiments, respectively) and RCP 8.5 (hereafter called the N_RCP85 and F_RCP85 experiments, respectively) scenarios are chosen to compare with the current climatology to investigate future climatic change over East Asia.

Simulated near-surface temperature and precipitation from the REF experiment are compared with Asian Precipitation – Highly-Resolved Observational Data Integration Towards Evaluation of the Water Resources (APHRODITE) data sets (http://www.chikyu.ac.jp) (Yatagai et al. 2012). The APHRODITE data contain daily precipitation and near-surface temperature with a spatial resolution of 0.25° × 0.25° and exclude ocean areas. For future climate simulation, two different types of large-scale forcing from HG2 are downscaled using the RSM. They are driven by the HG2 following the RCP 2.6 and 8.5 scenarios, which are labeled according to the approximate values of global radiation forcing (in W m\(^{-2}\)) in 2100 (Moss et al. 2010). The RCP 2.6 scenario assumes that global annual greenhouse gases emissions peak between 2010 and 2020, with emissions declining substantially thereafter. The RCP 8.5 scenario is characterized by increasing greenhouse gas emissions over time and is representative of scenarios that result in high greenhouse gas concentration levels. To assess the climate changes in the future, the near- and far-future experiments examining the 26-year period covered by the two types of scenarios simulations are compared with the REF experiment.

3. Evaluation of current climate simulation

In this section, simulated results from the REF experiment are examined to confirm the reproducibility of the general characteristics of current climatology. It is generally suggested that for results to be considered credible, surface variables such as precipitation and temperature should be compared with corresponding observations to predict the future scenarios (Liang et al. 2004; Wang et al. 2004). Note that some diagnostics used in this section are based on Lee et al. (2013). The seasonally averaged precipitation for land observed by the APHRODITE and its difference fields between observation and simulated results by the HG2 and RSM are shown in Fig. 2. With regard to current summer climatology of June–July–August (JJA) months, two major areas of strong precipitation are observed: the intertropical convergence zone over the tropics and the East Asia summer monsoon (EASM) precipitation band extending from southern China to Korea and Japan (Fig. 2a). The HG2 reproduces underestimation of precipitation over Korea and Japan (Fig. 2b), whereas the result from the RSM shows less underestimation (Fig. 2c). However, the precipitation simulated by both the RSM and HG2 is generally exaggerated over southern China and is underestimated over India. The RSM result tends to follow the precipitation pattern of the HG2 simulation. However, the results from the RSM represent an improved pattern by reducing precipitation over the western China region, with quite large biases over complex orographic regions such as India (cf. Figs. 2b, c). Narrow and strong bands of precipitation are indicated over the western areas of India, Indochina, and the Philippines (Fig. 2a). This extremely localized pattern is due to convective processes generated by narrow mountain areas (~1 km in height, ~500 km in width), which have been termed “mesoscale mountains” (Xie et al. 2006; Lee et al. 2013). Through satellite observation analysis and sensitivity experiments using a numerical model, Xie et al. (2006) determined that the mesoscale mountains play an important role in the Asian monsoon system (See Xie et al. (2006) for details). Therefore, it is clear that the RSM experiment properly simulates these orographic characteristics, whereas the HG2 run exhibits weakened and smoothed precipitation (Figs. 2b, c). This provides a clear demonstration of the added value of high-resolution downscaling. These results are consistent with Lee et al. (2013), which compared the simulated HG2 and downscaled RCM results.

In winter (December–January–February; DJF), the extended precipitation band northeastward from southern China to Japan related to the East Asia winter monsoon (EAWM) is shown in the APHRODITE observation data (Fig. 2d). The HG2 and RSM experiments quite well capture the precipitation pattern compared with observation; however, precipitation is generally overestimated over the EAWM region (cf. Figs. 2c, f). Compared with the observation, results from the downscaled RSM run exhibit
Fig. 2. Seasonally averaged precipitation (mm d$^{-1}$) obtained from (a) APHRODITE observation and difference distribution between the observation and current climate experiments from (b) HadGEM2 and (c) RSM for JJA. (d), (e), and (f) are the same as (a), (b), and (c), except for DJF.
an improved precipitation pattern by reducing and narrowing the precipitation band compared with that from the HG2 run, especially over eastern and southern China. Meanwhile, the tropical precipitation pattern is also quite well reproduced by both models; however, the amount is exaggerated over the tropical islands, especially in the RSM run (Figs. 2e, f). It is due to this fact the extreme biases in heavy rainfall region from HG2 simulation can be connected to large-scale forcing of the RSM experiment. Despite its low resolution (2.5°), the Global Precipitation Climatology Project (GPCP) data set (Huffman et al. 2001), which covers both land and ocean, is also compared with each simulation because the East Asian monsoon system covers not only the continent but also the western North Pacific. However, both simulations show similar positive biases over the ocean precipitation region (not shown here).

Figure 3 shows the 2-m temperature distribution obtained from observation of APHRODITE and its difference fields between observation and simulation results from the HG2 and RSM. For the current climate summer, the HG2 and RSM experiments satisfactorily reproduce the distribution of seasonal mean temperature (Figs. 3a, b, c). For JJA, The HG2 run generally well captures the observed distribution; however, it shows overall warming, whereas the RSM run shows more cooling over the EASM region as well as tropics and more warming over northern China (cf. Figs. 3b, c). For DJF, the results from both experiments exhibit a bias toward cold temperatures over land areas, as in previous studies (e.g., Zhang et al. 2008; Xu et al. 2010; Lee et al. 2013). However, those from the RSM show an improved pattern by reducing the cold biases although a distinct cold bias over the Tibetan Plateau region is aggravated by the RSM downscaling (cf. Figs. 3d, e, f).

It is clear that the results from the RSM experiment are cooler than those from the HG2 simulation in most of the domain (Figs. 3b, c, e, f). Additionally, for DJF, the RSM simulation is distinctive in showing further cooling over the Tibetan Plateau. Lee et al. (2013) mentioned one possible reason for these cooling patterns. Given that the overall elevation of the plateau and a different physics related to the land surface are used in both models (not shown), a difference in snow-albedo feedback between the two models seems to be the source of the cold bias. The importance of the snow-albedo feedback over the Tibetan Plateau was also mentioned by Hong et al. (2012).

Table 1 shows the basic pattern correlation coefficients (PCs) and root mean square error (RMSE) values for simulated precipitation and 2-m temperature from the HG2 and RSM experiments against the APHRODITE observation for each domain (Fig. 1). Note that better performance is seen as the PC approaches 1 and the RMSE nears 0. The skill scores for simulated surface precipitation and 2-m temperature indicate the capability of the models. With respect to precipitation, PCs from the HG2 run show higher (lower) values in summer and lower (higher) values in winter compared with those from the RSM experiment over whole CORDEX (East Asia) domain, but with lower RMSE in both seasons. PCs from the HG2 show higher values than that from the RSM run over the tropics and South China in both summer and winter. However, PCs from the RSM run show higher values than those from HG2 run over India, Mongolia, and the Korea–Japan domain in both summer and winter. In terms of temperature, PCs from the RSM run show higher values than those from the HG2 run over the whole subregion in both summer and winter, except the CORDEX region in summer. These results suggest that although downscaling does not always guarantee a good skill score, some pattern such as orographic characteristic precipitation and temperature (e.g., India, Mongolia, and Korea–Japan) can be improved by downscaling at high resolution.

Meanwhile, the performance for temperature is better than that for precipitation, as seen in previous studies (e.g., Chang and Hong 2011; de Sales and Xue 2013; Lee et al. 2013). The PCs for temperature for winter are higher than those for summer; however, the RMSEs for summer are smaller than those for winter in both models. Lee et al. (2013) used the same lateral boundary condition and concluded that HG2 simulation has a systematic cold bias in winter, which can be connected to large-scale forcing of the RSM downscaling. Those findings are also consistent with this study, although the RCM and the physics scheme used are different (Figs. 3e, f).

Figure 4 shows the probability distribution of domain-averaged daily mean temperature and precipitation in the period 1980–2005, obtained from the APHRODITE observation, HG2, and RSM simulation for the Korea–Japan region. Note that the probability distribution is tabulated with a bin size of 2°C for temperature and 2 mm d⁻¹ for precipitation. For temperature, the distribution obtained from the APHRODITE observation shows the maximum peak as about 40% in a 20–22°C bin (Fig. 4a). The maximum peak from the HG2 simulation is higher than that from observation at a bin section of
Fig. 3. Seasonally averaged 2-m temperature (°C) obtained from (a) APHRODITE observation and difference distribution between the observation and current climate experiments from (b) HadGEM2 and (c) RSM for JJA. (d), (e), and (f) are same as (a), (b), and (c), except for DJF.
22–24°C, whereas this peak is well captured by the RSM run. The bins above 24°C in the RSM run also give relatively good performance compared with the HG2 simulation. In regard to precipitation distribution, both the HG2 and RSM simulations quite well reproduce light precipitation ranging 0–4 mm d⁻¹ (Fig. 4b). However, HG2 tends to underestimate the probability of moderate precipitation ranging from 4 to 8 mm d⁻¹ relative to the observed data, and HG2 slightly overestimates the probability of heavy rainfall over 8 mm d⁻¹. For moderate as well as heavy precipitation, it is clear that the RSM experiment provides an improved probability distribution (even if the temperature distribution) that is significantly closer to observations than that from the HG2 output. The climatological distributions for temperature and precipitation by the RSM downscaling follow the results from the HG2 simulation, although some skills are improved over the East Asia domain or the Korea–Japan domain. However, the probability distribution for the daily-scale feature clearly shows improvement by dynamical downscaling using the RSM, especially in precipitation distribution. This improvement can be explained as the added value of dynamical downscaling. It is known as the added value of downscaling that the results related to the large-scale phenomena, orographic characteristics, and extreme event are improved by the high-resolution downscaling. Thus, it is clear that the distribution of temperature and precipitation in future climate simulations would be more reliable in the RSM than in the HG2 scenario.

4. Future climate changes

In this section, future climate change is analyzed, with a focus on temperature change and variation in precipitation over the East Asia region. To assess future climate change, simulated temperature and precipitation from the RCP 2.6 and 8.5 experiments are compared with those from current climatology (REF experiment). Additionally, the precipitation change related to the East Asian summer and winter monsoon system is presented.

4.1 Changes in Climatology

Figure 5 shows the time series of annual mean 2-m temperature obtained from the RCP 2.6, RCP 8.5, and REF experiments. Focusing on the linearly regressed trends, surface warming trends are apparent in both the future climate experiments. The simulated RCP 8.5 (RCP 2.6) scenario shows a steeper (gentler) slope than the REF simulation. These trends agree with the conclusion that surface warming is one of the major effects of global warming. Furthermore, if stabilization policies such as the RCP 2.6 scenario work

<table>
<thead>
<tr>
<th>PC/RMSE</th>
<th>JJA Precipitation</th>
<th>JJA Temperature</th>
<th>DJF Precipitation</th>
<th>DJF Temperature</th>
</tr>
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<tr>
<td>HadGEM</td>
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<td></td>
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</tr>
<tr>
<td>CORDEX</td>
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<td>0.93/2.13</td>
<td>0.89/2.24</td>
<td>0.96/3.92</td>
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<td>0.41/1.92</td>
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<td>0.87/1.82</td>
<td>0.97/3.22</td>
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<td>India</td>
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<td>0.76/1.42</td>
<td>0.50/1.23</td>
<td>0.94/2.38</td>
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</tr>
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<td>0.94/3.44</td>
</tr>
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<td>0.97/4.37</td>
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<td><strong>0.90/2.02</strong></td>
<td><strong>0.89/1.08</strong></td>
<td><strong>0.97/3.48</strong></td>
</tr>
</tbody>
</table>

The larger PCs (if it is same, with the smaller RMSE), by region, are highlighted in bold. The locations of sub regions are specified in Fig. 1.
successfully, significantly increased temperature is a possibility even if the warming trend is reduced. Lee et al. (2013) suggested that compared with the globally averaged warming obtained from the HG2 run, the downscaling run shows enhanced warming trends over the CORDEX domain, by about 1–1.5°C (Fig. 4 in Baek et al. 2013, and Fig. 7 in Lee et al. 2013). In this study, the RSM results from the RCP 8.5 scenario show slightly enhanced warming trends over the Korea–Japan region, by about 0.5–1.0°C, compared with results over the CORDEX domain (not shown).

Figure 6 shows the spatial distribution change of 2-m temperature over East Asia for near (2025–2050) and far future (2075–2100) against the REF (1980–2005) simulation. The RCP 2.6 scenario in the near future shows overall warming in summer (Fig. 6a), especially in northeastern China and the ocean northeast of Japan. The RCP 2.6 scenario in the far future shows further intensified warming, especially from Korea to the ocean northeast of Japan, but reduced warming over northeastern China (Fig. 6b). The RCP 8.5 scenario in the near future exhibits warming trends to similar those for the RCP 2.6 scenario in the near future (cf. Figs. 6a, c), whereas the significant warming over northern China, Korea, and Japan is predicted in the RCP 8.5 scenario in the far future (Fig. 6d). In winter, warming is pronounced over southeastern China to Korea and over Japan in near-future climate simulation by the RCP 2.6 scenario (Fig. 6e), and this warming is further intensified, especially near the sea of Okhotsk, in the far or near future by the RCP 8.5 scenario (Figs. 6f, g). The warming trend in winter is significantly more intensified in far-future climatology by the RCP 8.5 scenario compared with that in summer (Fig. 6h).

Changes in the 2-m temperature over CORDEX-EA, East Asia, and Korea–Japan regions from RCP 2.6 and 8.5 experiments for near and far future climate are tabulated in Table 2 and are compared with those from the REF experiment. In
Fig. 6. Difference in seasonally averaged temperature (°C) against the current climate obtained from the RCP2.6 and RCP8.5 experiments over the East Asia region for JJA (a, b, c, d) and DJF (e, f, g, h). Note that the averaged period for near- (far-) future climate is 2025–2050 (2075–2100), whereas it is 1980–2005 for the current climate.
both the RCP 2.6 and 8.5 experiments, increments of temperature in the East Asia and Korea–Japan regions in all periods and in all seasons are larger than the values in CORDEX-EA. For the RCP 2.6 scenario, the temperature increment is largest in autumn and winter in all domains, especially for far-future climatology. Focusing on the RCP 8.5 scenario experiments, the greatest differences are shown in winter, and these differences increase from spring to winter in all domains and periods. These temperature changes confirm that the gradient of temperature change between the summer and winter seasons is decreased, which can explain the extended summer periods and warmer winter, particularly in the Korea–Japan region. These results are also consistent with the previous study (Lee et al. 2013) that predicted extended summer periods and warmer winters in mid-latitude continental regions.

Differences in seasonal precipitation among the near future (2025–2050) and far future (2075–2100) and the current climatology for the Coordinated Regional Climate Downscaling Experiment (CORDEX) analysis zone and subregions (East Asia, Korea–Japan) for the spring (March–April–May; MAM), summer (June–July–August; JJA), autumn (September–October–November; SON), and winter (December–January–February; DJF) seasons.

<table>
<thead>
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<th>Near/Far</th>
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<th>JJA</th>
<th>SON</th>
<th>DJF</th>
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<td><strong>1.07/1.20</strong></td>
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<td>East Asia</td>
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<td>Korea-Japan</td>
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<td>RCP8.5</td>
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<td>CORDEX</td>
<td>1.40/4.14</td>
<td>1.54/4.35</td>
<td>1.71/4.63</td>
<td><strong>1.70/4.85</strong></td>
</tr>
<tr>
<td>East Asia</td>
<td>1.40/4.14</td>
<td>1.51/4.31</td>
<td>1.65/4.49</td>
<td><strong>1.73/4.90</strong></td>
</tr>
</tbody>
</table>

The largest differences, by region, are highlighted in bold. The locations of subregions are specified in Fig. 1.

4.2 Changes in the East Asia monsoon system

The East Asian monsoon is one of the most important large-scale circulation systems that impact the climate and weather in the East Asian region. To reveal the precipitation change in future climate related to the monsoon system, some results from the RCP 8.5 experiment compared with current climate experiment are shown in this section. Differences in 2-m temperature between the near- (2025–2050) and far- (2075–2100) future (RCP 2.6 and RCP 8.5) and current (REF, 1980–2005) climatology for the Coordinated Regional Climate Downscaling Experiment (CORDEX) analysis zone and subregions (East Asia, Korea–Japan) for the spring (March–April–May; MAM), summer (June–July–August; JJA), autumn (September–October–November; SON), and winter (December–January–February; DJF) seasons.

The East Asian monsoon is one of the most important large-scale circulation systems that impact the climate and weather in the East Asian region. To reveal the precipitation change in future climate related to the monsoon system, some results from the RCP 8.5 experiment compared with current climate experiment are shown in this section. Differences distribution of 850 hPa winds and specific humidity change rates against the current climate obtained from the RCP 8.5 experiment over the East Asia for summer and winter are shown in Fig. 8. In summer, low-level moisture differences in the near future between the current and RCP 8.5 experiments are slightly moderated (Figs. 7c, f). Meanwhile, the result from the RCP 8.5 scenario experiment in the near future shows similar changes to those from the RCP 2.6 scenario in the same period. Remarkably, a strong decline in winter precipitation is seen over the southern ocean of Japan, and enhanced precipitation is notable over southern China and the northern part of Japan (Fig. 7h), which is again related to EAASM. A detailed description of the East Asian monsoon is considered in the next section.
Fig. 7. Same as Fig. 6, except for the future change rates in seasonally averaged precipitation (mm day$^{-1}$). Closed contours (gray line) indicate the 95% significance level.
warm and wet air from low latitudes directed toward EASM areas in the East Asia region, with regions of major rainfall increase (Figs. 7c, d). In winter, the northwesterly winds related to Siberian high pressure and Aleutian low pressure are intensified, and moisture is increased, especially further in the far future. These intensified patterns lead to increased precipitation over the northern sea region of Japan, which is a common winter rainfall region closely related to the cold northwesterly winds and relatively warm sea surface temperature. These intensified East Asian winter monsoon systems generally lead to decreased precipitation over the southern ocean of Japan due to the strong dry and cold winds from northern region (Figs. 7g, h).

To characterize the variability of the sea-level pressure over East Asia for the current and future summer and winter climate, an empirical orthogonal function (EOF) analysis is applied. Figures 9a, b show the first and second EOF analyses of JJA sea-level pressure over East Asia from the current climate experiment, respectively. The first mode eigenvector from the REF experiment explains 45.2 % of the total variance. The dominant structure of the EASM is characterized by an intensified North Pacific subtropical high. The second EOF of the REF experiment, which explains 22.6 % of the total variance, shows a confrontation between the North Pacific subtropical high and the Okhotsk high, which is associated with the main summer precipitation bands of the EASM.

Figures 9c, d show the first two EOFs of the RCP 8.5 experiment for the far-future climate, which explain 49.2 and 19.9 %, respectively, of the total variance. By directly comparing these spatial patterns
with those of the REF experiment, the first EOF in the F_RCP85 experiment can be seen to share some of the spatial structure of both the first and second EOFs of the REF experiment. Compared with the REF experiment, the F_RCP85 experiment shows further intensified variability related to the confrontation between the North Pacific subtropical high and the Okhotsk high pressure in the first EOF mode (Fig. 9c). Those features are associated with the increased summer monsoon precipitation and wind changes (Figs. 7d, 8b). By taking into consideration the first EOFs and their corresponding PCs (Figs. 11a, b), it can be determined that the first EOF from the F_RCP85 experiment contributes to more intensified variability than that from the REF experiment. Meanwhile, PCs from the second EOFs from the REF and F_RCP85 experiments have a similar variability to each other (not shown).

Figures 10a, b show the first and second EOF analyses of DJF sea-level pressure over East Asia from the REF experiment, respectively. The first mode eigenvector from the REF experiment explains 39.9% of the total variance. The dominant structure of the EAWM is characterized by strengthening of the Siberian high. The second EOF of the REF experiment, which explains 29.4% of the total variance, shows a confrontation between the Siberian high and Aleutian low, which is associated with the main pattern of the EAWM. Figures 10c, d show the first two EOFs of the RCP 8.5 experiment for the far-future climate, which explain 42.7% and 29.3%, respectively, of the total variance. Their corresponding PCs associated with the eigenvectors of the EOF first mode are shown in Figs. 11c, d. Compared with the REF experiment, the F_RCP85 experiment shows a strengthened Siberian high in the first and second EOF modes. These features are also associated with increased precipitation due to the northward strong and cold winds and increased precipitation over the northern seaside region of Japan, which is a common winter snowfall region closely related to the cold northwesterly winds and warm and wet sea surface temperature (Figs. 7h, 10d).
8d).
With regard to temporal variation in the East Asian monsoon, Fig. 12 shows the time–latitude section of average precipitation of the current simulation and the far-future projection experiment along 120°–150°E. The REF experiment shows the maximum precipitation area near 31°N in May–June and near the 21°N in August, which is related to the East Asia summer monsoon band (Fig. 12a). The EAWM precipitation peak area is shown near the 31°N on December. Compared with the REF experiment, the F_RCP85 experiment shows a similar trend during band period of the East Asian monsoon (Fig. 12b). However, the East Asian summer monsoon precipitation (near 31°N) period is concentrated in June and increased in July. EAWM precipitation near the 31°N is significantly decreased on December. These features are associated with increased (decreased) precipitation of the F_RCP85 experiment for summer (winter) over the southern part of Japan (Figs. 7d, h).

5. Summary and concluding remarks
This study examined future changes to the climate over the East Asian region, with a focus on temperature variation and changes in precipitation, and future changes in the East Asian monsoon system. The current and future climate projection scenarios are downscaled using the RSM under the RCP 2.6 and 8.5 scenarios driven by the HG2 simulation, which are configured with an approximately 50-km-grid resolution over the CORDEX–East Asia domain. Simulations were conducted for the current climate and two types of future climates, namely, from 1980 to 2005 and from 2020 to 2100. Near- (2025–2050) and far-future (2075–2100) climate simulations using the RCP 2.6 and 8.5 scenarios were compared with the current (1980–2005) climatology for diagnosing the climatic change over East Asia.

To confirm the reproducibility of current climatology by regional model downscaling, the surface variables such as precipitation and 2-m temperature were compared with the observations data. It is clear
that the RSM is able to capture the major characteristics of precipitation and surface temperature distribution. In particular, precipitation patterns related to the EASM, EAWM, and mesoscale mountain range are properly reproduced as added value, although generally the wet and cold biases are aggravated in the RSM simulation. Additionally, short time-scale phenomena such as daily-scale temperature and precipitation are more accurately reproduced by the RSM than by the HG2. To identify potential future climate change, simulated temperature and precipitation obtained from the RCP 2.6 and 8.5 experiments were compared with those from the current climate simulation. The increasing temperature trends of each RCP scenario are consistently reproduced in the RSM downscaling. The result from the RCP 8.5 experiment shows a steeper trend in increasing temperature than the RCP 2.6 experiment, which also shows a current increasing trend. In both future climate projections, the increment in temperature is most dominant in the autumn and winter seasons. Meanwhile, the EASM and EAWM are intensified in the future climate experiment by the increased strength of the North Pacific subtropical high and the Okhotsk high pressure in summer and the intensified Siberian high in winter. These changes lead to a precipitation increase in summer and decrease in winter.

To reveal the precipitation change in future climate
related to the monsoon system, an EOF analysis was applied for sea-level pressure over East Asia from the current climate (REF) and far future-climate (F_RCP85) results of the RCP 8.5 experiment. The North Pacific subtropical high frequently becomes stronger in the far future. In addition, the variance related to the confrontation between the North Pacific subtropical high and the Okhotsk high pressure is further intensified in the far future. For the winter season, the intensified Siberian high is shown in the far future from the RCP 8.5 experiment in both first and second EOF modes. These features are associated with decreased precipitation due to the northward strong and cold winds and increased precipitation over the northern seaside region of Japan, which is a common winter snowfall region closely related to the cold northwesterly winds and warm and wet sea surface temperature.

Consequently, this study shows that if climatic change progresses without stabilization, such as in the RCP 8.5 scenario, the temperature will increase greatly over East Asia, magnifying the change relative to the CORDEX-EA region. Additionally, it is obvious that both summer and winter precipitation bands related to the East Asian monsoon are increased in the far-future climate by the intensified EASM and EAWM, although general winter precipitation without the main band region decreases. Similar intensified EASM results have been similarly shown in previous future-climate analyses using GCM simulations such as CMIP3 or CMIP5 (Seo and Ok 2013; Seo et al. 2013).

This study also confirms that high-resolution data for regional climate research can be successfully generated using the RSM. Although the downscaling results show greatly improved distribution (especially daily-scale features such as probability distributions) as added value due to the high resolution compared with the GCM, we cannot guarantee that the RSM models lead to more accurate predictions of future climate change. However, we agree that high-resolution RCM data make it possible to use various climatic elements such as variation in strength and/or frequency of monsoons and typhoons. Meanwhile, this study has some limitation and uncertainty due to our having used only one RCM and GCM. However, the results and contents can be shared and compared with other studies on the East Asia climate to reduce the uncertainty because this study used the same domain configuration with different model and physics framework as the CORDEX-EA project. In future studies, comparisons of multi-model downscaling or downscaling using the multi-GCM output will be analyzed. Furthermore, because ocean currents play an important role in climate change mechanism over the East Asia region, the regional ocean–atmosphere-coupled model can be employed in further studies of the current and future climate parameters in that region.

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