NOTES AND CORRESPONDENCE

Future Changes in Winter Precipitation around Japan Projected by Ensemble Experiments Using NHRCM

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Abstract

We investigate future changes in winter precipitation around Japan and their uncertainties using the downscalings of a non-hydrostatic regional climate model (NHRCM) with 20-km grid spacing according to global climate projections. The global climate projections were conducted by the atmospheric general circulation model with three patterns of sea surface temperature changes in the Coupled Model Intercomparison Project Phase 5 under the Representative Concentration Pathway 8.5. Moreover, three cumulus convective parameterizations were applied in the present and future climate experiments. The ensemble mean of nine future NHRCM experiments shows decreases in the winter precipitation on the coast of the Sea of Japan and over the Pacific Ocean in the south of the Japanese archipelago. The former decrease in precipitation results from a weakened winter monsoon. The latter corresponds to changes in extratropical cyclone number around Japan, which have a large uncertainty. On the other hand, winter precipitation increases over the northernmost part of Japan (Hokkaido) and the northeastern Asian continent. The strengthened northwesterly around Hokkaido, which results from the reduction of sea ice in the Sea of Okhotsk, causes increased precipitation in the inland area of Hokkaido. In addition, moistening due to global warming relates to increased precipitation in extremely cold regions. These signals are common to most experiments.

Keywords regional climate modeling; winter monsoon; climate change; downscaling

1. Introduction

In winter, the Japanese archipelago is influenced by the East Asian winter monsoon (EAWM). Dry and cold air masses from the Asian continent receive substantial water vapor and heat from the Sea of Japan, which causes large amounts of snow along the coast of the Sea of Japan, especially in the mountainous areas (Yamaguchi et al. 2011). The winter precipitation is influenced by the interannual and decadal variability in the sea surface temperature (SST) in the Sea of Japan (Hirose and Fuku-dome 2006; Takano et al. 2008; Fujita et al. 2014). In
contrast, areas along the coast of the Pacific Ocean, which is the leeward side of the EAWM, mostly have dry sunny days during the winter. However, even along the Pacific Ocean coast, developing extratropical cyclones sometimes bring heavy rainfall and snowfall (Takano 2002; Chen et al. 1991; Hayasaki and Kawamura 2012; Hayasaki et al. 2013).

Global warming due to anthropogenic greenhouse gases could lead to changes in the air temperature, ocean temperature, EAWM, and extratropical cyclones. Hori and Ueda (2006) indicated that the winter monsoon would weaken at the end of the 21st century according to the World Climate Research Programme (WCRP) Coupled Model Intercomparison Project Phase 3 (CMIP3) multi-model dataset. Mizuta et al. (2011) investigated future changes in the storm activity in the Northern Hemisphere in winter using the Meteorological Research Institute atmospheric general circulation model (MRI-AGCM). They showed that the total number of cyclones would decrease due to global warming, whereas the number of intense cyclones would increase significantly.

To simulate winter precipitation in Japan, high-resolution numerical simulations are needed, since it is strongly influenced by complex Japanese mountains. Dynamical downscaling using a regional climate model is a useful method for evaluating future changes in winter precipitation, including snowfall and rainfall (Hara et al. 2008; Kawase et al. 2013). Kawase et al. (2013) investigated the impacts of sea surface and atmospheric warming due to global warming on snowfall and snow depth along the Sea of Japan coast.

Since the future projections using global and regional climate models would have large uncertainties (Inatsu et al. 2015), multiple dynamical downscalings from several global climate simulations are important. The changes in global-scale SST patterns have various impacts on the mid- and high-latitude atmospheres, such as monsoons and extratropical cyclones (Mizuta et al. 2014). The simulation of precipitation is also influenced by cumulus convective parameterizations in GCMs, which could affect the future changes in Asian precipitation (Endo et al. 2012). In addition, the winter precipitation around Japan influenced by the local-scale SST changes in the Sea of Japan. The purpose of this study is to evaluate the future changes in winter precipitation and their uncertainties around Japan by analyzing the dynamically downscaled multi-global climate projections at the end of the 21st century. We focus on the impacts of changes in SST patterns and cumulus convective parameterizations.

2. Model specification and experiment design

2.1 MRI-AGCM AMIP experiments

The MRI-AGCM3.2 (Mizuta et al. 2012) is used as the parent global model. The horizontal resolution of MRI-AGCM3.2 is TL319 (grid spacing of approximately 60 km). In the Atmospheric Model Intercomparison Project (AMIP)-type present climate simulation (1983–2004), the monthly mean data from HadISST1 (Rayner et al. 2003) with $1^\circ \times 1^\circ$ resolution is input into the MRI-AGCM3.2, hereafter, HPA simulation. Here, the first year is a spin-up duration. Three present climate simulations were conducted using three types of cumulus convective parameterization: the Yoshimura scheme (YS) (Yoshimura et al. 2014), Kain–Fritsch scheme (KF) (Kain and Fritsch 1990, 1993), and Arakawa–Schubert scheme (AS) (Arakawa and Shubert 1974; Randall and Pan 1993).

For the future climate projection, the AMIP-type time slice experiments (Murakami et al. 2012) were performed. The SST was prepared using the monthly HadISST1 in the present climate (1983–2004) and three patterns of SST changes (SST clusters) from present (1979–2003) to future climate (2075–2099) in the Coupled Model Intercomparison Project Phase 5 (CMIP5) (Mizuta et al. 2014), hereafter, HFA simulation. Note that the integration periods is 20 years, whereas the SST clusters were analyzed using 25 years. The shorter integration period would underestimate the interannual variations. We focused on the Representative Concentration Pathway 8.5 (RCP8.5), which assumes the most accelerated global warming in all RCP scenarios (Moss et al. 2010). Three cumulus convective parameterizations are implemented in the future climate projections with each SST cluster as applied in the present climate simulation. Three HPA and nine HFA experiments are conducted in the present and future climate simulations (Table 1).

2.2 Specifications of the NHRCM

Dynamical downscaling was performed from July 20, 1984 to September 1, 2004 using non-hydrostatic regional climate model (NHRCM), which was developed by the MRI (Sasaki et al. 2008), with 20-km horizontal grid spacing from the MRI-AGCM AMIP experiments. All experiments are listed in Table 1. NHRCM is equipped with the KF scheme, the MRI/Japan Meteorological Agency (JMA) Simple Biosphere scheme (Hirai et al. 2007), and the improved Mellor–Yamada level 3 planetary boundary layer scheme (Nakanishi and Niino 2004) for the
cumulus convective parameterization, land surface process, and vertical turbulent diffusion, respectively. The simulation domain is shown in Fig. 1. This experimental design enables to evaluate the impacts of the changes in global-scale atmospheric circulation derived from SST changes on the winter precipitation in Japan with 20-km grid spacing, which reproduces the contrast of wintertime climate in Japan. The uncertainty derived from three cumulus convective parameterizations also evaluated.

We focused on the boreal winter from December to February (DJF). The simulated winter precipitation in the present climate (December 1983–February 2004) is compared with the Automated Meteorological Data Acquisition System (AMeDAS) obtained by the JMA in the same period.

### 2.3 Definition of the Asian winter monsoon index and cyclone existence density

An index of the EAWM is defined as the average of the northerly wind \( (-v) \) with \( v \) over the region of \( 25^\circ\text{N}–45^\circ\text{N} \) and \( 125^\circ\text{E}–150^\circ\text{E} \), which is the same definition of the Asian winter monsoon index (AWMI) used in Hu et al. (2000) except for the calculation region. This index is named as AWMI-JP. The cyclone existence density (CED) is defined using the 6-h sea level pressure (SLP). First, cyclone centers are detected using the following three criteria.

1. SLP at a center grid is lowest in a 10 × 10 grid box, i.e., 200 km × 200 km.
2. The meridional and zonal pressure gradient toward the center grid is negative.
3. The SLP at the center grid is 1.0 hPa lower than the mean pressure in the surrounding 200-km area.

After detecting the cyclone centers, we calculated the number of cyclone centers in the surrounding 300-km area, which is defined as the CED.

### Table 1. Experiment names of the NHRCM20 and simulation designs in AMIP-type experiments of MRI-AGCM3.2

<table>
<thead>
<tr>
<th>Experiment Name</th>
<th>Cumulus convective parameterization (AGCM)</th>
<th>Period</th>
<th>Emission Scenario (AGCM)</th>
<th>SST Cluster</th>
</tr>
</thead>
<tbody>
<tr>
<td>HPA-YS</td>
<td>Yoshimura</td>
<td>present</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>HPA-KF</td>
<td>Kain-Fritsch</td>
<td>present</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>HPA-AS</td>
<td>Arakawa-Schubert</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>HFA-YS-C1</td>
<td>Yoshimura</td>
<td>-</td>
<td>future RCP8.5</td>
<td>Cluster 1</td>
</tr>
<tr>
<td>HFA-KF-C1</td>
<td>Kain-Fritsch</td>
<td>-</td>
<td>RCP8.5</td>
<td>Cluster 2</td>
</tr>
<tr>
<td>HFA-AS-C1</td>
<td>Arakawa-Schubert</td>
<td>-</td>
<td>RCP8.5</td>
<td>Cluster 3</td>
</tr>
<tr>
<td>HFA-YS-C2</td>
<td>Yoshimura</td>
<td>future</td>
<td>RCP8.5</td>
<td>Cluster 1</td>
</tr>
<tr>
<td>HFA-KF-C2</td>
<td>Kain-Fritsch</td>
<td>future</td>
<td>RCP8.5</td>
<td>Cluster 2</td>
</tr>
<tr>
<td>HFA-AS-C2</td>
<td>Arakawa-Schubert</td>
<td>future</td>
<td>RCP8.5</td>
<td>Cluster 3</td>
</tr>
<tr>
<td>HFA-YS-C3</td>
<td>Yoshimura</td>
<td>future</td>
<td>RCP8.5</td>
<td>Cluster 1</td>
</tr>
<tr>
<td>HFA-KF-C3</td>
<td>Kain-Fritsch</td>
<td>future</td>
<td>RCP8.5</td>
<td>Cluster 2</td>
</tr>
<tr>
<td>HFA-AS-C3</td>
<td>Arakawa-Schubert</td>
<td>future</td>
<td>RCP8.5</td>
<td>Cluster 3</td>
</tr>
</tbody>
</table>

Fig. 1. Model domain and analysis areas. The outer enclosed area is the model domain. Region A is the analysis area for the AWMI-JP and MME Taylor diagram. Region B is the area for calculating precipitation over central Japan and around the Pacific ocean.
3. Future changes simulated by NHRCM

3.1 Winter precipitation

Figures 2a and 2b show the horizontal distribution of 20 years’ mean winter precipitation in three-ensemble-mean present climate simulations and nine-ensemble-mean future climate projections, respectively. Larger amounts of precipitation are simulated on the coast of the Sea of Japan than on the coast of the Pacific Ocean. A zonal precipitation band appears over the Pacific Ocean in the south of the Japanese archipelago. The winter precipitation has, however, some biases as compared with AMeDAS (Supplement 1). The winter precipitation is underestimated along the coast of Sea of Japan, whereas it is overestimated in other regions. Ishizaki et al. (2012) have also pointed out similar winter precipitation biases in the present climate simulations using four different regional climate models with 20-km horizontal grid spacing. The heights of mountains in the NHRCM with 20-km grid spacing are lower than their actual heights. The lower mountains in the NHRCM would reduce vertical motions, leading to less orographic enhancement of precipitation.

Figure 2c shows the difference in winter precipitation between the present climate simulations and future climate projections. Significant decreases in precipitation are projected along the Sea of Japan coast and over the Pacific Ocean in the south of the Japanese archipelago. In contrast, precipitation increases in the inland area of Hokkaido, located in the northern part of Japan, Korean Peninsula, and the eastern parts of China and Russia.

3.2 Future changes in the EAWM, extratropical cyclones, and total precipitable water

Figure 2d shows the DJF mean surface wind in the present climate. Strong northwesterlies associated with the EAWM prevail over the Japanese archipelago. In the future climate projections, weaker wind speed and southeasterly anomalies are dominant over the oceans around Japan (Figs. 2e, f), indicating a weakened EAWM. This results in decreased precipitation along the Sea of Japan coast where precipitation is strongly affected by the EAWM. The weakened winter monsoon due to global warming has been observed in previous studies (e.g., Hori and Ueda 2006). On the other hand, stronger onshore wind and westerly anomalies are projected around Hokkaido, which enhances the latent heat fluxes over the ocean (Fig. 2o) and promotes moisture transport. In addition, the stronger wind enhances the orographically induced upward winds in the mountainous area of Hokkaido and generates more precipitation (Fig. 2c).

Figure 2g shows the mean CED in the present climate simulations. The high CED appears over the northern part of the Sea of Japan and the Pacific Ocean near the Japanese archipelago. These features are consistent with previous cyclone detection studies. (e.g., Hayasaki and Kawamura 2012). The high CED corresponds to the precipitation band over the Pacific Ocean (Fig. 2a). The ensemble mean of future projections indicated that the CED decreases around Japan (Figs. 2h, i). The decrease in CED corresponds to the weakening of the precipitation band over the Pacific Ocean (Fig. 2c), whereas precipitation changes do not depend on CED changes in the higher latitude regions where the climatological precipitation is quite small (Fig. 2a).

Figures 2j and 2k show the total precipitable water (TPW) in the present and future climate, respectively. TPW is larger at lower latitudes. The warmer atmosphere can contain more water vapor since the saturated water vapor pressure depends on air temperature according to the Clausius–Clapeyron equation. In the future climate projection, TPW increases over the whole region due to global warming. The increased ratio of TPW is larger at higher latitudes and higher altitudes, e.g., the Asian continent and the inner area of Hokkaido, which corresponds to the increase in precipitation in the northern regions (Fig. 2c). It has been shown that snowfall would increase in Siberia during wintertime using the CMIP3 multi-model dataset (Räissänen 2008; Brown and Mote 2009). The relationship between changes in latent heat flux and precipitation is unclear except for Hokkaido (Figs. 2m–o).

4. Uncertainty in future projections

4.1 Variation in precipitation changes

Figure 3 shows the number of experiments that projects an increase in the future precipitation in each grid. All experiments produce more precipitation north of 40°N except for the northern part of the Sea of Japan. Most experiments, on the other hand, project decreased precipitation along the Sea of Japan coast and over the Pacific Ocean, which corresponds to the ensemble mean of precipitation changes (Fig. 2c). As described in Section 3, changes in the winter monsoon, extratropical cyclones, and water vapor could be related to the increased precipitation over the Sea of Japan, the decreased precipitation over the Pacific Ocean, and the increased precipitation at higher latitudes, respectively.
Fig. 2. Climatology and future changes in (a–c) DJF precipitation and (d–f) surface wind, (g–i) cyclone existence density (CED), (j–l) total precipitable water (TPW), and (m–o) latent heat flux simulated by three HPA and nine HFA experiments. (a, d, g, j, m) Three HPA experiments mean, i.e., present climatology, (b, e, h, k, n) nine HFA experiments mean, i.e., future climatology, and (c, f, i, l, o) difference between three HPA experiments mean and nine HFA experiments mean, i.e., mean future changes. (c, f, i, o) White-hatched areas represent significant changes at the 95% confidential intervals according to the Mann–Whitney U test and (l) all area represent significant changes. White vectors are drawn over the area where the decreases in surface wind speed are significant.
Table 2 shows the future changes in the AWMI-JP. All experiments except for HFA-YS-C1 show decreases in the AWMI-JP. The future changes in the regional mean precipitation are separately evaluated at elevations higher and lower than 300 m above sea level (mASL) over central Japan (Region B in Fig. 1). Note that Region B includes both land and ocean. In all the experiments, precipitation decreases above 300 mASL (Table 2), especially the HFA-AS experiments. On the other hand, below 300 mASL, four experiments show decreased precipitation, whereas the others show increased precipitation. Therefore, winter precipitation in the mountainous areas could be mainly controlled by changes in the EAWM, whereas the contribution of the EAMW is relatively small over the plains and ocean.

Experiments using the SST C1 cluster show less weakened winter monsoons than those using other SST clusters (Table 2). Mizuta et al. (2014) indicated that the composites of the CGCMs in CMIP5 showed a weakened Aleutian low, indicating a weakened winter monsoon. However, the composite of CGCMs categorized into SST cluster C1 showed a less weakened Aleutian low, meaning a less weakened winter monsoon. In the two experiments using the SST C2 cluster (HFA-YS-C2 and HFA-KF-C2), precipitation increased below 300 mASL but decreased above 300 mASL. These experiments projected the increased precipitation along Japan, and the southwesterly anomaly of water vapor flux centered at about 30°N and 150°E is simulated at 850 hPa, which brings warm and moist air mass into Japan (Supplement 2). The convergence anomaly appears in the East China Sea and Pacific Ocean in the south of Japanese archipelago. The increase in the CED over the East China Sea and the western parts of Japan could be related to the changes in water vapor flux (Supplement 2). Over the Sea of Japan, changes in the location of Japan sea Polar air mass Convergence Zone could also affect the changes in precipitation (figure not shown). On the other hand, over the mountainous areas, the increase in precipitation would be cancelled out by the effect of weakened winter monsoon, which inhibit precipitation in the Japanese mountains.

4.2 Evaluation of variability in future projections using an MME Taylor diagram

Figure 4 shows the normalized standard deviation and spatial correlation coefficient of future changes in the precipitation, meridional surface wind, CED, and TPW over Region A (Fig. 1) between each experiment and the ensemble mean, which is similar to the Taylor diagram (Taylor 2001). This type of diagram was called as the multi-model ensemble (MME) Taylor diagram by Kawase et al. (2009). The references (stars in Fig. 4) are the ensemble mean of the experiments. The skill score in the original Taylor diagram is considered to be the similarity score between each experiment and the ensemble mean in the MME Taylor diagram (dotted arc-like curves in Fig. 4).

For the precipitation changes (Fig. 4a), the similarity scores are around 0.6–0.8 in most experiments. The average spatial correlation is 0.815. The low similarity scores and spatial correlations result from the interexperimental variation of changes in the precipitation band over the Pacific Ocean and the Japanese archipelago. Some experiments show increased precipitation over the Japanese archipelago and decreased precipitation over the Pacific Ocean (HFA-YS-C2, HFA-YS-C3, and HFA-KF-C2), whereas some experiments show decreased precipitation around the Japanese archipelago (HFA-YS-C1, HFA-AS-C1, and HFA-AS-C3) (Supplement 2). The normalized standard deviations in almost all the experiments are larger than those in the MME mean (1.0), indicating that the experiments partly cancel out each other’s opposite changes. Experiments using the SST C1 cluster (circles) show a similar spatial correlation. The horizontal distributions of precipitation changes are similar among these experiments (Supplement 2). The experiments using the AS
Table 2. Changes in the Asian winter monsoon index around Japan (AWMI-JP) and precipitation above and below 300 mASL over Region B (See Fig. 1) during the winter.

<table>
<thead>
<tr>
<th>EXP</th>
<th>AWMI-JP in the present climate</th>
<th>Change in AWMI-JP</th>
<th>Changes in precipitation over 300 mASL</th>
<th>Changes in precipitation below 300 mALS</th>
</tr>
</thead>
<tbody>
<tr>
<td>HFA-YS-C1</td>
<td>2.372</td>
<td>0.005</td>
<td>-24.0</td>
<td>-2.2</td>
</tr>
<tr>
<td>HFA-KF-C1</td>
<td>2.415</td>
<td>-0.142</td>
<td>-9.2</td>
<td>17.0</td>
</tr>
<tr>
<td>HFA-AS-C1</td>
<td>2.331</td>
<td>-0.100</td>
<td>-40.3*</td>
<td>-11.8</td>
</tr>
<tr>
<td>HFA-YS-C2</td>
<td>2.372</td>
<td>-0.330**</td>
<td>-27.7*</td>
<td>27.9**</td>
</tr>
<tr>
<td>HFA-KF-C2</td>
<td>2.415</td>
<td>-0.515**</td>
<td>-16.1</td>
<td>46.4**</td>
</tr>
<tr>
<td>HFA-AS-C2</td>
<td>2.331</td>
<td>-0.231**</td>
<td>-47.7**</td>
<td>-12.5</td>
</tr>
<tr>
<td>HFA-YS-C3</td>
<td>2.372</td>
<td>-0.214*</td>
<td>-11.0</td>
<td>24.4</td>
</tr>
<tr>
<td>HFA-KF-C3</td>
<td>2.415</td>
<td>-0.241**</td>
<td>-23.5</td>
<td>24.9*</td>
</tr>
<tr>
<td>HFA-AS-C3</td>
<td>2.331</td>
<td>-0.173</td>
<td>-53.3**</td>
<td>-16.7</td>
</tr>
</tbody>
</table>

**95 % confidence interval according to the Student t-test
*90 % confidence interval according to the Student t-test

Fig. 4. MME Taylor diagram of (a) DJF precipitation, (b) meridional surface wind, (c) CED, and (d) TPW over Region A in Fig. 1
scheme (white symbols) also show a similar spatial correlation. These experiments project precipitation decreases over the Japanese archipelago and the Pacific Ocean.

The spatial correlation of the meridional wind, which relates to the AWMI-JP, is higher than those of precipitation (Fig. 4b). The average spatial correlation is 0.916, which indicates that the meridional wind shows similar changes among the experiments as compared with precipitation changes. The result is consistent with a decrease in AWMI-JP in all experiments (Table 2). The CED, on the other hand, shows lower similarity scores in most experiments. The spatial correlations are less than 0.9, except for HFA-AS-C2 (Fig. 4c), and the average spatial correlation is 0.816. The changes in the TPW show the highest similarity scores (Fig. 4d). The variability of TPW changes is much smaller than those of the EAWM-JP and the CED. The horizontal pattern of TPW changes would be robust in the future projections. Figure 4 indicates that the variability of precipitation changes mainly results from the large variability of changes in extratropical cyclones.

Extratropical cyclones are closely related to the meandering of the westerly jet, which is affected by not only the atmospheric circulation at mid and high latitudes but also atmospheric conditions in the tropics, i.e., teleconnections. In the tropics, both differences in the SST cluster and cumulus convective parameterization are important since precipitation is sensitive to the SST, and deep convection often develops over the ocean. It will be necessary to analyze changes in convection in tropics simulated by the MRI-AGCM, which is influenced by both SST clusters and cumulus convection parameterizations, to understand the more detailed mechanism of change in Japan’s wintertime precipitation.

5. Summary

Future changes in winter precipitation and their uncertainties are investigated using the dynamically downscaled multi-global climate projections at the end of the 21st century. The ensemble mean of the NHRCM experiments shows significant decreases in winter precipitation along the Sea of Japan coast and over the Pacific Ocean in the south of the Japanese archipelago. The former is mainly related to the weakened winter monsoon, and the latter is related to changes in the extratropical cyclones around Japan. On the other hand, winter precipitation increases over the inland area of Hokkaido and the northeastern Asian continent, which results from intensified westerly winds in the northern part of the Sea of Japan and moistening in extremely cold regions due to global warming.

The ensemble experiments indicate that the change in precipitation has some uncertainties. Analyzing atmospheric conditions, changes in extratropical cyclones show a larger uncertainty, whereas changes in the winter monsoon and the TPW show smaller uncertainties. Consequently, the variability of future changes in winter precipitation around Japan primarily results from the large variability of changes in extratropical cyclones.

Supplements

Supplement 1 shows a bias of winter precipitation compared with AMeDAS. Supplement 2 shows changes in the DJF precipitation, surface wind, CED, and water vapor flux at 850 hP in each ensemble experiment.

Acknowledgments

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