Changes in mean atmospheric structures around Japan during July due to global warming in regional climate experiments using a cloud-system resolving model

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Abstract:
Regional climate experiments using a cloud-system resolving non-hydrostatic model with a horizontal resolution of 5 km are conducted in order to project changes in precipitation extremes in the vicinity of Japan during the warm season due to global warming. The results of a global 20-km model from May to October for 10-year periods in the present and future climates are adopted as the initial and boundary conditions. The simulated results project an increment in 90th-percentile values of daily precipitation on the Pacific side of the Japanese Islands during July in the future climate. Monthly mean fields during the month in the future climate show that abundant specific humidity of 20 g kg⁻¹, 3 g kg⁻¹ larger than that in the present climate, is supplied from the Pacific Ocean. In the future climate, mean equivalent potential temperature reaches 370 K near the sea surface south of western Japan, while a middle-level (around 5 km) drier region extends from the Asian Continent to the northwestern part of western Japan. As a result, convective instability is intensified in the vicinity of Japan and intense, deep convective systems form on the Pacific side of Japan.

KEYWORDS Global warming; climate change; precipitation extremes; regional climate model

INTRODUCTION

According to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2007), warming of the climate system is unequivocal, and the increase in near-surface temperature in East Asia in the late 21st Century (2090–2099) is expected to be around 2 K relative to that in 1980–1999. The effect of the warming on the regional-scale climate, including changes in weather extremes, is one of the most important subjects that need to be addressed in terms of economic activity and the global environment.

Several recent global warming experiments using global models have projected an increment of intense precipitation in many parts of the world, including in the vicinity of Japan (IPCC, 2007). Kitoh et al. (2005) reported that precipitation intensity was projected to increase over about one-third of the globe, based on the daily precipitation output from a three-member ensemble experiment using the Meteorological Research Institute global ocean-atmosphere coupled general circulation model under the A2 and B2 scenarios of the Special Report on Emission Scenarios (SRES). Watterson and Dix (2003) also showed similar predictions based on the results of a five-member ensemble climate change experiment using the Australian Commonwealth Scientific and Research Organization atmosphere-ocean model under the SRES A2 and B2 scenarios. However, most studies have focused mainly on global climate change using a coarse grid larger than 100 and several tens of kilometers with a horizontal resolution.

The majority of intense precipitations are caused by convective systems. The structures of rainfall systems, especially convective systems, should be represented in numerical models in order to obtain detailed information regarding future changes in intense precipitation. Previous studies have reported that finer-mesh non-hydrostatic models with a horizontal resolution of several kilometers were required to realistically reproduce intense precipitation (Wakazuki et al., 2007; Sasaki et al., 2008). Based on those studies, regional climate experiments using a 5-km mesh cloud-system resolving regional non-hydrostatic model (NHM-5km) are conducted in the vicinity of Japan during the warm season using the results of global warming experiments performed with a 20-km mesh hydrostatic atmospheric general circulation model (AGCM-20km; Mizuta et al., 2006). The results of the NHM-5km show an increment in 90th-percentile values of daily precipitation on the Pacific side of the Japanese Islands during July in the future climate. The purpose of this study is to clarify changes in atmospheric conditions that generate the convective systems that in turn bring about the increment. The distributions of intense updrafts simulated by the NHM-5km are also compared.

MODEL AND EXPERIMENT DESIGN

Time-slice climate experiments in the present and future climates under global warming conditions were performed using NHM-5km from 17th May to 31th October over a period of 10 years in each case. A non-hydrostatic model developed by the Japan Meteorological Agency and Meteorological Research Institute of Japan (Saito et al., 2001, 2006) was adopted. NHM-5km was nested within 6-hourly results of 25-year time-integrated experiments with AGCM-20km for the present (1990–1999) and future climates (2086–2095). The experiment domain comprises 669 × 527 horizontal grids (3345 × 2635 km) and 50 vertical layers (top height: 22 km), covering a wide region from the eastern part of the Asian Continent to the Japanese Islands. The spectral boundary coupling method is applied above a height of 7 km (Yasunaga et al., 2005). A cumulus parameterization (Kain–Fritsch) scheme and an improved
Mellor–Yamada Level 3 planetary boundary layer scheme are adopted in the NHM-5km experiments. The designs of the AGCM-20km and NHM-5km experiments are described in detail by Kitoh et al. (2009) and Kanada et al. (2008). The high performance of NHM-5km in reproducing characteristics of precipitation has been verified in previous studies (Wakazuki et al., 2007; Nakamura et al., 2008; Kanada et al., 2008; Nakano et al., 2010).

RESULTS

General characteristics of intense daily precipitation in July

Kitoh et al. (2009) pointed out a future increase in the appearance frequency of intense precipitation in the vicinity of Japan during the warm season. In this paper, we focus on July belonging to the rainy (Baiu) season in East Asia, since heavy rainfall events are often caused by precipitation systems over the Baiu frontal zone. Figure 1 shows the horizontal distributions of 90th-percentile values of daily precipitation in July for each 10-year period in the present and future climates. The reproducibility of precipitation and precipitation extremes of this NHM-5km has been verified by Kanada et al. (2008), although some topography-dependent tendency in horizontal distribution of precipitation has been pointed out. In both climates, most of the intense 90th-percentile values are distributed on the Pacific side of the Japanese Islands. In the future climate, regions of extremely high values (> 150 mm day⁻¹) appear between 132°E and 139°E, with the increase being most pronounced around 137°E.

Future changes in monthly mean atmospheric conditions in July

First, the horizontal distributions of monthly mean relative humidity (RH) at a height of 5 km and equivalent potential temperature (θe) at a height of 500 m in July for each 10-year period are examined (Figure 2). In the present climate, the region of high RH (> 60%) which corresponds to the Baiu frontal zone, extends from the eastern part of the Asian Continent to Japan. In the future climate, this region shifts southward to the region south of the Pacific side of the Japanese Islands. A region of lower RH (< 50%) along with the westerly, covers the northwestern part of western Japan. A region of remarkably high θe exceeding 360 K is found over a wide region of the sea south of the Japanese Islands, extending close to the islands themselves (Figures 2c and 2d).

Figure 3 shows vertical profiles of monthly mean
temperature, specific humidity \((q)\), \(RH\), and \(\theta\), in July for each 10-year period in the present and future climates averaged over the areas defined by rectangles in Figure 2. In the future climate, the sea surface temperature in East Asia is expected to increase by around 2 K relative to that during the period 1990–1999. The warming of around 2 K is also found near the surface in region-S and region-N (Figure 2c). The magnitude of warming increases with altitude, reaching around 5 K at a height of 10 km. As a result of increasing sea surface temperature, remarkable increases in \(q\) larger than 2 g kg\(^{-1}\) are found at low levels in both regions (Figure 3f). The increments show a rapid decrease with altitude, and are most pronounced in region-S, reaching 3 g kg\(^{-1}\) near the surface; however, \(RH\) near the surface shows little change (Figure 3d) because the increment in temperature is sufficient large that it counteracts the increment in \(q\). The profile of \(RH\) in region-S suggests the existence of deep convective systems that transport large amounts of water vapor upward above the middle level (around 5 km). Most of the vertical layers over the Japanese Islands (region-N) become drier. The \(\theta\) at the low level in region-S shows a significant increase of 12 K in the future climate (Figure 3i). The increment in \(\theta\) at the middle level is smaller than that at the low level, indicating that the supply of warmer and more humid low-level air from the southern sea and middle-level drier air from the northwest acts to intensify convective instability in the vicinity of Japan.

**Future changes in the mean values of the three largest updrafts in July**

Mean values of the three largest updrafts for each grid point, simulated by the NHM-5km, are examined on changes in convective activities. Figure 4 shows their \(N\)-\(S\) cross-sections in July, averaged between 130°E and 137°E. The distributions of monthly mean \(RH\), wind fields and \(q\) of 18 g kg\(^{-1}\) for each 10-year period are overlaid in Figure 4. In the present climate, the region of \(RH\) exceeding 60%, which corresponds to the Baiu frontal zone, extends between 31°N and 35°N (~400 km) at a height of 5 km. This region becomes wider in the future climate, extending between 28°N and 34°N (~600 km). Drier air (\(RH\) less than 50–55%) extending from the Asian Continent is clearly found from the north at a height of around 5–6 km. Deep convective systems with intense updrafts (> 0.7 m s\(^{-1}\)) widely form in coastal regions on the Pacific side of the Japanese Islands, where low-level humid air and middle-level drier air extend from the south and north, respectively. According to profiles of the three largest updrafts averaged over a large region covering most parts of western Japan (130°E–137°E and 30°N–36°N), the peak values are found at heights of 4.5 and 5.5 km in the present and future climates, respectively. Differences between the profiles are generally found above a height of 4.5 km. The estimated values of monthly mean lifting condensation level (LCL), depth of the level of free convection (LFC) from LCL, convective available potential energy (CAPE), and convective inhibition (CIN) on the Pacific side of the Japanese Islands (130°E–137°E, 30°N–32°N) are 463 m, 75.7 hPa, 1139 J kg\(^{-1}\), and 26.3 J kg\(^{-1}\) in the present climate, and 468 m, 82.9 hPa, 1538 J kg\(^{-1}\), and 30.2 J kg\(^{-1}\) in the future climate, respectively. A higher LFC and larger CIN indicate less favorable conditions for the formation of moist convection, although CAPE increases by about 35% in the future climate. Because latent instability is released when uplifted air parcels reach the LFC, terrain-induced updrafts over the Japanese Islands represent a potential trigger for the formation of moist convection. A region of intense updrafts forms along the Pacific side of Japan, extending to around 140°E (not shown), where significant increments in intense precipitation are projected in the future climate.

![Figure 4](image-url)

Figure 4. North-south cross-sections of the mean values of the three largest updrafts between 130°E and 137°E in the (a) present and (b) future climates. Monthly mean relative humidity and specific humidity of 18 g kg\(^{-1}\) are overlaid upon the figure using black and red-dotted contours, respectively. (c) Vertical profile of the three largest updrafts averaged throughout the black dotted rectangles in (a) and (b). Blue and red lines indicate present and future climates, respectively. Red dotted rectangles indicate the regions used to calculate values related to latent instability. Monthly mean wind fields in the sections are shown by arrows.
DISCUSSION AND REMARKS

Regional climate experiments were performed using the NHM-5km in order to project future changes in precipitation extremes in the vicinity of Japan during the warm season due to global warming. The present analysis detects remarkable increments in intense precipitation on the Pacific side of the Japanese Islands in July in the future climate.

Monthly mean atmospheric conditions in July in the future climate show a supply of abundant specific humidity of 20 g kg$^{-1}$ from the Pacific Ocean, 3 g kg$^{-1}$ larger than that in the present climate. Mean relative humidity shows little change, whereas the mean near-surface equivalent potential temperature ($\theta_e$) south of the Japanese Islands reaches 370 K in the future climate in the lower atmosphere. At the middle level (around 5 km), a drier region with lower $\theta_e$ extends from the Asian continent to the northwestern part of western Japan. A delay in the northward march of the Baiu front and enhancement of the drier air mass from the northwest are also detected in the results of ensemble experiments performed using a global 60-km model (not shown).

Monthly mean values related to latent instability in July for each 10-year period reveal a higher LFC and larger CIN on the southern side of the Japanese Islands, indicating less favorable conditions for the formation of moist convection in the future climate. However, once moist convection is induced, more intense updrafts are able to form because of a 35% increase in CAPE compared with that in the present climate. The distributions of the mean values of the three largest updrafts simulated by the NHM-5km reveal the formation of deep convective systems on the Pacific side of the Japanese Islands, where increments in intense precipitation is projected in the future climate. Terrain-induced updrafts over the Japanese Islands could potentially trigger the formation of moist convection. These features are consistent with the intensification tendency of convective instability over the Japanese Islands found in monthly mean atmospheric conditions in July for each 10-year period from the present to future climates.

Using the results of regional climate experiments under the Kyosei-project, Wakazuki et al. (2005) suggested that an increment in the supply of water vapor in the lower atmosphere could affect disturbances over the Baiu frontal zone. Additional studies of changes in meso-scale convective systems under global warming conditions are urgently required to reveal the mechanism of increments in intense precipitation; i.e., to project the future changes in precipitation extremes that are expected to have a significant influence on East Asia. Given the high uncertainties in such analyses, it might be better to perform multi-model boundary and/or ensemble experiments. Downscaling experiments using NHM-5km nested in the results of ensemble experiments performed by AGCM-20km are also planned for the last two years of the near-future climate (2038 and 2039).

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