Identification of key factors in future changes in precipitation extremes over Japan using ensemble simulations

Akihiko Murata, Hidetaka Sasaki, Hiroaki Kawase and Masaya Nosaka
Meteorological Research Institute, Japan

Abstract:
Key factors in future changes in wintertime precipitation extremes over an area of the Pacific Ocean side of Japan (the Tokai region) at the end of the 21st century are identified using ensemble simulations projected by a non-hydrostatic regional climate model (NHRCM), driven at the lateral boundaries by an atmospheric general circulation model forcing under the Representative Concentration Pathway 8.5 scenario. The 99th percentile of projected daily precipitation, a measure of precipitation extremes, noticeably increases over the Tokai region in winter. Differences in meteorological variables related to precipitation between the present and future climates are investigated. It is found that a key factor in changes in precipitation extremes is the increases in specific humidity over a deeper layer (from the lower to middle troposphere). The low-level moist flow associated with an extratropical cyclone is southerly and impinges on coastal mountains in the Tokai region, leading to enhanced convergence and precipitation. This orographically induced precipitation can be enhanced when mid-level specific humidity increases in the future climate, as well as at lower levels.

KEYWORDS global warming; ensemble simulations; regional climate model; precipitation extremes; specific humidity; Japan

INTRODUCTION

Attempts have been made to clarify the mechanisms of an atmospheric phenomenon using model outputs from ensemble simulations. If several ensemble members exist, the relationship between the atmospheric phenomenon and a key factor that controls the phenomenon can be examined. For example, if an ensemble member exhibits heavy precipitation and high moisture flux convergence whereas another member exhibits light precipitation and low moisture flux convergence, the results suggest that moisture flux convergence affects precipitation. This information may lead to prevention of flood disasters.

Several studies have addressed this issue. For example, Hanley et al. (2013) conducted convective-scale ensemble simulations to examine the mechanisms of a convective event in central Europe. They demonstrated that ensemble members that better represented upper-level potential vorticity were in closer agreement with observations in terms of the development of squall lines in the convective event. In the field of climate modeling, Joshi et al. (2008) examined mechanisms for the land/sea warming contrast in the future climate. They investigated the sensitivity of the land/sea contrast to physical processes using global climate model outputs from ensemble members. They found that the physical processes associated with large-scale cloud and stomatal closure were important.

In this study, we first conducted ensemble simulations using the non-hydrostatic regional climate model (NHRCM) developed by the Meteorological Research Institute (MRI) of the Japan Meteorological Agency (JMA) to project future changes in precipitation extremes over Japan. Next, we examined the mechanisms of robust future changes in precipitation extremes over Japan using projections from ensemble members of NHRCM with a grid spacing of 20-km (NHRCM20). The goal of our study is to prove the effectiveness of our approach in clarifying the mechanisms of regional climate change. Few studies have investigated possible mechanisms for future changes in climate using an ensemble of regional climate model simulations. To the authors’ knowledge, this is the first time that the ensemble approach has been used to examine the mechanisms of regional climate change in Japan.

METHODS

Numerical model

NHRCM, developed by Sasaki et al. (2008), is a climate version of the JMA nonhydrostatic model (Saito et al., 2006, 2007), which is used operationally in the JMA numerical weather prediction system. Detailed descriptions of the specifications of NHRCM are given in previous papers on regional climate simulations using NHRCM (e.g., Sasaki et al., 2011; Murata et al., 2013).

Experiment design

Detailed descriptions of the experimental design are given in Kawase et al. (2015), so only a brief summary is provided here. In this study, NHRCM20 was used for all numerical experiments. The model domain was set to cover Japan and consisted of 211 × 175 grid points (Figure 1). The vertical coordinate was terrain-following and contained 40 levels that ranged from 20 m (from the ground surface) at the lowest level to 21.9 km at the highest level. Boundary conditions for NHRCM20 were generated from a simulation using the MRI atmospheric general circulation model (AGCM) with 60-km horizontal resolution (MRI-AGCM3.2H, hereafter referred to as AGCM60) (Mizuta et al., 2012).

To reproduce the present climate, AGCM60 was run
with the conditions provided by the Atmospheric Model Intercomparison Project AGCM simulation for the 20th century experiment of the Intergovernmental Panel on Climate Change (IPCC Fourth Assessment Report (AR4) (IPCC, 2007). For sea-surface temperature (SST) and sea-ice concentration, monthly mean data from the Hadley Centre (Rayner et al., 2003) were used. The monthly data for climatology of sea-ice thickness from Bourke and Garrett (1987) was also employed.

In the simulations for future climate, AGCM60 was run with the conditions of increased concentrations of greenhouse gases and higher SST, consistent with the greenhouse gas scenario of Representative Concentration Pathway (RCP) 8.5 (Riahi et al., 2007). The SST for use in the GCM simulation is the summation of three components (Mizuta et al., 2014): (1) the future change in SST projected by the Coupled Model Intercomparison Project, phase 5 multimodel dataset, (2) the linear trend in the SST for 2075 through 2099, and (3) the detrended observational SST for 1979 through 2003. These three components depend on both time and grids.

To downscale with NHRCM20, time-slice simulations were conducted for 20 years: from 1984 to 2004 for the present climate and from 2080 to 2100 for the future climate at the end of the 21st century. For each year, a model simulation started on 20 July and lasted until 1 September of the following year. To account for model spinup, the results of the first 43 days were discarded. This 1-year time-slice method allowed us to compute multi-year simulations simultaneously. The data from 1 September to 31 August of the following year were used for this study.

Ensemble simulations using NHRCM20 in terms of the boundary conditions were conducted. For the future climate, we conducted 9 experiments using a variety of boundary conditions provided by the AGCM60 simulations. The AGCM60 simulations consisted of ensemble member matrix (3 × 3) as a function of SST and convective parameterizations; the three SST fields are generated with cluster analysis (Mizuta et al., 2014), and the three convective parameterizations are as follows: the Yoshimura scheme (Yoshimura et al., 2014), the Arakawa-Schubert scheme (Arakawa and Schubert, 1974; Randall and Pan, 1993), and the Kain-Fritsch scheme (Kain and Fritsch, 1990; Kain, 2004). For the present climate, we performed three experiments using different boundary conditions: The AGCM60 simulations consisted of three ensemble members as a function of convective parameterizations mentioned above.

**Observed data**

The performance of NHRCM20 was assessed based on error statistics calculated by comparing the amount of precipitation from the model simulations for the present climate and that from rain gauge data for the same period. The rain gauge data were extracted from the Automated Meteorological Data Acquisition System (AMeDAS), administered by JMA, with a dense network of meteorological stations throughout Japan at an average interval of 17 km. There are 1200 stations for observation of precipitation. The temporal resolution (1 h) of AMeDAS data is equal to that of the NHRCM20 output.

**EVALUATION OF THE PRESENT CLIMATE**

We estimate errors in extremely intense precipitation on a daily time scale in the present climate reproduced by NHRCM20. The 99th percentile of daily precipitation is used as a measure of extremely intense precipitation. Days without precipitation (dry days) are excluded from the calculation of percentiles. A simulated dry day is defined as a day with less than 1 mm day⁻¹ of precipitation, because the minimum unit of AMeDAS precipitation data used is 1 mm within the period for the present climate (i.e., from 1984 to 2004). We compare the frequency distributions of the 99th percentile derived from the simulated and observed data. Figure 2a indicates the relative frequency of the 99th percentile for each month and station location. The data for these histograms is based on simulated (ensemble mean) and observed data for all months and all station locations. The frequency distribution of the 50th percentile is also presented for comparison (Figure 2b). The simulated precipitation, corresponding to observed precipitation, is area-averaged. This area is set as the annular area bounded by a circle with a 20-km radius centered on each AMeDAS station.

The overall distributions of the 99th and 50th percentile of model precipitation closely match those observed (Figure 2a). These results indicate that the frequency distribution of extremely intense precipitation, as well as daily precipitation of medium intensity, is well reproduced by NHRCM20. It should be noted that similar results are obtained when all days (i.e., wet and dry days) are used (not shown).

**PROJECTION OF FUTURE CLIMATE CHANGE**

Changes in precipitation extremes over Japan projected by NHRCM20 are examined. Figure 3 depicts the horizontal distribution of the rate of change of the 99th percentile of daily precipitation in winter (December, January, and February), where ensemble-mean daily precipitation is used. The rate of change is defined as 100 × \((F/P − 1)\) [%], where \(P\) is the 99th percentile in the present climate and \(F\) is the
99th percentile in the future climate. It should be noted that only data indicating heavy precipitation are plotted; here, heavy precipitation is defined as ensemble-mean daily precipitation of more than 50 mm day\(^{-1}\) in the present experiment. It should also be noted that only robust data are plotted, where robustness is estimated by signs of the change. When the signs of the change for all nine ensemble members are equal (i.e., all nine members have positive values, or all nine members have negative values), the data are plotted in Figure 3.

The future climate simulations indicate that extremely intense precipitation in winter increases over part of the Pacific Ocean side (the Tokai region). The 99th percentile of daily precipitation changes significantly over the Tokai region in December (Figure 3a). This region also experiences noticeable changes in the 99th percentile in January and February (Figures 3b and 3c). One of the reasons for these changes is that heavy precipitation of the Tokai region in the present climate is less than that in the regions where winter monsoon brings heavy snow (e.g., the Japan Sea side). A rectangular area exhibiting these changes is set in an effort to focus on the meteorological situation there (Figure 3). For this region, the 99th percentile of daily precipitation is recalculated using the regionally averaged daily precipitation. This procedure is identical to those for station data.

![Figure 2](image2.png)

**Figure 2.** Frequency distributions of the (a) 99th (bin width is 10 mm day\(^{-1}\)) and (b) 50th (bin width is 1 mm day\(^{-1}\)) percentiles of daily precipitation in the present climate for modeled (mdl) and observed (obs) values. The data for these histogram is based on simulated and observed data for all months and all station locations.

![Figure 3](image3.png)

**Figure 3.** Horizontal distribution of changes in the 99th percentile of daily precipitation [%], defined as 100 × (future/present – 1), in (a) December, (b) January, and (c) February projected by NHRCM20. The data are plotted when the signs of change for all nine members are equal and when ensemble-mean daily precipitation in the present climate exceeds 50 mm day\(^{-1}\). The rectangular area in each panel denotes the target area (see text for details).

**DISCUSSION**

**Specific humidity**

To explore the mechanisms of increases in extreme daily precipitation over the Tokai region in winter, we investigate the effects of meteorological variables (Table I) on precipitation. Specifically, we use meteorological variables one day before precipitation and the data within the rectangular area in Figure 3 from December to February.

Future changes in specific humidity in the lower troposphere are correlated with those in precipitation extremes. Figures 4a, 4c, and 4e depict scatter diagrams between specific humidity at the surface and the 99th percentile (three data sets are used around 99th percentile rank, to be precise) of daily precipitation over the target area for each month. It should be noted that quantities for both the present climate (nine data items: three data items for each of three cases) and the future climate (27 data items: three data items for each of nine cases) are plotted.

The 99th percentile of daily precipitation is approximately proportional to specific humidity (Figures 4a, 4c, and 4e). That is, precipitation increases with increasing moisture, suggesting that low-level moisture plays a critical role in enhancing precipitation. This proportionality can be displayed because the simulated precipitation and moisture...
KEY FACTORS IN FUTURE PRECIPITATION EXTREMES

Table I. Statistical significance of future changes in meteorological variables for the (a) 99th and (b) 50th percentiles. "T" denotes that difference in the variable between the present and future climates is statistically significant at the 5% level of the Wilcoxon–Mann–Whitney rank-sum test. "F" denotes that the difference is not statistically significant.

(a)

| Meteorological variables                  | Dec | Jan | Feb |
|-------------------------------------------|-----|-----|-----|
| Precipitation                             | T   | T   | T   |
| Surface moisture flux convergence         | F   | T   | F   |
| 850-hPa moisture flux convergence         | F   | F   | F   |
| 500-hPa moisture flux convergence         | F   | F   | F   |
| Surface convergence                       | F   | F   | F   |
| 850-hPa convergence                       | F   | F   | F   |
| 500-hPa convergence                       | F   | F   | F   |
| Surface specific humidity                 | T   | T   | T   |
| 850-hPa specific humidity                 | T   | T   | T   |
| 500-hPa specific humidity                 | T   | T   | T   |
| Surface relative humidity                 | F   | F   | F   |
| 850-hPa relative humidity                 | F   | F   | F   |
| 500-hPa relative humidity                 | F   | F   | F   |

(b)

| Meteorological variables                  | Dec | Jan | Feb |
|-------------------------------------------|-----|-----|-----|
| Precipitation                             | F   | F   | F   |
| Surface moisture flux convergence         | F   | F   | F   |
| 850-hPa moisture flux convergence         | F   | F   | F   |
| 500-hPa moisture flux convergence         | F   | F   | F   |
| Surface convergence                       | F   | F   | F   |
| 850-hPa convergence                       | F   | F   | F   |
| 500-hPa convergence                       | F   | F   | F   |
| Surface specific humidity                 | F   | T   | T   |
| 850-hPa specific humidity                 | F   | F   | T   |
| 500-hPa specific humidity                 | F   | F   | F   |
| Surface relative humidity                 | F   | F   | F   |
| 850-hPa relative humidity                 | F   | F   | F   |
| 500-hPa relative humidity                 | F   | F   | F   |

 vary with ensemble members. Therefore, ensemble simulation results are very effective in examining physical mechanisms for projected precipitation extremes.

An even more important feature in Figures 4a, 4c, and 4e is that the group of data points for the future climate is separated from that for the present climate. To determine whether this separation is statistically significant, the Wilcoxon–Mann–Whitney rank-sum test (Wilks, 2011) is conducted. This test indicates that the difference in specific humidity at the surface between the present and future climates is statistically significant at the 5% level, as well as in the 99th percentile of daily precipitation (Table I). The difference in specific humidity at 850 hPa and 500 hPa is also statistically significant. Contrast, differences in relative humidity, convergence, and moisture flux convergence are not statistically significant throughout the levels. These results indicate that increases in the absolute value of moisture have a significant effect on precipitation extremes on a daily time scale. It should be noted that an advantage of our data analysis method is that the method can test whether the group of data points is divided into two categories: the present and future climates.

Median precipitation is also examined for comparison. The 50th percentile (three data sets are used around 50th percentile rank, to be precise) of daily precipitation is not proportional to specific humidity (Figures 4b, 4d, and 4f). In these cases, differences in precipitation are not statistically significant (Table I). Moreover, specific humidity between the two climates is not statistically significant except at the surface in January, and at the surface and 850 hPa in February. This limited separation of the groups of specific humidity data again indicates that the absolute value of moisture significantly affects precipitation extremes on a daily time scale.

Convergence

When the 99th percentile of daily precipitation occurs, convergence at the surface is positive in most cases (Figures 5a, 5c, and 5e) although differences in convergence between the present and future climates are not significant (Table I). Moreover, convergence is approximately proportional to the northward component of the surface wind speed, indicating that the low-level moist southerly flow from the Pacific Ocean accompanying an extratropical cyclone impinges on coastal mountains and rises to form orographic precipitation. However, for the 50th percentile of daily precipitation, convergence at the surface is negative in most cases, with no clear relationship between convergence and southerly wind speed (Figures 5b, 5d, and 5f). These results suggest that higher values of convergence near the surface are necessary for extremely intense precipitation, although convergence for the two climates is not statistically different.

SUMMARY AND CONCLUDING REMARKS

We examined mechanisms of projected wintertime heavy precipitation over the Tokai region of Japan, where ensemble simulations with NHRCM20 projected significant changes in heavy precipitation at the end of the 21st century. NHRCM20 was driven at the lateral boundaries by AGCM60 forcing under the RCP8.5 scenario.

First, we evaluated the reproducibility of precipitation in Japan. The frequency distributions of both the 99th and the 50th percentiles of simulated daily precipitation closely matched those observed. That is, NHRCM20 reproduced the overall distribution of extreme daily precipitation, as well as daily precipitation of medium intensity. Next, we examined the projection of extremely intense precipitation in the future climate. It was found that the Tokai region experiences noticeable changes in the 99th percentile of projected daily precipitation in winter.

We attributed these changes to future changes in moisture. It was found that the group of data points for low-level specific humidity in the future climate, like the 99th percentile of daily precipitation, was separated from that in the present climate. This separation was statistically significant at the 5% level using the Wilcoxon–Mann–Whitney rank-sum test. Moreover, the 99th percentile of daily precipitation is
approximately proportional to specific humidity. In contrast, these features were not seen in the 50th percentile of daily precipitation, with few exceptions. These results indicate that low-level moisture plays a critical role in enhancing extremely intense precipitation on a daily time scale.

Convergence at the surface was positive in most 99th percentile precipitation cases, although the difference in convergence between the present and future climates is not significant. Moreover, convergence was approximately proportional to the northward component of the surface wind speed, indicating that the low-level moist southerly flow from the Pacific Ocean impinged on coastal mountains, which was responsible for the formation of orographic precipitation. In contrast, no clear relationship exists between convergence and southerly wind speed in the 50th percentile of daily precipitation.

In conclusion, noticeable changes in extreme daily precipitation over the Tokai region due to global warming result from increases in specific humidity over a deeper layer (from the lower to the middle troposphere). Low-level moist layers are produced by the southerly flow from the Pacific Ocean accompanying an extratropical cyclone. This southerly flow impinges on coastal mountains, enhances convergence, and produces precipitation. Rainfall rate probably becomes higher when mid-level specific humidity increases, as at lower levels.

We demonstrated that ensemble simulations are useful for identifying key factors in future changes in heavy precipitation. Our approach can be generalized to future changes in other meteorological variables (e.g., temperature and wind) and on other time scales (e.g., hourly and monthly), although we focused on daily precipitation extremes. We examined future changes in precipitation extremes in winter. A main reason for addressing the issue of wintertime precipitation is that precipitation accompanying tropical cyclones, which has much larger uncertainty due to cyclone tracks, should be excluded. Further studies are required to explore this issue.

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