Projected Changes in Precipitation Characteristics around Japan under the Global Warming

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Abstract

A coupled ocean-atmosphere climate model is used to depict changes in precipitation characteristics around Japan in the 21st century. A comparison between high (T106 atmosphere) and medium (T42) resolution versions for the present-day climate shows that the higher resolution version better represents not only the mean but also the frequency distribution of precipitation. The climate projection of the 21st century by the high resolution version shows that mean precipitation increases more than 10% in 100 years from the present, especially in warm seasons. Increases in frequencies of non-precipitating and heavy (≥30 mm day\(^{-1}\)) rainfall days and decrease in relatively weak (1–20 mm day\(^{-1}\)) rainfall days are significant.

1. Introduction

The change in hydrological cycle is one of the greatest societal concerns for the global warming projections. For disaster prevention, water resource management, and agricultural purposes, information on changes not only in mean precipitation, but also in frequency distribution are desirable.

Observationally, Iwashima and Yamamoto (1993) first pointed out the possibility of increase in heavy precipitation events in Japan over the 20th century based on a limited data set available at that time. More comprehensive data sets are being compiled in many countries, and evidences of increasing trends in extremely heavy precipitation during the second half of the 20th century are emerging (Groissman et al. 1999; Frich et al. 2002; Fujibe et al. 2005). This is in gross agreement with a conceptual explanation that relates increase in precipitation extreme with that in water vapor of the warming climate (Trenberth 1999; Allen and Ingram 2002).

Climate model results generally agree with the overall tendency of increase in precipitation extremes (Hennessy et al. 1997; Semenov and Bengtsson 2002), but describing extreme events and their geographical distribution requires high-resolution models (Voss et al. 2002; Emori et al. 2005).

In this paper, a high-resolution coupled ocean-atmosphere climate model is used to depict changes in precipitation characteristics around Japan under the influence of global warming.

2. Model and experiment

The coupled general circulation model (CGCM) used in this study is called MIROC (Model for Interdisciplinary Research On Climate) version 3.2, developed cooperatively by CCSR1, NIES2, and FRCGC3 of Japan. It has five component models; the atmosphere, ocean, sea ice, land surface, and river, coupled by a flux coupler. Two versions of the model have been developed: one a high-resolution version (Hi-CGCM) and the other a medium-resolution version (Mid-CGCM). The Hi-CGCM has atmospheric horizontal resolution of T106 spectral truncation (~100 km transform grid) and 56 vertical levels, 1/4° x 1/6° and 48 levels for the ocean and sea ice, and a 0.5° x 0.5° grid and 5 soil layers for the land. The Mid-CGCM consists of T42 (~300 km grid), 20-level atmosphere and 1° x 1.4° 44-level ocean and sea ice. The land model of the Mid-CGCM shares the same grids as the atmosphere. The component models are equipped with the state-of-the-art physics package, and their details are described by the K-1 Model Developers (2004). The Hi- and Mid-CGCMS are tuned in parallel, and their physics are virtually equivalent; a few exceptions are either resolution dependent in nature or those required to keep stable equilibrium climate in the long run.

After spin-up with preindustrial climate conditions,
corresponding to the year 1900 for the Hi-CGCM and 1850 for the Mid-CGCM, the models were integrated to the year 2100. Historical records of climate forcing were given till the year 2000 and SRES A1B scenario of IPCC (2000) was given from 2001 on. The details of the historical reproduction and future scenario experiments are to be described elsewhere. The 21st century simulations were also performed following the SRES B1 scenario which gives smaller response, but the qualitative aspects of projections were similar. Therefore, the results with A1B are reported in this paper.

3. Impact of resolution on the present-day precipitation

In this section, we compare present-day simulations of precipitation around Japan between Hi- and Mid-CGCMs.

Figure 1 shows seasonal mean precipitation of the present climate: December-January-February (DJF) and June-July-August (JJA) means for an observational data set (CMAP; Xie and Arkin 1997; 1979–98 climatology given on a 2.5° x 2.5° grid) and for the two versions of the CGCM (1971–2000 climatology). Overall features are well represented by the model, but the geographical distributions affected by topography are better resolved in the Hi-CGCM; for example, in the wintertime, the north-westerly monsoon season, the contrast between the windward and lee sides of the Honshu (Japanese Main) Island is more clearly represented in the Hi-CGCM than in the Mid-CGCM. In the summertime, the moist south-westerlies bring heavy precipitation in the Pacific Ocean side of the western Japan or in the Korean Peninsula, which appears more realistic in the Hi-CGCM. The 2.5° resolution of the CMAP data may not be sufficient to describe details of the orographic influences. Comparisons with other high-resolution data sets, e.g., climatology based on station data or on TRMM satellite estimate (not shown because the former lacks ocean coverage and the latter is not available north of 40°N), indicate clearer contrasts within the Japanese islands, which agrees more with the Hi-CGCM result.

The mean annual precipitation averaged over land-grids covering the four main islands of Japan by the station-based Climate Research Unit data set (Mitchell et al. 2004) is 1651±202 mm (the mean and the interannual standard deviation for the period 1971–2000). Corresponding figure for the Hi-CGCM is 1743±121 while it is 1640±137 mm for the Mid-CGCM. In terms of such a mean, the advantage of high resolution is not very obvious.

Figure 2 examines observed and simulated histograms of precipitation frequency as a function of daily rainfall class. The daily rainfall frequency is accumulated over a common 2.5° x 2.5° grid covering the East Asian area (30°N–40°N, 120°E–140°E) for all the calendar months for 5 years. The observational estimate is based on the GPCP 1DD data set, a multi-satellite estimate of daily rainfall ( Huffman et al. 2001; 1° x 1° resolution). Five years (1997–2001) of data were available, and the model estimates were made also for 5 years at the end of the 20th century.

As can be seen in the figure, the Mid-CGCM has a tendency to overestimate weak rain frequency, say in the <20 mm day⁻¹ range, while it tends to systematically underestimate over-30-mm day⁻¹ frequency in comparison with the Hi-CGCM. An estimate of error bars for the model histograms of Fig. 2 (not shown) based on interannual variations shows that these tendencies are statistically significant. Insufficient spatial details in the Mid-CGCM provide less chance to represent extreme precipitation. Emori et al. (2005) discusses sensitivity in the tails of such frequency distribution that is influenced much by physical parameterizations. In the present results, however, convection and the relevant physics are kept the same, and the impact of resolution is focused.

The rightmost bar of Fig. 2 is for over-50-mm day⁻¹ frequency, which is seriously underestimated by the Mid-CGCM. Figure 3 shows spatial distribution of average annual number of days with over-50-mm day⁻¹ precipitation. The Hi-CGCM simulates climatological occurrences of heavy precipitation much better than the Mid-CGCM does. Voss et al. (2002) have also reached a similar conclusion about the impact of resolution in their AGCM experiment. It should be noted that statistics shown in Fig. 3 are those computed on respective data sets’ original grids, and therefore a part of the underestimation of the Mid-CGCM is due to the larger grid used. However, such an underestimation is clearly visible even when the statistics are computed on a common grid (not shown), as can be inferred by the rightmost bar of Fig. 2.

4. Future projection

Having seen the advantage of the higher resolution,
the projected future changes in precipitation characteristics around Japan is described in this section based on the Hi-CGCM results for the 21st century simulation. Changes in circulation and other aspects over the East Asia have been discussed by Kimoto (2005).

Annual mean precipitation over the Japanese land grids for the period 2071–2100 of the Hi-CGCM A1B scenario experiment is 1993±141 mm. Compared with the figures given in the previous section, these correspond to 14 and 16% increases for the mean and the interannual standard deviation, respectively.

Figure 4 shows geographical distributions of the change in seasonal mean precipitation for DJF and JJA. The difference of the Hi-CGCM integration between the periods 2071–2100 (21C, hereafter) and 1971–2000 (20C) is depicted. Dots in the figure indicate statistically significant features based on a t-test using year-to-year variations of the histogram.

Fig. 5. Percentage change from 20C (1971–2000) to 21C (2071–2100) in daily precipitation frequency averaged over the East Asian area as in Fig. 2. A 1° x 1° grid is used for the computation. The Hi-CGCM result. Grey shading indicates the 99% confidence interval, estimated based on year-to-year variations of the histogram.

According to the result of t-test, indicated by the dots in Fig. 5, these features are statistically significant. Panels (a)–(c) of Fig. 6 show the geographical distributions of the changes in frequency of (a) non-precipitating, (b) 1–20 mm day⁻¹, and (c) over 50 mm day⁻¹ events in terms of annual number of days. Statistical significance is indicated by the dots as in Fig. 4. The increases in non-precipitating and heavy rainy days and the decrease in weak rainy days are the features commonly seen in the vicinity of the Japanese Islands.

Finally, Fig. 7 examines the seasonality of the frequency change in terms of latitude-time sections for the non-precipitating and over-50-mm day⁻¹ classes. The longitudinal average is applied between 130°E and 145°E to cover Japanese land mass. The panel for the 1–20 mm day⁻¹ class looks almost opposite to the one for non-precipitating days, as can be inferred comparing panels (a) and (b) of Fig. 6, and therefore is skipped. The average seasonal cycle of non-precipitation class exhibits a pronounced increase in winter and decrease in summer. On the other hand, the increase in the heavy rainfall is large during warm, rainy seasons.
Fig. 7. Seasonal cycle of change from 20C (2071–2000) to 21C (2071–2100) in the frequency (number of days per month) of (a) <1 mm day\(^{-1}\) and (b) >50 mm day\(^{-1}\) rainfall classes simulated by the Hi-CGCM. The ordinate is latitude and the abscissa is time in month. Longitude average between 130\(^{\circ}\)E and 145\(^{\circ}\)E is applied. Small and large dots indicate 95 and 99% statistical significance, respectively, estimated on the basis of inter-annual variations assuming independence of each year during the last 30 years of the 20th and 21st centuries.

5. Conclusions

The use of high resolution climate model enabled us to depict projected future change of the precipitation characteristics over Japan area; the mean precipitation increases, especially in warm seasons, and frequencies of non-precipitating and heavy (>30 mm day\(^{-1}\)) rainfall days increase, by about 10 and 5 days a year, respectively, during 100 years from 1971–2000 to 2071–2000, while those of relatively weak (1–20 mm day\(^{-1}\)) rainy days tend to decrease by 16 days a year. The general tendency of such changes in frequency distribution is in good agreement with the result reported by Fujibe et al. (2005). It is also interesting to note that the shift of the frequency distribution toward heavier side as shown in Fig. 5 resembles an estimate by Karl and Trenberth (2003) based on observed global climatology. The increase of heavy rain around Japan is pronounced during warm seasons; increased preparedness for heavy rainfall events is warranted. The non-precipitating days increase during winter when the monsoon winds weaken.

It is interesting to compare such simulated tendency of change with observed records, but no comprehensive daily statistical data have been available to the authors. However, Fujibe et al. (2005) has recently examined a newly compiled long-term set of Japanese station rainfall data and reports for the 20th century trends of increased heavy rainfall days and decreased weak rainy days. Using the same data, Fujibe (2005, personal comm.) also shows increase in non-precipitating days. Statistics and simulations of extreme events are subject to large uncertainty, and close examination of observed records and simulations with multitudes of climate models are necessary to increase credibility of presently reported results.

Acknowledgements

The authors acknowledge the K-1 project members for support and discussions and Dr. F. Fujibe for information on his results. They thank Dr. H. Kanzawa and two anonymous reviewers for constructive comments. This work was supported by the Research Revolution 2002 (RR2002) project of the Ministry of Education, Culture, Sports, Science and Technology, by the Core Research for Evolutional Science and Technology (CREST) of the Japan Science and Technology Agency, and by the Global Environment Research Fund (GERF) of the Ministry of the Environment of Japan. The model computation was carried out using the Earth Simulator, and the figures were drawn by GrADS.

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Manuscript received 27 April 2005, accepted 15 June 2005

SOLA: http://www.jstage.jst.go.jp/browse/sola/