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Assessment of climate change impact on river discharge in cold and mountainous region in Japan

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Abstract To evaluate the impacts of climate change on river discharge, we applied a hydrological simulation to one of the major river basins in Japan, located in a cold and mountainous region. A super-high-resolution atmospheric general circulation model (AGCM) with a horizontal resolution of about 20 km, developed by the Meteorological Research Institute of Japan Meteorological Agency (JMA-MRI), was used for the future projection with a simple bias correction. River discharge was estimated using a distributed hydrological model that was calibrated in advance using long-term observation data. The results showed that even if the amount of precipitation does not change greatly in the future, river discharge will change significantly with air temperature rise, owing to increased rainfall, decreased snowfall in winter and decreased snowmelt in early spring. These changes will become more serious in northern cold mountainous regions because the water resources of these regions are currently dominated by the snowmelt.

Key words climate change; AGCM; river discharge; snow melt; distributed hydrological model; bias correction

INTRODUCTION

Increases in land surface temperature will have a significant affect on the hydrological cycle, particularly in regions where the available water resources are mainly dominated by the melting snow or ice (Barnet *et al.*, 2005). The disappearance of permafrost layers, glacial recessions and changes in snowmelt will also have a severe impact on the hydrological cycle in cold and mountainous regions (Qiu, 2008). The snow depth in the northern Japan projected for the 2070s will decrease by 40% compared to the current climate condition (Hara *et al.*, 2008). The decreasing trend of decadal averaged river discharge was already detected in early spring since the 1970s, especially in the northern part of Japan (Ma *et al.*, 2010). Thus, to clarify the impact of climate change on river discharge in cold and mountainous regions is becoming one of the urgent issues for policy making and planning for integrated river water management under the inevitable warming climate. To address these issues, a super-high-resolution global atmospheric general circulation model (AGCM) with 20 km horizontal resolution was developed by the Meteorological Research Institute of Japan Meteorological Agency (JMA-MRI) to project changes in future climates more precisely (Mizuta *et al.*, 2006; Kitoh *et al.*, 2009). The model made it possible to assess the impact of climate change in a specific river basin on a regional scale. Thus, in the present study, we attempt a hydrological simulation using MRI-AGCM as an input variable for a distributed hydrological model and applied the model to a cold mountainous region in Japan.

METHODS

Study area

We focused on the Tedori River basin located in Ishikawa prefecture. The total basin area is 809 km^2 with a stem channel length of 72 km. The maximum elevation is approximately 2702 m at Mt. Hakusan and 92% of the basin is covered by coniferous forest. The annual precipitation is concentrated in the mountainous area (approx. 3000 mm) and gradually decreases along the lower reach (approx. 2500 mm). The river water is supplied for drinking water for 75% of the total population of Ishikawa prefecture, irrigation, and hydropower generation. There are two dam reservoirs (Tedori: 190.0 × 10^6 m^3 and Dainichi: 23.9 × 10^6 m^3) used for flood control, water supply and river environment conservation. The channel network, location of dams and reference point for river discharge are shown in Fig. 1.

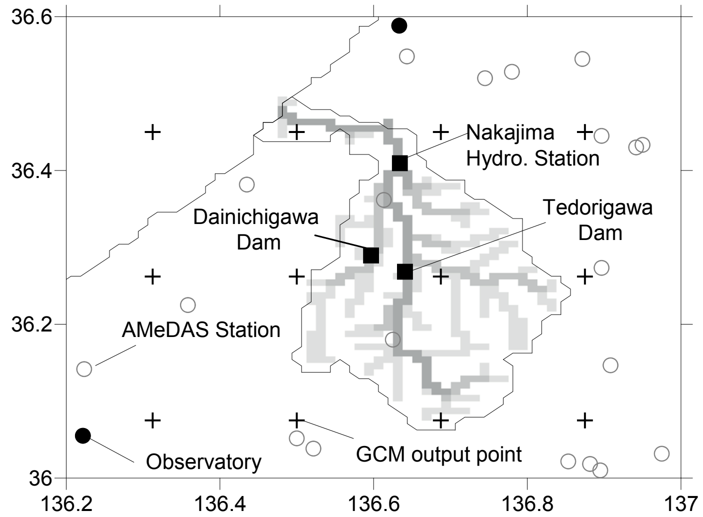

Fig. 1 Channel network and location of dams, hydrological observation station, AMeDAS, observatory (SDP) and GCM output points around the Tedori River basin.

Observed data

Surface meteorological datasets such as precipitation, air temperature, wind speed, and sunshine duration were obtained from about 1300 Automated Meteorological Data Acquisition System (AMeDAS) sites. Atmospheric and vapour pressure data are obtained from 155 observatories. To validate the runoff simulation, observed river discharge data were obtained from the Water Information System managed by the Ministry of Land, Infrastructure and Transport (MILT), Japan (online data). Daily average river discharge data are available from the 1960s for most major river basins in Japan. Furthermore, long-term daily average river discharge datasets at reference points (Nakajima) in the Tedori River basin were also obtained from the Japan River Association (offline data).

SVAT model

To validate the performance of the hydrological model and AGCM output with the climate today, it was necessary to prepare observed meteorological datasets, such as those of total rainfall infiltration into the soil layer (net rainfall + snowmelt) and water losses from the soil layer (evapotranspiration). The Soil–Vegetation–Atmosphere Transfer (SVAT) model was used to obtain unmeasured input variables for hydrological simulations from routinely observed meteorological data. The detailed information of the SVAT model was summarized in Sato *et al.* (2008). In the SVAT model, precipitation was converted to snow when the hourly air temperature was less than approximately +2.2°C, and snow density was set at a constant (100 kg/m^3) to simplify the calculation. The heat balance at the land surface was calculated to estimate potential evaporation (Kondo & Xu, 1997). The temperature of the isothermal soil layer (assumed to be the lower boundary of the SVAT model) was set at a depth of 6 m below the ground surface and was equal to the annual mean air temperature of each grid cell. Soil and snow temperature profiles were calculated using the thermal conductive model developed by Outcalt *et al.* (1975) and Fukuda & Ishizaki (1980) to obtain the values of soil and snow heat flux, G (W/m^2). The soil layer and snow pack were subdivided at 0.01-m intervals. The amount of snowmelt was estimated using the method followed by Kondo & Yamazaki (1990).

AGCM

The climate model used for the experiment was the AGCM of the MRI (MRI-AGCM3.2S). MRI-AGCM3.2S is based on a model developed jointly by the JMA and the MRI (Mizuta *et al.*, 2006). The model is the revised version of MRI-AGCM3.1S used for previous 20-km-resolution experiments (Kitoh *et al.*, 2009). The model had a horizontal resolution of triangular truncation 959

(TL959). The transform grid was composed of 1960 × 960 grid cells, corresponding to approximately 20-km grid intervals. It had 60 vertical layers (top at 0.01 hPa). The land surface model used was the new version of the JMA Simplified Biosphere (SiB; Ohizumi & Hosaka, 2000). Vegetation, snowpack, and soil processes were coupled with the atmospheric components of the AGCM (Nakaegawa & Vergara, 2010). As the lower boundary conditions, observed sea-surface temperatures (SSTs) and sea-ice concentrations were used for the current climate simulation (1979–2003). For the climate simulations of the end of the 21st century (2075–2099), the SSTs projected by the Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model ensemble (MME) dataset were used. These data were based on the A1B scenario of the Special Report on Emission Scenarios (SRES) in the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change.

Hydrological model

The Hydrological River Basin Environment Assessment Model (Hydro-BEAM) developed by Kojiri (2006) was used for the hydrological simulation. The model was a cell-concentrate-type distributed hydrological model that divided each grid cell into two pairs of rectangular hill slopes and one river channel. A spatial resolution of 1 km and a 10-minute time step were applied in this study. The surface flow and subsurface flow from the upper soil layer and channel flow were calculated using a kinematic wave model. The baseflow from the lower soil layer was calculated by a multi-layer linear storage function model. The reservoir operations such as flood control and water release were included in the model. However, the water withdrawal from the river channel, deeper seepage and long-term groundwater storage were not considered in this analysis. All of the input variables for Hydro-BEAM were interpolated to 1-km grid mesh data using the inverse distance-weighting (IDW) method.

RESULTS AND DISCUSSION

Reproducibility of the present climate

Figure 2 shows the difference of the annual precipitation among climate value (1981–2010), observed value (1981–2010), and AGCM output (1979–2003) of the Tedori River basin. Annual precipitation as a basin average was 2826.2 mm (climate value), 2823.7 mm (observed value), and 3031.3 mm (AGCM), respectively. The mesh precipitation data used in this study was interpolated by inverse distance-weighting (IDW) method considered the difference between observed/ output point. In addition to this, the climate value developed by JMA considers topographical effects such as precipitation gradient by elevation. Therefore, the amount of precipitation obtained from the climate value will be more reasonable than that obtained from the simple IDW method. Therefore, in the present study, we modified the monthly mesh precipitation values of the observed data and AGCM output based on the climate value, and then applied the data for the further analysis.

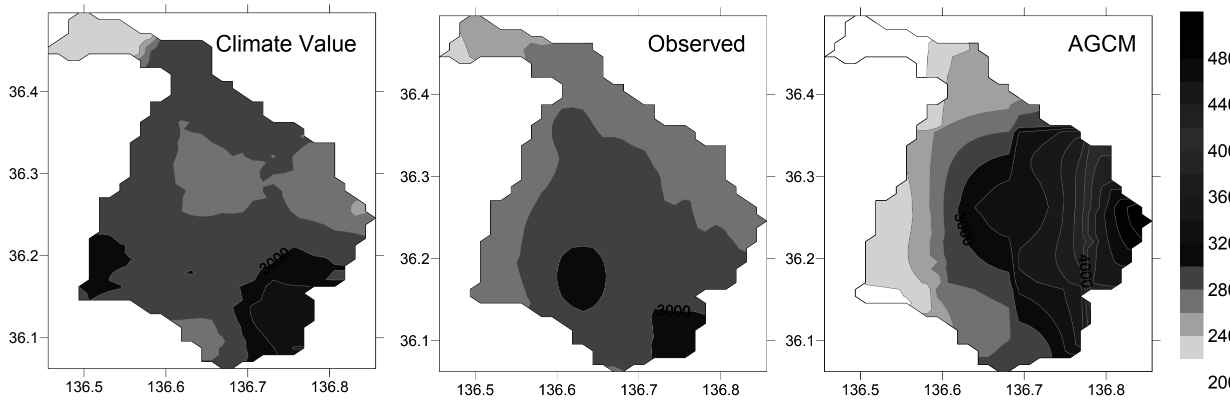

Fig. 2 Spatial distribution of annual precipitation (mm) created from climate value, observed value, and AGCM output.

The original precipitation data interpolated by the IDW method indicates the contour line around the observation station/AGCM output point. However, by applying the simple bias correction (multiplying the monthly bias correction ratio to the original data), the amount of monthly precipitation of each mesh agreed with the climate value. The bias correction ratio (BC) was calculated as follows:

$$BC = Precipitation_{climte\_value} / Precipitation_{original\_data} \quad (1)$$

The air temperature used in this study was considering the altitude correction factor in the interpolation procedures. The differences in air temperature amongst these three data were negligible and the bias correction for the air temperature was not conducted in the present study.

Difference between the SVAT model and AGCM

Figure 3 indicates the difference between the monthly water balances obtained from the SVAT model and AGCM. The observed and calculated monthly river discharges at the reference point (Nakajima) are also shown in Fig. 3. The monthly precipitation values completely correspond to the climate value due to the bias correction.

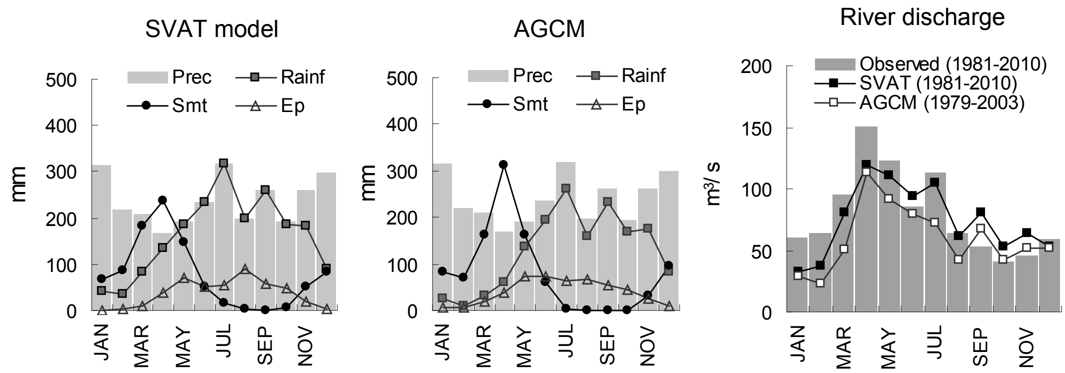

Fig. 3 Difference of monthly water balance and river discharge between SVAT model and AGCM. Prec: Precipitatiom, Smt: Snowmelt, Ep: Potential evaporation(SVAT) / Evapotranspiration (AGCM).

The rainfall value obtained from AGCM was smaller than that of the SVAT model. This is mainly because the rainfall data of the AGCM does not include the amount of rainfall interception by the surface vegetation. The amount of monthly evaporation represented almost the same value among the two models, and the contribution of the evaporation seems relatively small compared with the other water balance components. The largest difference was found in the snow melt. This was probably due to the difference of the model structure of each model (e.g. threshold temperature for dividing snow and rain). The parameters of the hydrological model were calibrated by comparing the calculated and observed river discharge as the reference point. In the present study, the parameters calibrated using the SVAT model are the input variables. Then, the same parameters were used for the hydrological simulation using AGCM output as the input variable. Hence, the reproducibility of the river discharge by the AGCM was slightly underestimated, but the model reproduced the seasonal variation quite well. Thus, we considered that the AGCM data (bias corrected) appropriate for assessing the impact of climate change.

Future climate projected by the AGCM

According to the projection by the AGCM (A1B scenario), the air temperature in the future (2075–2099) will rise by about +2.87°C relative to present climate (1979–2003) in the Tedori River basin. On the other hand, the annual and monthly precipitation does not change significantly (Fig. 4). Figure 5 summarises the change of water balance in the Tedori River basin between present and future climate conditions. Even though the amount of precipitation does not change so much in the future, the water balance will change significantly with the temperature rise. The rainfall in the winter (Dec. to Feb.) and spring (Mar. to May) will increase. However, the amount of the peak snow melt (Apr.) will decrease significantly and the peak will appear about one month earlier (Mar.) than the present climate. The impact of evapotranspiration change in the Tedori River basin seems to be small.

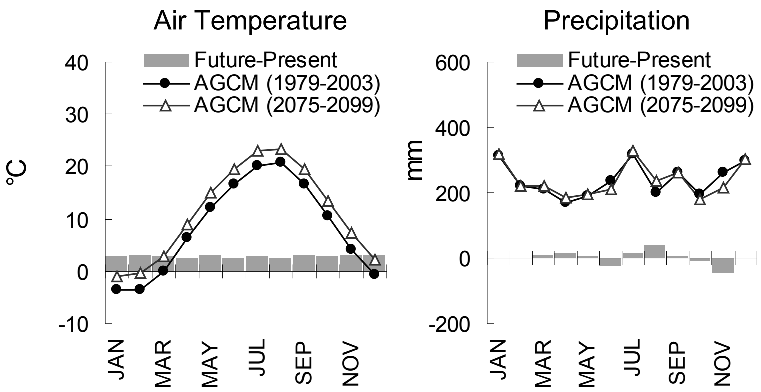

Fig. 4 Comparisons of monthly average air temperature and precipitation projected by AGCM between present and future climate condition.

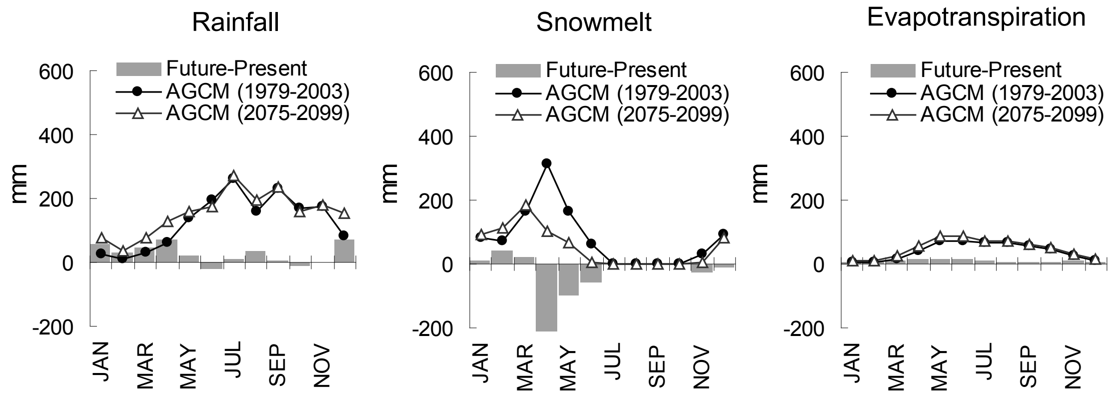

Fig. 5 Comparisons of monthly rainfall, snowmelt, and evapotanspitation projected by AGCM between present and future climate condition.

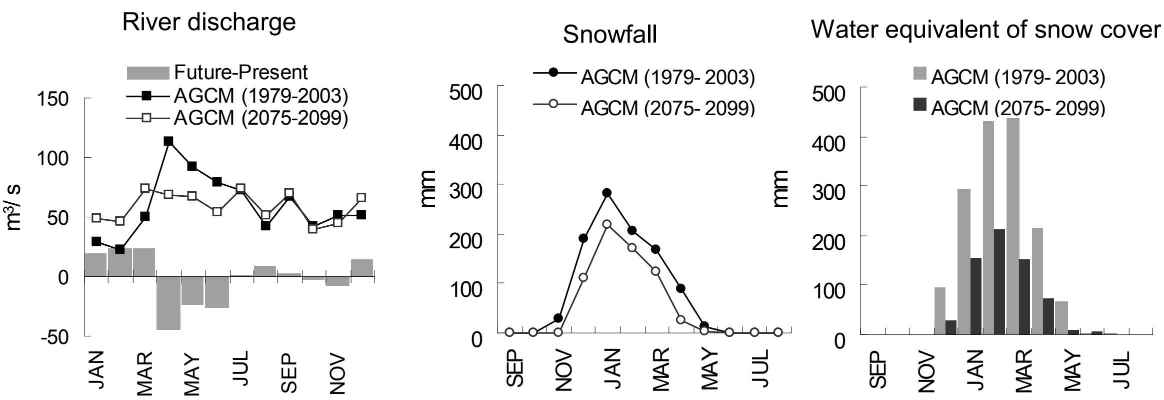

Fig. 6 Comparisons of the monthly river discharge, snowfall, and water equivalent of snow cover projected by AGCM between present and future climate condition.

Impact of climate change in the cold mountainous region

The river discharge in future will change significantly due to the increase of rainfall in the winter to spring and decrease of snowmelt in the early spring. In the case of Tedori River basin, the monthly river discharge from December to March will increase, and then decrease from April to June (Fig. 6, left). These changes make the seasonal change of the river discharge unclear. In the cold regions in Japan, irrigation water use for paddy fields greatly depends on the river discharge in the late spring (April to May). The decreases of river discharge in this period will have a severe impact on the agricultural production in this region. The amount of snowfall will decrease and the period of snow cover will also decrease in the future climate condition (Fig. 6, centre, right). It will also have a great impact on local industries like ski resorts and the total expenses of snow removal from railways, airports and highways, etc.

CONCLUSIONS

To evaluate the impact of climate change on river discharges in Japan, a distributed hydrological simulation was performed using a super-high-resolution AGCM (MRI-AGCM3.2S) with a horizontal resolution of about 20 km to obtain the input meteorological forcing data. The AGCM with simple bias correction accurately reproduced hydrology under present-day climate conditions on regional scales. It was found that even if the amount of precipitation does not change much, river discharge will change significantly due to increases in rainfall and decreases in snowmelt as air temperature rises. Finally, the water balance analysis revealed that the increase in winter flow and decrease in spring flow were induced by the increase of winter precipitation and the subsequent decrease in snowmelt. These changes will become more serious in northern cold mountainous region because the water resources of these regions are currently dominated by the snowmelt.

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