Possible effects of climate change on hydrologic processes in a snowy region of Japan

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Abstract In snowy regions, snowmelt runoff is an important source of water for irrigation, domestic use and hydropower. However, climate change is expected to raise temperatures and reduce snowfall, which is expected to shorten the snow-melt season and decrease river discharge. In turn, this is expected to influence water use. We simulated hydrologic processes including snow processes and their possible changes in the future for the Ishikari River catchment area by using a method based on the heat and water balances. Mesh data of temperature and precipitation provided by the Japan Meteorological Agency's Regional Climate Model (RCM20) were applied to the simulation. The results suggest that shortages of irrigation water will occur as a result of decreases in snowmelt runoff.
Keywords climate change, snowy regions, hydrologic processes, RCM20, water use

INTRODUCTION

According to a report by the Intergovernmental Panel on Climate Change (IPCC)(Parry *et al.* (eds.), 2007), the phenomenon addressed in that report has the potential to affect numerous meteorological variables, including precipitation and snowmelt, which in turn can alter the quantities of water resources. Current administrative plans for water utilization do not take into account the potential effects of climate change. To conduct river management such that it considers those effects, it will be necessary to establish methods for predicting changes in the hydrological cycle and related changes in water resources on the scale of the river basin.

We calculated hydrologic processes, taking into account snow hydrology and its possible changes in the future, for the Ishikari River catchment area (14,330 km^2) in Hokkaido, Japan, by using a calculation model proposed by Usutani *et al.* (2006). The model takes into account heat transport at the ground surface, the forest canopy and the atmosphere, and hydrologic processes, so as to estimate the amounts of accumulated snow, snowmelt and evapotranspiration for each 1-km mesh. Mesh data of temperature and precipitation on a scale of 20 km by 20 km provided by the Japan Meteorological Agency's Regional Climate Model (RCM20)(Kurihara *et al.*, 2005), which simulates climate conditions under a scenario of global warming, were converted to 1-km mesh data by a downscaling technique and were applied to the hydrologic model.

The water budget of the catchment area and the river discharge were calculated by using the regional climate output of the present state and the predicted states. It was calculated that the snow-melting season would start in early March rather than the present early April. The flow reduction for the second half of the snowmelt season was particularly notable. A comparison between water use based on water rights and estimated runoff suggests that water shortages will occur in late spring and early summer.

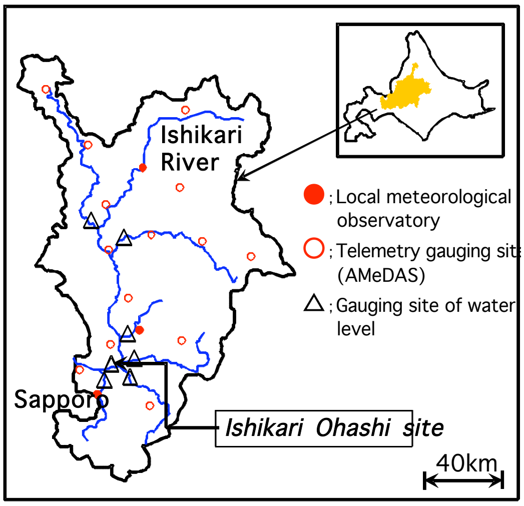


Fig. 1 Outline of study area.

STUDY AREA AND INPUT DATA

This study addresses the Ishikari River basin in Hokkaido, Japan (Fig. 1). The basin is between the latitudes of 43°N and 44°N. The main stream of the river, one of the longest rivers in Japan, is 268 km, and the catchment area is 14,330 km^2. In Sapporo, the main city in the basin, the monthly air temperature is 22.0 °C in August (the warmest month) and -4.1 °C in January (the coldest month). Snow cover lasts for roughly the four months of December through March. Annual snowfall is 630 cm, and the greatest annual snow depth is 101 cm (normal value 1970 - 2000).

We used the output data of a high-resolution Regional Climate Model of 20-km mesh size (RCM20) that was developed by the Meteorological Research Institute (MRI) and the Japan Meteorological Agency (JMA) to analyze the effects of climate change on hydrologic processes. The SRES-A2 scenario, proposed by the IPCC (IPCC 2000), was adopted for the future run. In RCM20, the outputs for estimation experiments on the present climate (1981 to 2000), the near future climate (2031 to 2050) and the future climate (2081 to 2100) are available.

METHODOROGY

The calculation method for hydrologic processes is schematically shown in Fig. 2. Firstly, amounts of rainfall, snowmelt and evapotranspiration are estimated using the observation data and the heat balance model for each 1-km by 1-km grid. Characteristics of snow, such as the water equivalent of accumulated snow, are also quantified. Next, the runoff from the basin is calculated by inputting those values.

Snowmelt and evapotranspiration are controlled by the heat balance between the atmosphere and the ground surface, including accumulated snow. To properly estimate the heat flux in the vegetation layer and at the ground surface, the two-layer model proposed by Kondo *et al*. (1994) was employed. Snowmelt was estimated by the heat flux provided to the ground surface, while evapotranspiration was estimated by the latent heat flux from the ground surface and the vegetation layer. This method was applied to calculate the hydrologic processes in dam basins taking into account the water equivalent of snowpack, the snowmelt and the evapotranspiration (Nakatsugawa *et al*., 2006).

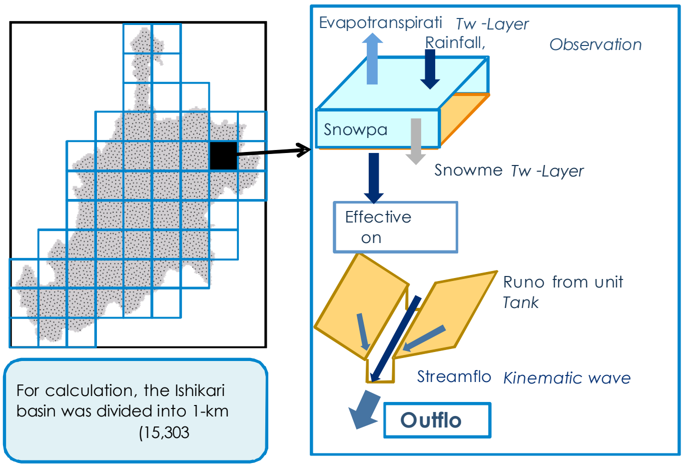


Fig. 2 Schematic of the calculation method.

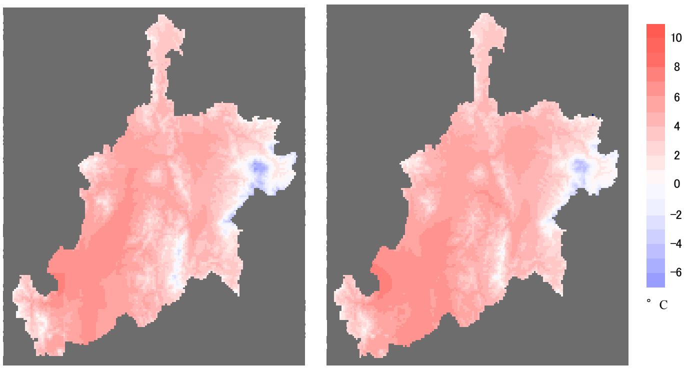
For each mesh, the outflow from the upstream mesh was estimated by channel routing, as was the runoff within the mesh (slope runoff). The discharge at the tail end of the mesh was added up, and that sum was the runoff into the downstream mesh. Channel routing was calculated using a kinematic wave model, whereas slope runoff was calculated within a mesh by the tank model (Usutani *et al.*, 2006).

To apply the RCM20 output to the hydrological model for a basin, an attempt was made to downscale to 1-km by 1-km mesh. Because air temperature depends on elevation, downscaling of temperature data was made by correcting for the elevation of the 1-km meshes. The spatial distribution of annual mean temperature estimated by this downscaling is shown at left in Fig. 3; spatially interpolated observation results using the Kriging method are shown at right. The estimated results are similar to the observations, thus confirming the validity of this downscaling.

On the other hand, no dependency on elevation was found for precipitation, because there were too few data for high elevations. Thus, the mesh data for precipitation of RCM20 were directly used. Additionally, the decision to regard precipitation as rainfall or snowfall was made with reference to temperature and humidity (Kondo *et al.*, 1994). The precipitation data of RCM20 are shown at left in Fig. 4; they are compared with the observation results interpolated by using the Kriging method at right. Consequently, we consider the RCM20 output to closely reproduce the observations.

RESULTS AND ANALYSIS

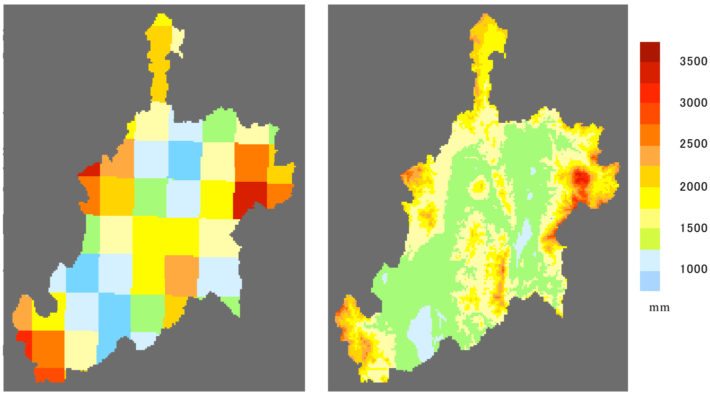
To confirm the validity of the model, an attempt was made to reproduce the discharge using the RCM20 data. Fig. 5 compares the discharge obtained by adding the maximum intake for irrigation to the observed discharge data (the mean value on the same day of 1981 from 2000) with monthly mean discharge reproduced by using the RCM20. Discharge was estimated at the Ishikari Ohashi site, which is 26.6 km upstream of the river mouth and whose drainage area is 12,697 km^2. The maximum intake is estimated to be 72.3% of the water subject to water rights, as determined from water use records. It was confirmed that the patterns of the hydrographs are similar, although the calculation underestimated the discharge compared with the observation in July and August. Thus, the calculation model was verified as being able to provide



Temperature provided by downscalingpf RCM20(Present) averaged from 1981 to 2000

Temperature provided by interporation of observation data averaged from 1998 to 2001

Fig. 3 Distributions of yearly mean temperature based on RCM20 and observation.



Precipitation provided by RCM20(Present) averaged from 1981 to 2000

Precipitation provided by interporation of observation data averaged from 1998 to 2001

Fig. 4 Distributions of yearly total precipitation based on RCM20 and observation.

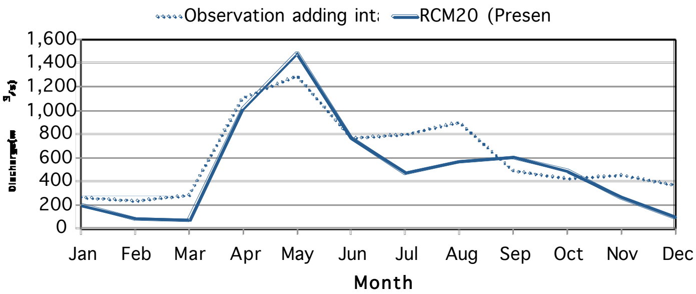


Fig. 5 Monthly mean discharges observed and estimated by using RCM20.

reliable results for hydrologic processes.

The water budget of the basin calculated by the RCM20 experiment is shown in Table 1, and the change in the water budget is shown in Table 2. The values in Table 2 are indicated by setting 1.0 as the values for the RCM20 (Present) case.

First, the temperature is predicted to rise by 1.8 °C in 2050 and 3.0 °C in 2100 compared with 2000. Moreover, though rainfall and snowfall are both expected to increase in 2050, the possibility of snowfall decreasing by 11% in 2100 is suggested from the temperature rise. In addition, it is estimated that the amount of evapotranspiration may increase by 11% as of 2050 and 12% as of 2100.

Fig. 6 shows the average discharge for the day of the RCM20 experiment and the daily average discharge calculated from the RCM20 experiment calculation data. Moreover, the change in discharge for each month is shown in Table 3. The change is

Table 1 Hydrologic condition calculated by the RCM20 experiment.

	Rainfall (mm/yr)	Snowfall (mm/yr)	Evapotranspiration (mm/yr)	Runoff (mm/yr)	Yearly avg. temp. (°C)
RCM20 (Present)	**1,056**	**650**	**743**	**963**	**5.0**
RCM20 (Near-future)	**1,375**	**728**	**826**	**1,276**	**6.8**
RCM20 (Future)	**1,236**	**577**	**836**	**977**	**8.0**
Present Reproduction*	**1,012**	**767**	**518**	**1,262**	**5.2**

*Calculated using data from 1998 to 2001

Table 2 Changes in water budget calculated by the RCM20 experiment and in temperature.*

	Rainfall	Snowfall	Evapotranspiration	Runoff	Increment of temp. (°C)
RCM20 (Near-future)	**1.30**	**1.12**	**1.11**	**1.33**	**+1.8**

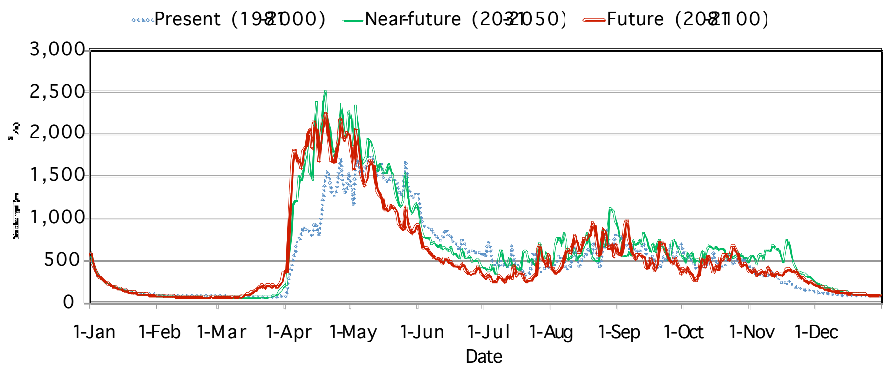


Fig. 6 Hydrographs calculated by the RCM20 experiment for the Ishikari Ohashi site.

Table 3 Change in monthly runoff calculated by the RCM20 experiment.

	Jan	Feb	Mar	Apr	May	Jun
RCM20 (Near-future)	**0.98**	**0.92**	**1.10**	**1.71**	**1.06**	**0.84**
RCM20 (Future)	**0.97**	**0.90**	**1.96**	**1.77**	**0.86**	**0.65**

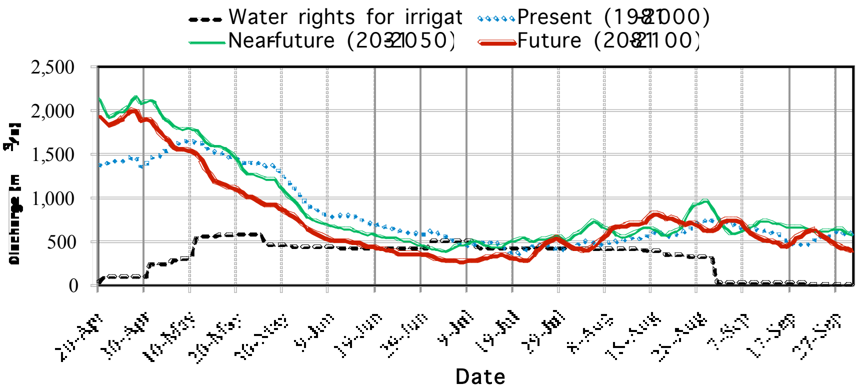
	Jul	Aug	Sep	Oct	Nov	Dec
RCM20 (Near-future)	**1.03**	**1.22**	**1.10**	**1.17**	**1.95**	**1.46**
RCM20 (Future)	**0.75**	**1.15**	**0.94**	**0.95**	**1.29**	**1.31**

*Values of RCM20 (Present) = 1.0.

indicated by setting 1.0 as the values of the RCM20 (Present) case. The results show increases in discharge from April through May and a shift in the snowmelt peak to earlier in the season, and decreases from late June to early July (the end of the snowmelt season).

To verify the effects of changes in outflow on water use, we focused on the influence of such changes on irrigation, which accounts for the majority of water use in the Ishikari River basin. According to current data, power generation and irrigation account for about 97% of water use. Water rights in Hokkaido allow large amounts of water to be used in mid-May, for rice paddy tilling, and in early July, for protecting rice from cold damage by keeping the paddy water level high.

Fig. 7 shows the daily maximum intake of irrigation water and the daily river



outflow at the Ishikari Ohashi site during the irrigation period of April to September. The maximum intake is the total of the amounts set by water rights. The results indicate water shortages for roughly the one month from mid June due to river outflow below the amount of water rights in the case of future climate around 2100. Thus, possible damage to irrigation toward the end of the snowmelt season was suggested.

Fig. 7 Hydrographs and amount of irrigation water at the Ishikari Ohashi site.

CONCLUSIONS

In this study, mesh data of RCM20 were downscaled to 1-km mesh data for application to a hydrologic model for the Ishikari River basin. The calculated results for the cases of present, near-future (around 2050) and future (around 2100) using the RCM20 data indicated increases in discharge from April through May and a shift in peak snowmelt to earlier in the season, and decreases from late June to early July, which is the end of the snowmelt season. By comparing irrigation water with estimated river outflow, the possibility of water shortages for the roughly one month from mid June in the case of the future climate was shown. To mitigate the water shortage risk in this snowy region, comprehensive water management that adapts to climate change is needed.

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