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Simulating river discharge in a snowy region of Japan using output from a regional climate model

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Abstract. Snowfall amounts have fallen sharply along the eastern coast of the Sea of Japan since the mid-1980s. Toyama Prefecture, located approximately in the center of the Japan Sea region, includes high mountains of the northern Japanese Alps on three of its sides. The scarcity of meteorological observation points in mountainous areas limits the accuracy of hydrological analysis. With the development of computing technology, a dynamical downscaling method is widely applied into hydrological analysis. In this study, we numerically modeled river discharge using runoff data derived by a regional climate model (4.5-km spatial resolution) as input data to river networks (30-arcseconds resolution) for the Toyama Prefecture. The five main rivers in Toyama (the Oyabe, Sho, Jinzu, Joganji, and Kurobe rivers) were selected in this study. The river basins range in area from 368 to 2720 km^2. A numerical experiment using climate comparable to that at present was conducted for the 1980s and 1990s. The results showed that seasonal river discharge could be represented and that discharge was generally overestimated compared with measurements, except for Oyabe River discharge, which was always underestimated. The average correlation coefficient for 10-year average monthly mean discharge was 0.8, with correlation coefficients ranging from 0.56 to 0.88 for all five rivers, whereas the Nash-Sutcliffe efficiency coefficient indicated that the simulation accuracy was insufficient. From the water budget analysis, it was possible to speculate that the lack of accuracy of river discharge may be caused by insufficient accuracy of precipitation simulation.

1 Introduction

In Japan, snowfall amounts have fallen sharply in some regions. The Japan Meteorological Agency (JMA, 2005) reported that annual maximum snow depth has significantly decreased since the peak was from early 1980s through 1990. Although a slight upward trend has been observed since then, snowfall levels remain much lower than those in the early 1980s. This downward trend can be attributed mainly to a dramatic rise in mean winter temperatures in northern and western Japan since the mid-1980s, resulting in a noticeable decrease in river discharge in spring (Ma et al., 2010). Moreover, snowfall amounts have been predicted to decrease further in all of Japan's regions except Hokkaido, under a scenario in which temperatures rise by 2.8 °C by the end of the 21st century (JMA, 2008).

Toyama has 15 weather observation stations. However, meteorological observation points are scarce in the mountainous areas. To understand the possible effects of climate change on water resources in this prefecture, quantitative analysis is needed. Such analysis requires information on changes in river discharge determined from both observation and simulation. Hydrological simulations at the river-basin scale generally use data obtained from ground-based meteorological stations. The distribution and density of meteorological stations affect the accuracy of such hydrological modeling, especially for high mountainous river basins. In view of the above, some studies have attempted to use regional climate models to obtain the meteorological information required by hydrological simulations (e.g., Kite and

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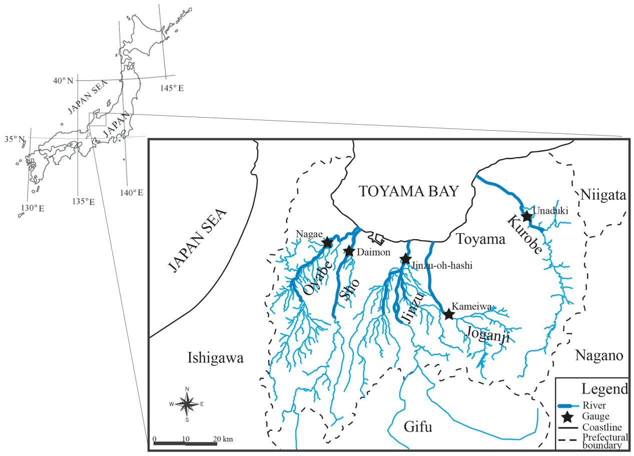

Fig. 1. Location of Toyama Prefecture and its main five rivers.

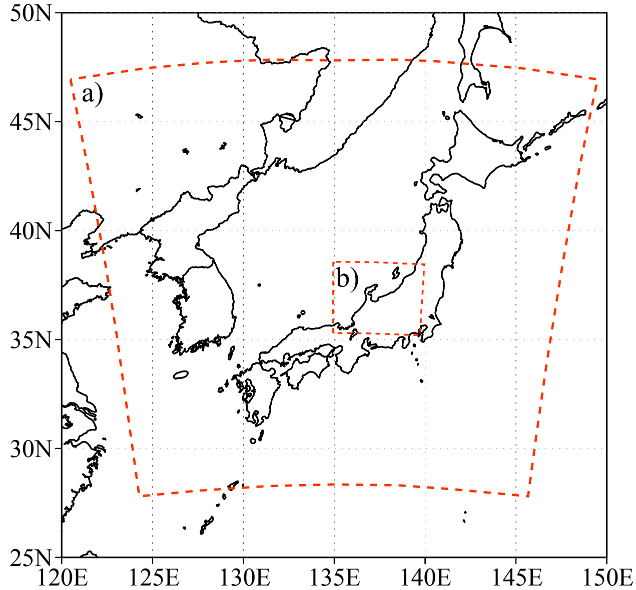

Fig. 2. Domains of the WRF model: **(a)** the parent domain (in 18-km spatial resolution); **(b)** the inner domain (in 4.5-km spatial resolution).

Haberlandt, 1999; Wood et al., 2004; Weber et al., 2010). The Weather Research and Forecasting (WRF; http://www.mmm.ucar.edu/wrf/users/) model, one of the regional climate models supported by the National Center for Atmospheric Research (NCAR), has many users and is freely available for community use. A land-surface scheme is included in the WRF model to simulate the runoff for each grid. Therefore, it is practicable for river discharge modeling using the runoff data with a river routing process. Kawase et al. (2012) reported the maximum snow depth could be accurately simulated using the WRF model over the Hokuriku District, including the Toyama region in the late 20th century. However, the hydrological analysis using the WRF model output has never been examined.

In this study, we conducted a numerical investigation of river discharge by downscaling data derived from the WRF model to 4.5-km resolution, instead of using station data. Five main rivers in Toyama (Oyabe, Sho, Jinzu, Joganji, and Kurobe rivers) were selected for this study. A 20-year-long numerical experiment, intended to reproduce the current climate, was carried out for the 1980s and 1990s to verify model performance in this area.

2 Study area and model setting

Toyama Prefecture (4247 km^2 in area, Fig. 1), located approximately at the center of the Sea of Japan coast, includes high mountains of the northern Japanese Alps on three of its sides. The topographic relief is greater than 3000 m, and the monthly mean temperature and total precipitation in January–February are approximately 2.7 °C and 600 mm, respectively. The entire prefecture is part of the heavy snowfall region along the Sea of Japan. Toyama's rich natural environment includes areas of sea, mountain, river, and plain, with four clear seasons and abundant plant and animal life. Rain and snowfall in the mountains deliver rich, clean water throughout the year, supporting the industry and lifestyle of Toyama.

The WRF model is a mesoscale numerical weather projection system designed to serve both operational forecasting and atmospheric research needs. The model uses fully compressible, nonhydrostatic equations. We used the Advanced Research WRF (ARW) version 3.2.1 (Skamarock et al., 2008) with a two-way nesting technique and the WRF single-moment six-class microphysics scheme (Hong and Lim, 2006). In this version, the Noah land-surface model (Chen and Dudhia, 2001) is adopted to simulate the land-surface process. The output variables from the WRF model are over one hundred including downward longwave and shortwave fluxes at the ground surface, surface air pressure, accumulated total grid-scale precipitation, surface air temperature, wind speed at 10 m height, etc. Two components of runoff, namely, subsurface and surface runoff, are calculated for one grid without the river-routing process. In this study, we used the WRF model with dynamic downscaling to simulate runoff data as input variables for a river-routing model.

The calculation domain of WRF was set to two levels. The parent domain was set to a wide area, between 25–50° N and 115–155° E on an 18-km grid. The inner domain was located in a smaller area between 35.25–37.5° N and 136.25–139° E with a 4.5-km grid (Fig. 2). National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) 6-hourly reanalysis data were used as the lateral boundary condition. The output variables used for river-discharge simulation from the WRF model were (1) subsurface runoff and (2) surface runoff.

Table 1. Published and estimated river basin area of the five rivers in Toyama Prefecture.

Name of river	Basin area (km^2) published	Basin area (km^2) estimated	Basin area by prefectures (%)
Oyabe	667	669	Toyama (100)
Sho	1180	1194	Toyama (36.4), Gifu (63.6)
Jinzu	2720	2813	Toyama (27.1), Gifu (72.9)
Joganji	368	389	Toyama (100)
Kurobe	682	734	Toyama (100)

Table 2. Ten-year average runoff (mm) and relative error between observations (ob) and estimations (ca) for the five rivers.

Gauge (catchment area, km^2)	River	1980s		1990s		error (%)	
		ob	ca	ob	ca	1980s	1990s
Nagae (606)	Oyabe	2872	1772	2840	1633	−44.7	−47.8
Daimon (1184)	Sho	1030	2641	984	2484	201.6	176.0
Jinzu-oh-hashi (2786)	Jinzu	2175	2454	2116	2325	17.2	14.0
Kameiwa (363)	Joganji	1393	4670	1763	4462	283.4	180.2
Unaduki (677)	Kurobe	1754	3837	1247	3608	256.2	265.6

Table 3. Correlation coefficients (CC) and Nash-Sutcliffe efficiency coefficients (NC) of monthly mean discharges for the five rivers in the 1980s and 1990s.

	Oyabe		Sho		Jinzu		Joganji		Kurobe	
	CC	NC	CC	NC	CC	NC	CC	NC	CC	NC
1980s	0.76	−1.45	0.51	−3.35	0.74	−0.14	0.72	−9.44	0.65	−1.28
1990s	0.44	−2.52	0.41	−5.20	0.80	0.28	0.77	−3.85	0.60	−4.61

Channelized river flow is simulated by a river-routing model, part of the Soil-Vegetation-Atmosphere Transfer and Hydrological Cycle (SVAT&HYCY; Ma et al., 2000) model. Here, river routing is designed as linear. That is, water flow is given a constant velocity in the channel system. The river networks for the Oyabe, Sho, Jinzu, Joganji, and Kurobe rivers were constructed using the GTOPO30 dataset (http://eros.usgs.gov/#/Find_Data/Products_and_Data_Available/gtopo30_info) with 30-arcseconds resolution. The estimated basin areas are shown in Table 1 and are close to the reported values.

The sum of both subsurface and surface runoff calculated by the WRF on a 4.5-km grid was redistributed onto the river network system on a 30-arcseconds grid, and the river routing was conducted from upstream to downstream. In consideration of the mountainous topography, the velocity of the river flow was set at $0.6\,m\,s^{-1}$ (Ma et al., 2010). The effect of dams was not considered in this study.

The WRF model was run for hydrological years spanning from 1 July of the "previous" year to 31 July of the "current" year. Taking into account the initial effects, the first month was considered the spin-up period of the model, and the remaining period was used for the analysis.

Daily discharge data for the five rivers are available from the Japan River Association. River flow was measured in a hydrological year from August of the previous year to July of the current year to avoid snow pack.

3 Results and discussion

In Kawase et al. (2012), interannual variation in regional mean maximum snow depth and its drastic decrease from the late 1980s were well simulated in the control run for present climate compared to JMA station data. In this study, the model performance was checked for past river discharge using the runoff output data for the 1980s (from August 1980 to July 1990) and 1990s (from August 1990 through July 2000) at the Nagae (Oyabe River), Daimon (Sho River), Jinzu-oh-hashi (Jinzu River), Kameiwa (Joganji River), and Unaduki (Kurobe River) gauge stations.

A ten-year average runoff was compared for each river (Table 2). The result showed that the simulated runoffs were overestimation compared with that of observed one, ranged from 14 % in the Jinzu River to 283 % in Joganji River, except for the Oyabe River. It was underestimation in the

Table 4. Correlation coefficients (CC) and Nash-Sutcliffe efficiency coefficients (NC) of 10-year average monthly mean discharges for the five rivers in the 1980s and 1990s.

	Oyabe		Sho		Jinzu		Joganji		Kurobe	
	CC	NC	CC	NC	CC	NC	CC	NC	CC	NC
1980s	0.83	−7.52	0.81	−8.95	0.85	−0.93	0.88	−20.09	0.83	−3.85
1990s	0.56	−8.5	0.81	−21.76	0.85	0.08	0.86	−11.81	0.69	−12.93

Table 5. Simulated basin average precipitation (Prec.), runoff (R_ca.) and their different (Loss) for the five river basins in the 1980s and 1990s (unit: mm).

River	1980s			1990s		
	Prec.	R_ca.	Loss	Prec.	R_ca.	Loss
Oyabe	2538	1772	766	2451	1633	818
Sho	3407	2641	766	3292	2484	808
Jinzu	3101	2454	647	2998	2325	673
Joganji	5110	4670	440	4907	4462	445
Kurobe	4319	3837	482	4202	3608	594

Oyabe River with a range of −44 % to −48 % through two decades. The calculated monthly mean discharges were compared with observations over time; the correlation coefficients ranged from 0.41 to 0.80 (Table 3), with an average of 0.64, for all rivers in the 1980s and 1990s. In the comparison of 10-year average monthly mean discharges, the correlation coefficients were clearly improved. The average correlation coefficient was increased to 0.80 and the range of correlation coefficients was from 0.56 to 0.88 (Table 4).

Figure 3 depicts the representative river discharge in the 1980s and 1990s. In general, the simulations were overestimated compared with observations, except for the Oyabe River, where discharge was underestimated throughout the two decades. The seasonal variation was represented well. Discharge was lower in winter (December to March) and higher in spring and early summer (April to July) in both the 1980s and 1990s except in the Oyabe River. The results indicated that the simulations are affected by terrain, underestimated for the Oyabe located in the western part of Toyama, and overestimated in the remaining area. The relative errors for the Jinzu River, which has the largest basin area, were slightly smaller than those for the other rivers. There were maximum differences of 4675 mm in 1999 in the Joganji River and 3522 mm in 1988 in the Kurobe River.

The Nash-Sutcliffe efficiency coefficient (Nash and Sutcliffe, 1970) is used to evaluate the hydrological modeling. The values are ranged from 1 (perfect match of calculated discharge to that of observed one) to minus infinity. An efficiency of 0 indicates that the model can simulate an average discharge. The negative value shows that there is a big difference between the simulated and observed discharges. In this study, the high value for monthly mean discharge was obtained in the Jinzu River, ranged from 0.28 for the 1990s to −0.14 for the 1980s (Table 3). On the other hand, it also indicated that the simulation accuracy for other rivers was insufficient. A comparative summary of the 10-year annual runoff between the calculations and observations is shown in Table 4.

Simulated river basin average annual precipitations of the five rivers are listed in Table 5. The difference between the precipitation and runoff for each river presents the water loss on evapotranspiration and shows in a normal range for this region (about 500 mm, Ma et al., 2010), namely, the land-surface model used in the WRF had a rational performance. It is possible to speculate that the lack of accuracy of river discharge may be caused by insufficient accuracy of precipitation simulation. A low precipitation over the Oyabe basin results the underestimation of river discharge and it is contary in other river basins.

4 Conclusions

Toyama Prefecture is one of heavy snowfall regions in Japan. The monthly mean temperature and total precipitation in the period of January–February are around 2.7° C and 600 mm, respectively. A numerical investigation of river discharge was conducted using runoff data derived by the WRF model (4.5-km grid) and a linear river-routing model (approximately 30 arcseconds). The model performance was evaluated for the main five rivers in Toyama Prefecture, which have basin areas ranging from 363 to 2786 km^2.

Using the climate of the 1980s and 1990s, the simulations overestimated river discharge compared to observations, except for the Oyabe River. However, the seasonal variation was reproduced, with low discharge in winter (December to February) and high discharge in spring and early summer (March to July) in both the 1980s and 1990s.

Among the five rivers, the Oyabe River was the only one where the calculations were always less than measured values. We believe that this result may be related to the terrain. The Oyabe River basin is relatively flat. Much water vapor comes from the Japan Sea across the basin; it then converges and begins to precipitate farther inland and in the alpine regions. In addition, discharges of the Sho, Joganji, and Kurobe rivers were overestimated in April–June in both the 1980s

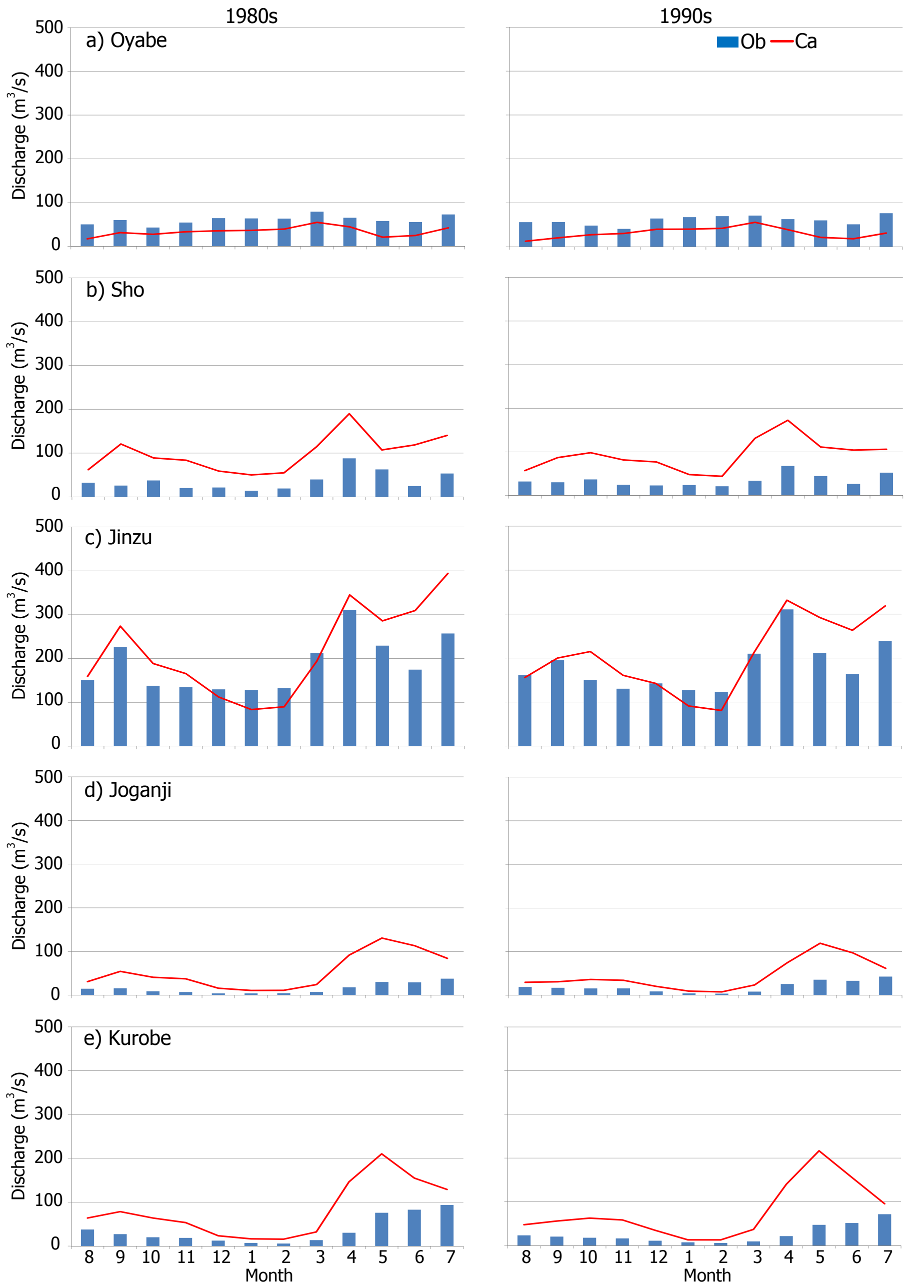

Fig. 3. Comparison of 10-year monthly mean discharge from observations and simulations for the five rivers in the 1980s and 1990s: **(a)** Oyabe River, **(b)** Sho River, **(c)** Jinzu River, **(d)** Joganji River, and **(e)** Kurobe River. (Ob: Observed discharge; Ca: Calculated discharge).

and 1990s. For the Jinzu River, discharge calculations for both the 1980s and 1990s agreed well with measured values.

The calculated monthly mean discharges had average correlation coefficients ranging from 0.64 to 0.80 for all rivers in the 10-year-long time series and the 10-year average series. However, most of the Nash-Sutcliffe efficiency coefficients were lower than zero, showing the simulation accuracy of river discharge was insufficient. Acorrding to the water budget analysis, it was suggested that the accuracy of precipitation simulation must be improved.

As the next step, we will also conduct a more detailed discharge simulation using other land-surface models and considering the uncertainty existing in the calculations, particularly for models that have stringent water balance.

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