京都大学防災研究所年報 第 52 号 B 平成 21 年 6 月
Annuals of Disas. Prev. Res. Inst., Kyoto Univ., No. 52 B, 2009

Climate Change Impact on Water Resources Management in the Tone River Basin, Japan

Sunmin KIM, Yasuto TACHIKAWA*, Eiichi NAKAKITA and Kaoru TAKARA

* Dept. of Urban and Environmental Eng., Kyoto University

Synopsis

To investigate water resources problem under climate change condition, one of the main river basin in Japan, the Tone River basin was modeled and simulated. The Tone River is the main water source to the metropolitan Tokyo, Japan, and upstream of the basin is in snow-dominated regions. Future climate condition was set by output of a super high-resolution atmospheric model (AGCM20) that was developed by the Japan Meteorological Agency (JMA) and the Meteorological Research Institute (MRI), Japan. Evaluation for the future water resources condition in this study considering reservoir operation shows that reproducing current dam release pattern is able to realize even with the shifted snowmelt inflow under the future climate condition. In this case, the water level regulations should be revised, and the shortage of the reservoir water in summer season should be carefully considered. At the outlet of the study basin, Kurihashi station, effects of the controlled water release from the dam reservoirs was negligible, and the shifted snowmelt effect was also not severe and therefore the future water resources condition at the station may not be very different to the current condition.

Keywords: climate change, high-resolution atmospheric model, hydrologic impact analysis

1. Introduction

Intergovernmental Panel on Climate Change (IPCC) Assessment Report 4 (AR4) states that globally averaged temperatures have apparently increased since the mid 20th century, which is assumed due mainly to human activities such as fossil fuel burning and deforestation (IPCC, 2007a). This anthropogenic warming is now believed to influence many of the Earth's physical and biological systems (IPCC, 2007b). It is also believed that climate change is expected to strongly affect the hydrologic cycle in coming decades (e.g. Gedney et al., 2006; Milly et al., 2005). Long-term changes in water resources depend mainly on the amount of precipitation and evapo-transpiration, and the temperature increase strongly affects on changes in precipitation and evapo-transpiration amounts (Piao et al, 2006).

Many researchers suggest that climate change accelerates water cycles with more precipitation and increased evapo-transpiration, limiting freshwater resources less in the next century (Betts et al, 2007; Oki and Kanae, 2006). However, increased precipitation does not necessarily mean sustainable water resources because less frequent but heavier precipitation may lead to extreme events such as floods and droughts (Andreadis and Lettenmaier, 2006). Under future climate conditions, the risk of water problems may change and even increase due to variations in seasonal patterns and increased numbers of extreme events.

In areas dominated by snow, seasonal variations in water resources due to climate change become more apparent (Barnett et al., 2005). A warmer world will mean less snowfall in winter and earlier snow melting in spring, shifting much surface runoff to earlier seasons (Mote et al., 2005; Dettinger et al., 2004). Adam et al. (2009) showed that decreased snowpack produces decreases in warm-season runoff in many mid- to high- latitude areas according to their global-scale investigation. The magnitude of the climate change impact depends on the characteristics of the river basin (e.g. Nijssen et al., 2001), and thus there have been many regionalized climate change impact study so far.

Water Resources Condition in Tokyo

Future water supply conditions, especially for fresh water, are difficult to assess not only because of uncertain changes in climate condition but also because of rapid and uncertain changes in society (Vorosmarty et al., 2000). The population and its water use mainly determine domestic and industrial water demand. As the urban population increases, fresh water must be drawn increasingly from distant watersheds as local surface and groundwater sources cease to meet water demand for water or become depleted or polluted. Obtaining additional water resources invariably requires time to prepare required equipments and facilities, and rapidly changing climatic and environmental conditions demand that urban and national water supply conditions be monitored regularly and comprehensively.

Heavily populated Tokyo Metropolitan should not be an exception. Despite Japan's abundant average annual precipitation of 1,690 mm/year (MLIT, 2007), which is twice the global average of 807 mm/year, the water supply's seasonal nature and Japan's high population density prevent the water supply from being sustainable. Over 70% of rain falls in Japan happens from May to September, and the population density of Japan is 338person/km^2. Thus, water allocation in Japan is only about 3,230m^3/person/year, which is half of the world average of 8,559m^3/person/year (UNESCO-IHP, 2002). Given Tokyo's population density of 13,416person/km^2, the already critical nature of the area's water resources becomes apparent.

The main objective of this study is to assess the possible climate change impact on the Tone River basin using the output of a super-high-resolution atmospheric model having 20-km spatial resolution and 1-hr time resolution (hereafter AGCM20). Tone River is the main water source to the metropolitan Tokyo, Japan, and upstream of the basin is in snow-dominated regions. Details on the atmospheric model, AGCM20 are given in the next section.

Methodology

The climate change impact on the Tone River basin water resource should be viewed as a complex interaction between the natural system (e.g. climate, hydrology, etc) and the social system (e.g. dams, reservoirs, reservoir operation policies, etc) as well. To simulate these linkages and to investigate any possible hydrologic impacts on the Tone River basin (upper basin of Kurihashi gauging station, having 8772 km^2 of basin area), a distributed hydrologic model was composed to simulate the response of the climate/ hydrology/ water resources system. Details on the hydrologic modeling and simulation are given in section 4.

Fig. 1 shows the concept of the hydrologic impact study on the Tone River basin. There are two types of data sets for each observation and simulation output, precipitation and river discharge data. For precipitation data, observed data set is from the AMeDAS (Automated Measurement Data Acquisition System) of the JMA, and the AGCM20 provides two terms of simulation output for present and future climate scenarios. The other data set is river discharge data. At the Tone River basin, it is able to accept fairly long terms of observed river discharge data for each sub-basin. This observed river discharge data can provides two types of usage; hydrologic model calibration and evaluation of simulated river discharge using the AGCM20 output data. Even though the main object of the hydrologic impact study is to check and evaluate any changes in the simulated river discharge

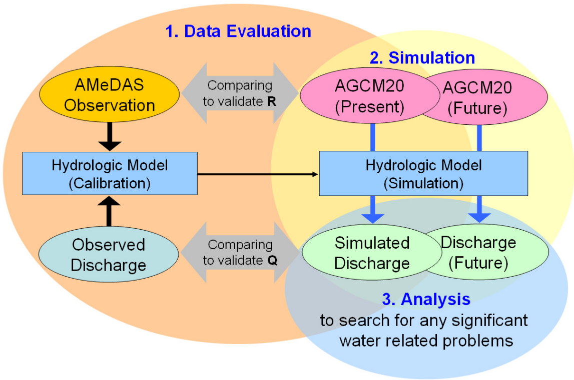

Fig.1 Research concept of the Tone River basin hydrologic impact analysis

with the AGCM20 output data, it is essential to evaluate the AGCM20 output from various aspects to understand the confidence level of the AGCM20 output data.

Thus, data evaluation was fulfilled in two aspects in this study. As shown in "1.Data Evaluation" part in Fig. 1, firstly, AGCM20 precipitation output for present (1979~2003, controlled simulation) was evaluated through a comparison with AMeDAS observation over the Japan Island. And the simulated discharge was also evaluated using the observed river discharge data of each sub-basin in the Tone River basin. Here, the simulated discharges are converted river discharge information using the AGCM20 output data through the distributed hydrologic model.

After the characteristics of the AGCM20 output data was comprehensively investigated, the AGCM20 output for the present and future climate scenarios were translated into the river discharge information using a distributed hydrologic model ("2.Simulation" part of Fig. 1), and the simulated river discharge for the present and future climate was analyzed ("3.Analysis" part of Fig. 1). There are seven dam reservoirs controlling water resource in the Tone River basin, and every reservoir was also modeled to simulate its effects on the water resources management in the basin.

It should be noted that hydrologic impact on the subject basin was mainly evaluated on the water resource management aspect in this study. Changes in hydrologic extremes, such as floods and droughts, are also one of the biggest concerns under the uncertain future climate condition. However, it is not included in this paper. Further analysis is under going to consider proper analysis on the possible changes in hydrologic extremes. Further information on the ongoing research and future research direction are given in the conclusion section.

Organization of this paper is as follow. Section 2 illustrates details on the atmospheric model, AGCM20 providing the future climate information for the hydrologic impact analysis. In section 3, the AGCM20 output data was evaluated with the observed precipitation data of Japan to understand the atmospheric model performance. Section 4 illustrates the distributed hydrologic model composition and calibration procedure on the subject basin. In this section, the simulated river discharge data was once again evaluated by using the observed river discharge data. Section 5 is focusing on climate change impacts assessment on water resources system of the basin using atmospheric data (precipitation and evapo-transpiration) and river discharge data. Finally, section 6 discusses on the analysis results and concludes the paper.

2. Super-High-Resolution Atmospheric Model, AGCM20

Scale Issues in GCMs

Climate condition projections use numerical models to simulate global atmospheric and oceanic circulation. The rapid evolution of these general circulation models (GCMs) in the last three decades was enabled by increased in computer capacity and a better understanding of natural phenomena correspondingly improving model complexity, e.g., spatial resolution in model operation. Climate models used in the First Assessment Reports (AR1) of the Intergovernmental Panel on Climate Change (IPCC, 1990) were run at a coarse resolution using a 500 km × 500 km grid for the most detailed horizontal resolution. Models in Assessment Report 4 (AR4; IPCC, 2007a) were run at a 100 km × 100 km grid in the most detailed resolution.

Despite such improvements, the GCM spatial operating scale remains hydrologically coarse, and GCM output averaged for each grid cell makes it difficult to use GCM output as it is, in regionalized water resource problems. Expecting sophisticated terrain effects on hydrologic variables, such as precipitation and evapo-transpiration, from such data is not always reasonable, either. To bridge the spatial resolution gap between GCMs and hydrologic use, hydrologists often physically or stochastically downscale GCM output.

AGCM20

In 2007, Japan's Ministry of Education, Culture, Sports, Science, and Technology (MEXT) launched the Innovative Program of Climate Change Projection for the 21st Century (Kakushin21), and has developed AGCM20, a very-high- resolution atmospheric model having 20-km spatial and 1-hour temporal resolution. Due to the spatial scale of frontal rain bands and the difficulty of simulating physical tropical cyclone behavior using conventional GCMs, a high-spatial-resolution model was required to simulate extreme precipitation more accurately and to project trends based on climate change. After several test simulations, AGCM20 showed advantages in simulating orographic rainfall and frontal rain bands (Mizuta et al., 2006; Kitoh and Kusunoki, 2007). The resulting model conducts simulation using triangular truncation at wave number 959 with a linear Gaussian grid (TL959) in the horizontal based on 1920 × 960 grid cells about 20 km in size and 60 levels in the vertical. Thanks to this fine spatial resolution, AGCM20 has the advantages of avoiding conventional problems on a spatial scale, not requiring further regional downscaling using a regional climate model or statistical downscaling.

AGCM20 uses the HadISST1 dataset (Rayner et al., 2003) as observed monthly mean climatologic sea surface temperature (SST) for a boundary condition of controlled simulation. HadISST1 provides global sea ice and sea surface temperature (GISST) datasets from 1871 uniquely combining monthly, globally complete fields of SST and sea ice concentration on a 1° latitude × 1° longitude grid. SST projected for simulation was estimated from the ensemble mean of GCM simulation output under the A1B emission scenario (Nakicenovic et al., 2000) from the model output of the Coupled Model Intercomparison Project Phase 3 (CMIP3). According to the A1B scenario of the Special Report on Emissions Scenarios (SRES), IPCC, the global average temperature is expected to increase 2.5°C and the CO_2 concentration to become 720ppm by 2100. Under these conditions, the daily mean temperature average for Japan will increase up to +4.4°C by the end of this century. The ensemble mean of SST for AGCM20 projection simulation was additionally composed with an annual variation of the current HadISST1 SST to make the estimation more realistic. Refer to Mizuta et al. (2006) and Kitoh and Kusunoki (2007) for details on AGCM20 and Kusunoki and Mizuta (2008) for simulation environment details.

Hydrologic data from the AGCM20 are mainly rainfall, snowfall, evaporation and transpiration values that are for the distributed hydrologic model input data for long-term simulations. The model provides present (1979 - 2003) and future (2075 - 2099) climate scenarios, and these two data sets were analyzed to investigate whether there will be any considerable changes in water resource.

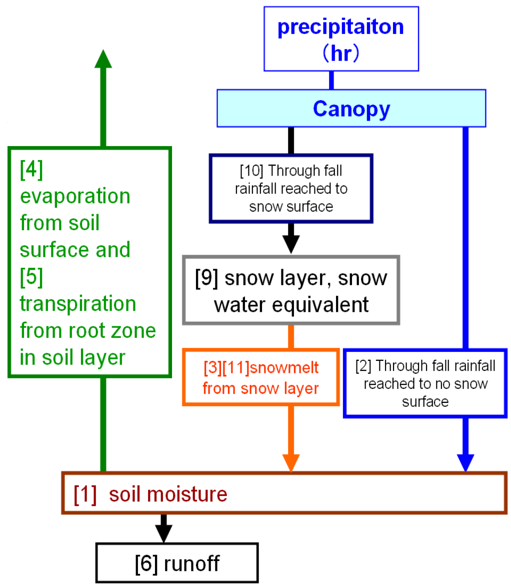

Fig.2 Structure of hydrologic output data from AGCM20

As shown in Fig.2, each variable are correlated each other upon the soil layer. The values adopted in this study are four variables that come in/out soil layer; (1) through rainfall to soil (PRCSN), (2) snowmelt to soil (SN2SL), (3) evaporation from soil (EVPSL) and (4) transpiration from soil root zone (TRNSL), which are all provided in daily resolution. Note that the snowmelt data (not snowfall data) was utilized in this study. This variable let the hydrologic model avoid snowfall-snowmelt modeling. Precipitation from the atmosphere (PRECIPI) is available in hourly resolution, and this data has utilized for downscaling of the daily PRCSN data into hourly data and feed into the hydrologic model simulations.

3. AGCM20 Output Evaluation using AMeDAS Observation

AMeDAS Observation

Automated Meteorological Data Acquisition System (AMeDAS) is a high-resolution surface observation network developed by JMA for gathering regional weather data and verifying forecast performance. Since the first operation on 1st November 1974, the system consists of more than 1,300 stations with automatic equipment to observe precipitation amounts (17 km of average interval throughout Japan) as shown in Fig 3. Among those, there are about 850 stations (21 km of average interval) to observe air temperature, wind direction and speed, atmospheric pressure, and humidity as well (JMA webpage: http://www.jma.go.jp/jma/kishou/know/amedas/kaisetsu.html).

In this study, before the AGCM20 output data was applied to investigate hydrologic impact on the Tone River basin, the 25 years of controlled simulation output (1979 ~ 2003) of AGMC20 was evaluated to understand the performance level of the atmospheric model. Because the same duration of the fine observations for precipitation are available from the AMeDAS, it is able to evaluate the precipitation output of the AGCM20 by comparing with the AMeDAS observations.

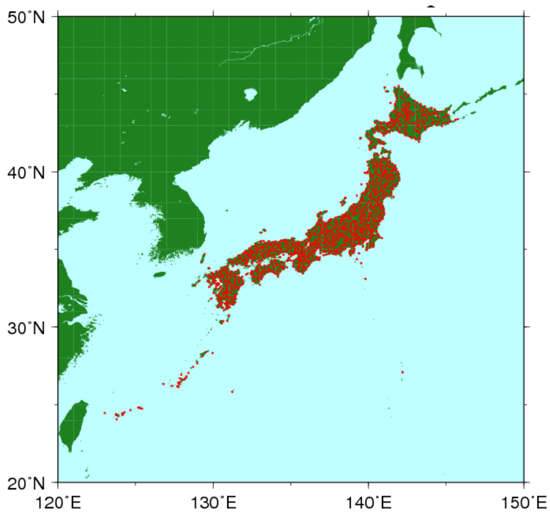

Fig. 3 AMeDAS observation points throughout Japan composing more than 1,300 stations

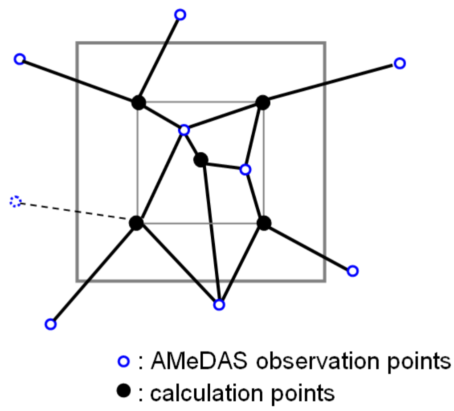

Fig. 4 Conversion procedure of the gauge observed AMeDAS precipitation data into 20-km spatially averaged values.

First of all, the point gauged AMeDAS precipitation data should be converted into spatial averaged values that is equivalent type of the AGCM20 output. As it is mentioned in the previous section, the AGCM20 output data has 20-km spatially averaged data, and the AMeDAS observation data was converted as the following procedures.

1) Define the center of the 20km resolution grid of the AGCM20 output, and also define four other points that apart ±5km from the center of the grid (black dots in Fig. 4).
2) Estimate rainfall amount of each point from the nearest three AMeDAS stations (blue circles in Fig. 4) using the inverse distance method, at every time step (1 hr).

3) Get an arithmetic mean of the five points (the black dots) in the grid box at every time step
4) If there is missing data at a certain station, next nearest station value is adopted (as dashed line in Fig. 4).
5) If the nearest one is over 30km apart, the value of the point is excluded.
6) If all the five points' values are not available, the value of the grid is marked as "missing".

After all conversion procedure, it was known that there were only 409 times of "missing" among hourly time step calculations of all over Japan from the Jan. 1st 1979 to Dec. 31st 2003 (over 280 million times of calculations), and thus it was negligible enough to ignore the missing data.

Evaluation of AGCM20 Output

Annual mean precipitation was calculated using the converted AMeDAS observation data and the AGCM20 output data as well (see Fig. 5a and 5b). According to the AMeDAS observation, annual mean precipitation during 1979 and 2003 is 1684.3 mm, and the AGCM20 output data shows 1695.2 mm of annual mean for the same duration, which can be regarded as a very good consistency. When annual mean precipitation was checked for three separate regions (Fig. 5a), values also show very good match as;

Region 1: from Kyushu to Kansai area
AMeDAS: 1985.8mm; AGCM20: 1959.1mm
Region 2: from Kantou to Tohoku area
AMeDAS: 1753.3mm; AGCM20: 1797.3mm
Region 3: Hokkaido area
AMeDAS: 1128.9mm; AGCM20: 1129.6mm

Spatial distribution pattern of the annual mean precipitation also shows considerably good matches between the AGCM20 output and the AMeDAS observation, showing 0.78 of correlation coefficient. However, spatial distribution of annual precipitation from the AGCM20 shows little bit blurring spatial distribution pattern comparing to the AMeDAS observation one (see region A and B of Fig. 5b).

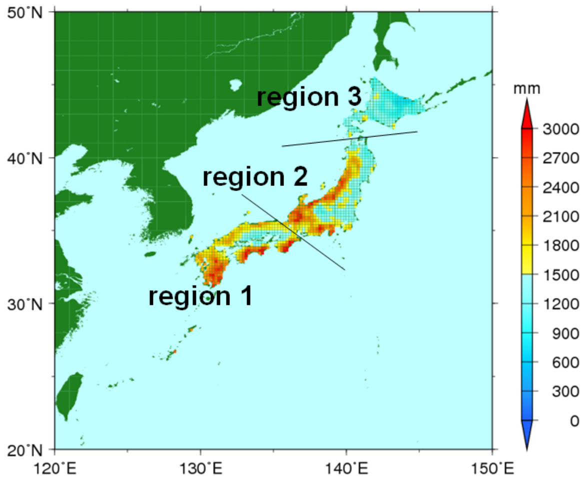

Fig. 5a Annual mean precipitation data from the AMeDAS observation of 1979~2003, showing 1684.3 mm of annual mean precipitation.

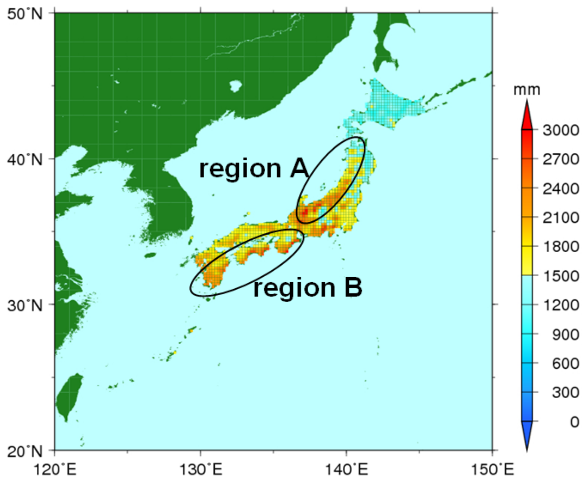

Fig. 5b Annual mean precipitation map from the AGCM20 output data of 1979~2003, showing 1695.2 mm of annual mean precipitation.

Region A is Hokuriku-Chihou, which means "northern-land region" in Japanese. It is in mountainous area ranging several hundred kilometers from the southwest to the northwest, and this topographic characteristic provides high amount of winter snowfall in this region (Akiyama, 1981, Iwamoto et al., 2008). As also shown in Fig. 5b, high portion of annual precipitation of this area was successfully simulated, and it mostly happens in winter season with huge amount of snowfalls. Although the AGCM20 successfully simulates this typical characteristics of snowfall patterns, clear distinction of spatial variation shown in the

AMeDAS observation was somewhat smoothen in the AGCM20 output (see Fig. 6a and 6b).

This smoothing effect of spatial distribution of the precipitation pattern was also found in the southern area of Japan Island (see the region B in Fig. 5b). The southern area of Japan Island is usually the subject of typhoon rainfalls in the late summer season, August and September, of Japan. Averagely, 27 typhoons are formed every year in the Northeastern Pacific Ocean, of which around 11 typhoons approach the Japanese Island and around 3 actually strike the island. The effect of typhoon induced heavy rainfalls in the southern area of Kyushu and Shikoku area (region B area in the Fig. 5a) is well presented in the observed annual precipitation (see Fig. 6c). However, the AGCM20 output for the present shows smoothen rainfall concentration in the summer season as comparably shown in Fig. 6c and 6d with the monthly mean precipitation of August.

One main reason of this smoothen effects of spatial pattern of the AGCM20 precipitation output is related to topographic data used in the atmospheric model. The AGCM20 runs on 20-km of spatial resolution and the topographic data in the model also have 20-km resolution. This 20-km resolution topographic data has rather flattened shape after the detailed topographic information is spatially averaged within the 20-km grid. Although there are several physical parameterization schemes

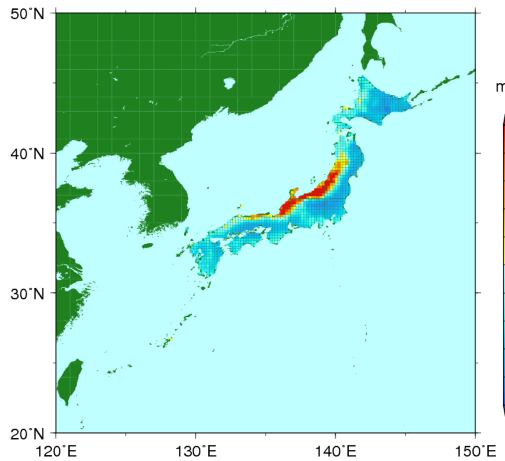

Fig. 6a Monthly mean precipitation for January from the AMeDAS observation (1979~2003)

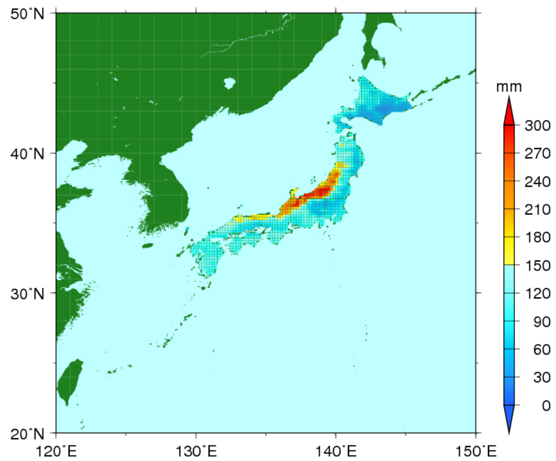

Fig. 6b Monthly mean precipitation for January from the AGCM20 output for 1979~2003

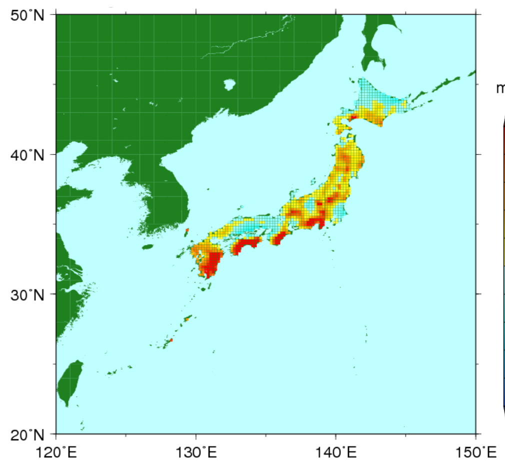

Fig. 6c Monthly mean precipitation for August from the AMeDAS observation (1979~2003)

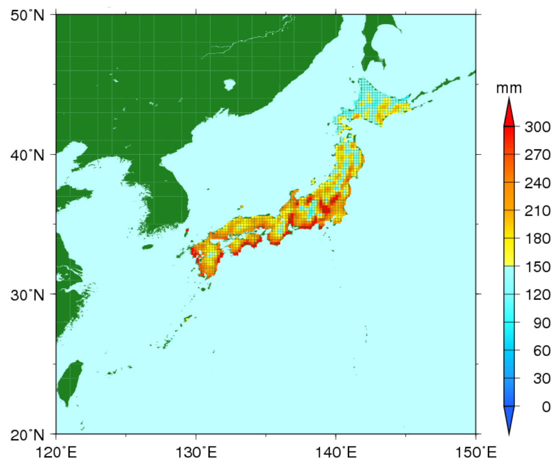

Fig. 6d Monthly mean precipitation for August from the AGCM20 output for 1979~2003

are applied in the AGCM20 (Mizuta et al., 2006) to properly consider the influence of flattened sub-grid scale topographic data, the atmospheric model performances could not be perfect as shown in Fig. 5 and 6. However, this level of model performance is very encouraging results when considers the model is the global scale atmospheric model.

Correlation coefficients of each monthly mean precipitation are 0.89 for Jan., 0.88 for Feb., 0.85 for Mar., 0.88 for Apr., 0.85 for May, 0.88 for Jun., 0.74 for Jul., 0.36 for Aug., 0.64 for Sep., 0.55 for Oct., 0.84 for Nov., and 0.88 for Dec., which shows higher consistency in winter season and lower consistency in summer season.

4. Distributed Hydrologic Model and Hydrologic Evaluation

Tone River Basin

The 16,840 km^2 Tone River basin northeast of Tokyo, Japan, is the site of a 322 km river emptying into the Pacific Ocean. The basin population is about 12 million, and the basin itself covers half of Japan's capital, which has a population of about 24 million. About half of the basin is covered by forest (45.5%) and 30% of the land is used for farming (paddy field: 18.2%, cropland: 11.2%). Residential districts account for 6.4% of land use and city use for 3.7%.

Compare to Japan's rather high amount of annual precipitation averages 1,690 mm/yr, the Tone River basin has smaller amount with 1,380 mm/yr (MLIT, 2007). Tokyo's high population density has severely compromised regional water resources. According to the Tokyo Metropolitan Government, Tokyo's population was 12.36 million (10% of the nation's population) in September 2003. With an area of 2,187 km^2, the overall population density is 565 persons/km^2, and even denser in the city's 23 central wards. This means that 8.34 million people occupied 621 km^2 as of September 2003, making a population density of 13,416-persons/km^2.

Up to the 1950s, Tokyo depended on the Tama River basin for its water supply, but its dependence on the Tone River basin increased, as the city grew larger and denser. Today, 75% of all water and 88% of the Tokyo metropolitan domestic water supply come from the Tone River and its tributaries. Seven dams control the upper Tone River and water produced from them – 6.5 million m^3/day – is sent to Tokyo through the Musashi Canal in the river's middle reaches. Study area is the 8,772 km^2 northern basin (see Fig. 7), which covers the starting point of the Musashi Canal.

Distributed Hydrologic Model

To investigate the hydrologic impacts of climate change on the Tone River basin, a distributed hydrologic model was composed with an object-oriented hydrologic modeling system, OHyMoS (Takasao et al. 1996; Ichikawa et al. 2000). OHyMoS, which has been developed in Kyoto University, Japan, enables user to easily build any complex hydrologic system by connecting a number of element

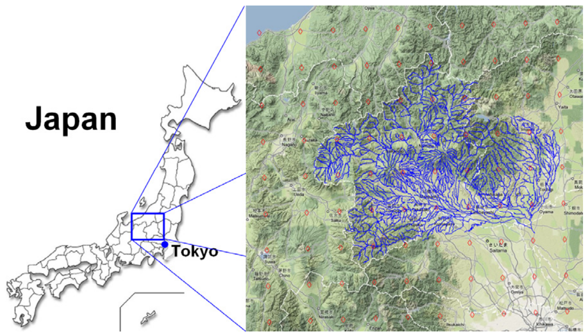

Fig. 7 Location of the subject basin, upper part of the Tone River basin (Kurihashi; 8,772 km^2)

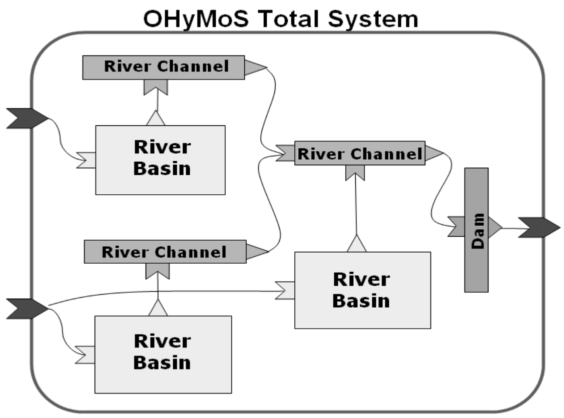

Fig. 8 Example of OHyMoS composed by several elements for rainfall-runoff simulation, channel routing simulation, and dam reservoir-operating simulation.

models (see Fig. 8), such as catchment rainfall-runoff simulation model, channel routing model, dam reservoir operating simulation model. One of the main elements for the rainfall-runoff simulation is kinematic wave model of Takasao and Shiiba (1988) and Tachikawa et al. (2004). The kinematic wave model utilized in the OHyMoS is for overland flow and channel routing simulation as well. Dam element model is also included in the system to simulate dam reservoir operation with decision-making processes of the dam operator.

Kinematic wave modeling not only for channel routing or overland flow but also for subsurface flow has been widely used in distributed flow computations because of its simplicity and computational efficiency (see Singh, 2001; Reed et al., 2004). Takasao and Shiiba (1988) analyzed the interaction between surface and subsurface flow on convergent/ divergent slopes using kinematic wave equations with a stage–discharge relationship considering surface–subsurface flow generation. Tachikawa et al. (2004) extended the concept to include unsaturated subsurface flow as well.

The continuity equation of the kinematic wave model for a slope segment is written as

$$\frac{\partial h}{\partial t}+\frac{\partial q}{\partial x}=r(t)\cos\theta \qquad (1)$$

where h is water depth and q is discharge per unit width; t and x are time and distance along water flow, respectively, and $r(t)$ is the rainfall amount on a node at time t. To define the relationship between h and q, a stage–discharge relationship incorporating the saturated and unsaturated subsurface flows as well as the surface flow of Tachikawa et al. (2004) is adopted.

When water depth h is less than the depth of the capillary pore layer d_c ($0 \le h < d_c$), flow is described by Darcy's law with a degree of saturation $(h/d_c)^\beta$ and saturated velocity v_c ($= k_{ci}$). Here, β is the degree of saturation ratio, k_c is saturated hydraulic conductivity in the capillary layer, and i is the slope gradient. If h increases ($d_c \le h < d_s$), the velocity of flow from the non-capillary pore layer is expressed as v_a ($= k_{ai}$), where k_a is the saturated hydraulic conductivity in the non-capillary layer. When the water depth is greater than that of the soil layer ($d_s \le h$), overland flow is added, using Manning's resistance law. The equations relating discharge per unit width q to water depth h are formulated as Equation 2:

$$q(h)=\begin{cases} v_c d_c (h/d_c)^\beta, & (0\le h<d_c) \\ v_c d_c + v_a(h-d_c), & (d_c \le h < d_s) \\ v_c d_c + v_a(h-d_c)+\alpha(h-d_s)^m, & (d_s \le h) \end{cases} \qquad (2)$$

where $\alpha = (i)^{1/2}/n$, $m = 5/3$, and n is Manning's roughness coefficient. Model parameters in the stage–discharge relationship are d_c, d_s, k_c, k_s and n. Each slope segment has its own stage–discharge relationship determined by topography, land use, and soil type.

The developed hydrologic model was calibrated manually using the observed data of rainfall and daily inflow into each sub-basin in the Tone River basin using the summer season (July ~ October) data of five years (1994 ~ 1998). The rainfall data was prepared using the AMeDAS data, and a monthly uniform evaporation amount was estimated from the observed data. There are five parameters to be optimized in the model and they are roughness coefficient n, soil depths d_s, d_c, hydraulic conductivities k_a and k_c, which determine the velocity of saturated and unsaturated subsurface flow, respectively.

Dam Reservoir Operation Modeling

There are 7 dam reservoirs to control water resource in the basin, and every reservoir has an optimized operation rule to maximize its own function. This dam reservoir operation function is also considered in the developed hydrologic model. To understand the dam reservoir operating pattern, observed daily water level, inflow and outflow of ten years (1994~2003) were prepared from the dam database of the Ministry of Land, Infrastructure and Transport (MLIT), Japan. Fig. 9 shows one example of the observation at Yagisawa dam, which is located

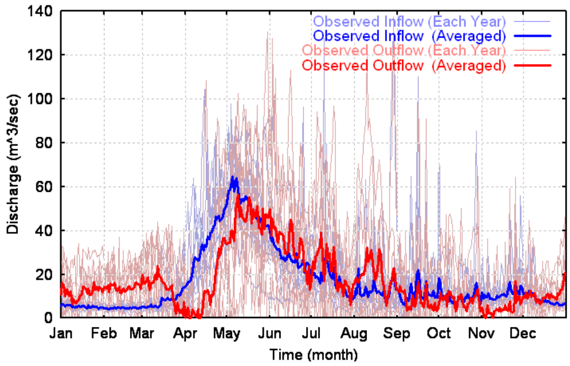

Fig. 9a Observed inflow (blue) and outflow (red) of each year (1994~2003) and day-by-day averaged values of inflow (bold blue) and outflow (bold red).

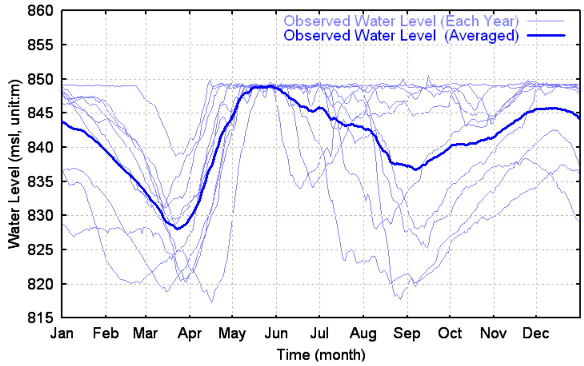

Fig. 9b Observed water level of each year (1994~2003) and day-by-day averaged values of water level (bold blue).

at the most upper part of the Tone River basin (167.6 km^2). In the figures, day-by-day averaged values (bold blue and red lines) show the annual trends of the inflow and outflow.

In the case of the Yagisawa dam basin, main water resource into the dam reservoir is snowmelt inflows from April to May. The reservoir prepares some storage space in the early spring for this snowmelt inflow, and provides some amount of water to the downstream. The water level reaches to the normal high water line (NHWL; 850.0m) in the middle of May and maintains this level until July (concretely, from 21st May to 1st August). Another big release from the dam is in August and September to prepare flood inflow. During this release, water level should be higher than 830.0m until 26th August, 827.8m until 1st September, and 816.8m until 25th September. After the end of September, the dam holds inflow little by little and water level rises to the normal high water line.

The observed water level (Fig. 9b) generally follows the prescribed regulations, but there are also many times of irregular operations. Because the amounts and arrival times of dam inflows will be different every year and it is hard to expect, a certain level of irregular operation by operator's intuition might be unavoidable. However, it is not easy to consider this kind of irregularity into the operation model, and if the dam model works on the perfect inflow information, simulation would not be realistic.

In this study, a simple but very effective dam reservoir operation model was adopted, which is mainly for long-term reservoir operations focusing on water resources management. The main rules in this reservoir operation is to reproduce the given dam outflow, which is the averaged historical outflow as shown in Fig. 9b with the bold blue line. This 10-year of average outflow becomes the standard outflow in the reservoir operation model of this study. The regulation rules to reproduce the given outflow are as follow: (1) if water level is between the minimum water line and the surcharge water line, store the inflow and release the target outflow, (2) if water level reaches to the surcharge water line, release the target outflow and inflow as well, (3) if water level is lower than the minimum water line, outflow is 0.0 m^3/s until the water level is getting higher than the minimum water line, and (4) the relationship of the water level and the reservoir volume is following the H-V relationship of the subject dam. In the previous study (Kim et al., 2009) testing this dam reservoir operating simulation showed effective application of this method into the study to check the long-term water resources management.

Hydrologic Evaluation of AGCM20 data using Observed River Discharge Data

The rapid evolution of the general circulation models (GCMs) in the last three decades allows us to expect reasonable hydrologic dataset from the model output. However, it is still very necessary to evaluate the model output to properly utilize it into a designed purpose, such as assessing climate change impact on hydrologic cycle in the future. Since the ultimate goal of the GCM output usage in the hydrologic field is analyzing water related problems, e.g. flood and water resources condition, it would be more appropriate if the GCM output is evaluated from a hydrologic viewpoint, namely basin scale and river discharge based standpoint. Furthermore, before using any hydrological model to simulate possible future conditions, one has to be convinced that the simulation result corresponding to the baseline period has similar flow characteristics to the corresponding historical data (Dibike and Coulibaly, 2007).

Reliance on the GCM model output, especially on the projection simulation output can be achieved through an evaluation of the model output reproducibility for the current climate condition. Here, the current climate condition output should provide similar river flow pattern when it is converted into river discharge data through a hydrologic model. The distributed hydrologic model on the Tone River basin composed for various basin scales ranging from 60 km^2 to 8,772 km^2, and each basin provides more than 10 years (maximum 25 years) of observed discharge data, and averaged annual discharge pattern of the observation provides a guide line to evaluate the simulated discharge pattern from the hydrologic model simulation using the AGCM20 output.

As shown in Fig. 10, there are various types of discrepancy between the simulations outputs and the observations, however, this discrepancy diminished when the catchment size is larger than 5,000 km^2. In the case of the Yagisawa Dam basin having 167 km^2 of basin area, the runoff simulation using the AGCM20 output data provides underestimated discharge amount comparing to the observation, while it shows similar pattern of the annual discharge. The simulated discharge of the Murakami catchment also shows similar annual discharge pattern, however total amount of the annual runoff shows almost doubled volume to the observed one. The Sonohara basin shows failed simulation results both for annual discharge pattern and total amount.

As covering basin area is getting larger, the simulated annual runoff pattern shows improved performance showing good matches to the observations, as shown in the right side of Fig. 10. While the simulation results still show slight overestimation, the annual discharge pattern provides very good match to the observation. Considering the AGCM20 output has 20-km spatial resolution, which is equivalent to 400 km^2 of area; it is able to understand that the runoff simulation gives stable results when the analyzing data is wider than 10 grids.

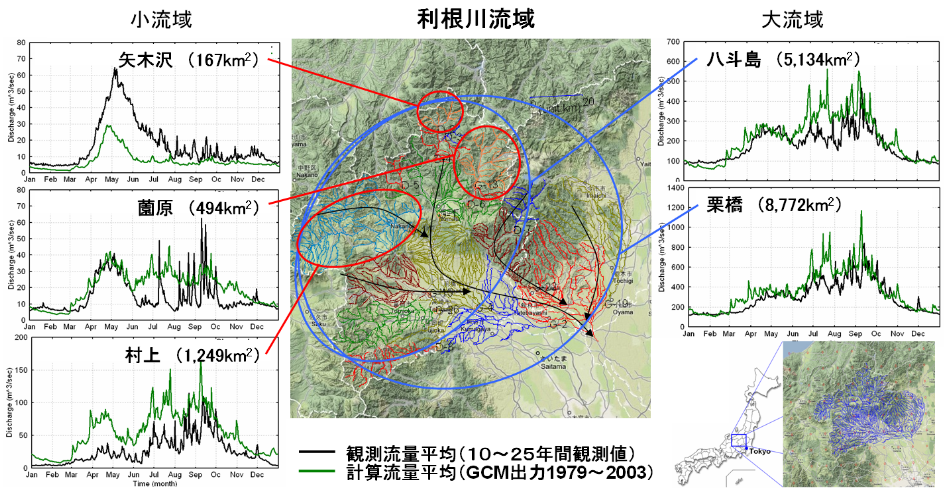

Fig. 10 Annually averaged observed discharge (black line) and simulated discharge (green line). There are various types of discrepancy of the simulation output to the observation of the small size catchments, however, this discrepancy diminished when the catchment size is over 5,000 km^2.

Scale Dependant Reproducibility

To confirm that the AGCM20 output has scaly different reproducibility as discussed in the previous section, one more brief evaluation on the AGCM20 precipitation output was carried out. As shown in Fig. 11, spatially averaged values from variant covering areas, such as 1×1 gird, 2×2 girds, 3×3 girds, etc., were calculated from both AMeDAS observation data and the AGCM20 output data.

Using the spatially averaged values for each covering area, 25 years of precipitation data was averaged into day-by-day and it produces one set of daily time series consisting of 365 values. And then, the daily precipitation data was again averaged for every 5 days, and 365 days of daily time series converted into 5-days time series. After the data set both for AMeDAS observation and AGCM20 output were prepared, these two time series were examined.

First of all, correlation coefficient was calculated for all over Japan Island as shown in Fig. 12a. Higher correlation value means better match of AGCM20 output precipitation data with the observed one, which stands for nice performance of the atmospheric model. As shown in Fig. 12a, when the correlation coefficient was check grid by grid (1×1 gird covering area), the correlation coefficient shows variant values ranging from 0.2 to 0.9. However, this variant performance level was diminished when the analyzing area is more than 3×3 girds area.

To understand the bias amount of the two data sets, root mean square (RMS) of the AGCM20 output was calculated to the AMeDAS observation values. As it is shown in Fig. 12b, the variant amount of RMS values become stabilize when the analyzing area is wider than 3×3 girds area, as it is same to the case of the correlation coefficient checking.

Lastly, tangent of the AGCM20 output time series to the observation was calculated and presented in Fig. 12c. According to these three values to understand the characteristics of the AGCM20 output, it was able to see that the AGCM20 output can be stably analyzed when the spatial scale is more than 3×3 girds area.

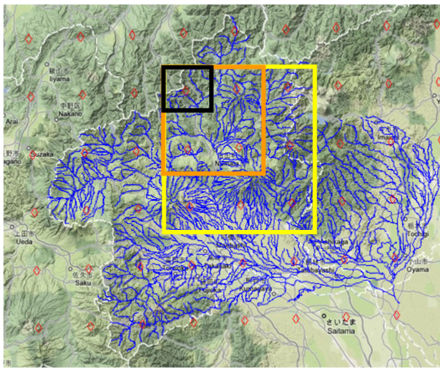

Fig. 11 Scale dependant reproducibility testing domain; 1×1, 2×2, 3×3 girds (example of the Tone River basin)

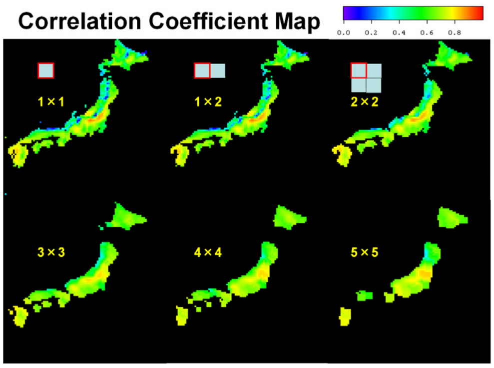

Fig. 12a Correlation coefficient of the two time series data set of AMedas and AGCM20 output

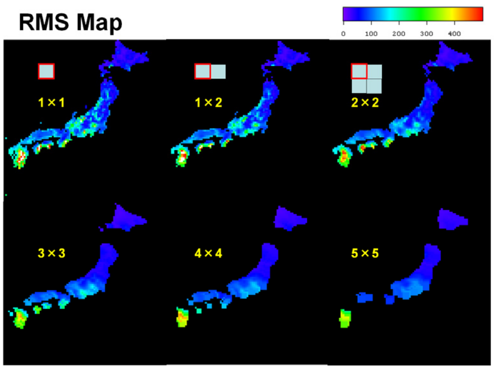

Fig. 12b Root mean square of the AGCM20 bias to the AMeDAS observation

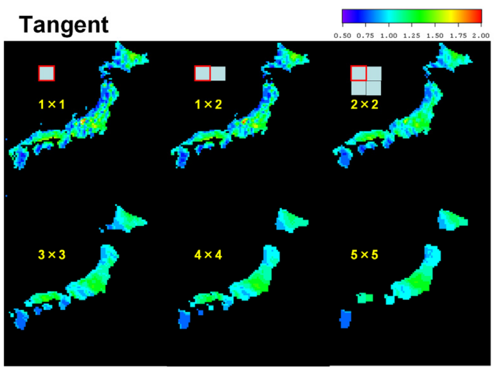

Fig. 12c Tangent of the AGCM20 values

5. Climate Change Impact on the Tone River Basin

Changes in Precipitation and Evapotranspiration

Basin averaged precipitation values on Tone River were calculated from the output of AGCM20. The basin averages is an arithmetic mean of 24 grids of AGCM20 that covers the Tone River basin. 25 years of present, (1979~2003) and future (2075~2099) climate scenarios from the AGCM20 output were analyzed in this study. The analyzed variables are PRCSN, SN2SL, EVPSL and TRNSL.

Fig.13a shows monthly variation of precipitation (PRCSL+SN2SL) that is estimated from the present term (from 1979 to 2003) and future term (from 2075 to 2099) in Tone River basin. It shows how the seasonal pattern is going to be changed in the future comparing to the present pattern. The most noticeable change is increase of precipitation amount in winter season. In the future term, there is noticeable increase of precipitation (besides snowmelt amount) in December, January and February. On the other hand, the precipitation in spring and summer season decrease in the future only except in the middle of summer, July. Overall, the seasonal variation of the present term is going to be diminished in the future.

Another noticeable change is decrease of snowmelt (SN2SL) amount in spring, especially in April and May. The decadal average of the annual snowmelt amount for the present term is 271.99 mm and for the future term is 168.41 mm, which shows around 38 % of decrease. These two main changes diminish the seasonal variance of the current precipitation pattern in the future.

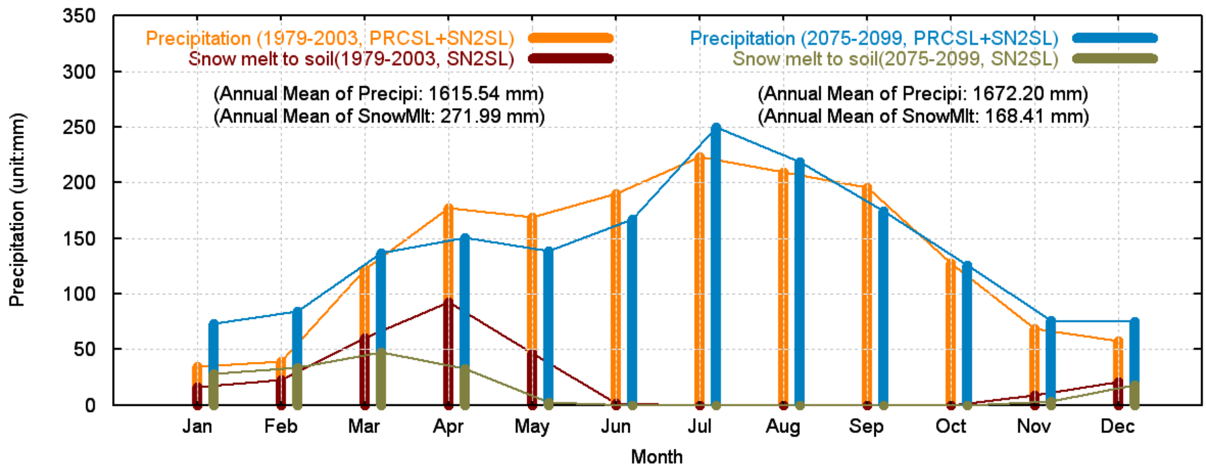

Fig. 13a Monthly precipitation pattern of the Tone River basin, and annual average for the present and future

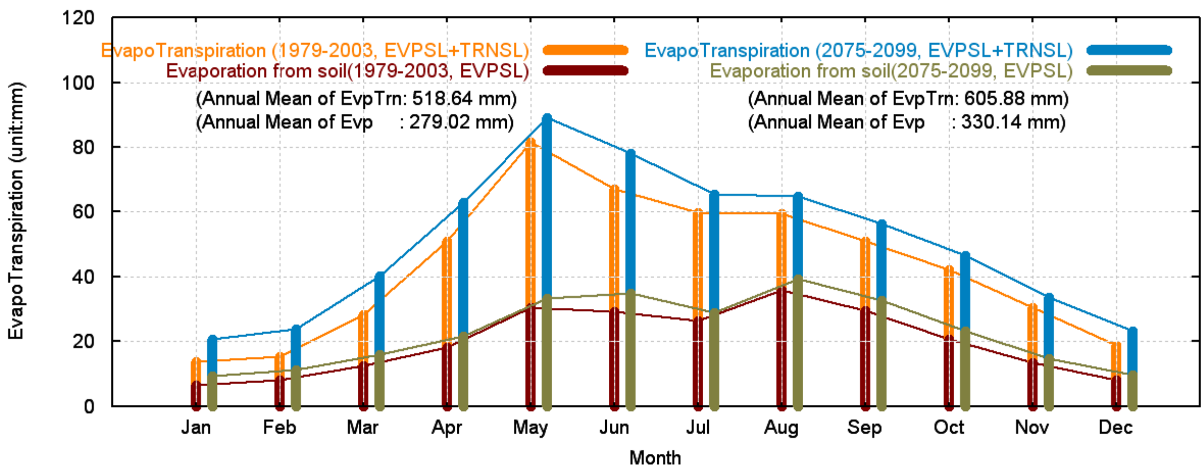

Fig. 13b Monthly evapo-transpiration pattern of the Tone River basin, and annual average for present and future

As annual precipitation amount is expected to be increased in the future, evaporation and transpiration amount is also to be increased in the next century. Fig.13b shows monthly variation of evaporation and transpiration (EVPSL+TRNSL) for the present and future terms. Annual evapo-transpiration of the present term is 518.64 mm and future term is 605.88 mm, showing 16.8 % of increase in the next century. Increase of the evaporation amount (51.12 mm of increase) is larger than the increase in the transpiration amount (36.12 mm of increase). Monthly pattern of evapo- transpiration of future has the same pattern to the present term with an increased amount.

The increase of precipitation and evapo-transpiration as well are the key evidence that proves considerable temperature increase in the future. Significant change in the snowmelt amount gives more concrete proof on the global warming situation. However, due to increased evapo-transpiration amount, according to the AGCM20 simulation output, net precipitation amount (PRCSL+ SN2SL-EVPSL-TRNSL) is to be decreased from 1096.90 mm to 1066.32 mm in the next century.

Takara et al. (2009) conducted detailed analysis on the Tone River basin, to determine potential changes in water resources using a drought indicator, the standardized precipitation index (SPI). According to their study, SPI for long term (12 months duration) showed more frequent wet conditions for the present and more frequent dry conditions for the future, which may relate to the decreased net-precipitation amounts of the future. Under future climate conditions, the risk of water problems may change and even increase due to variations in seasonal patterns and increased numbers of extreme events.

Considering dam reservoir operation

To investigate the hydrologic impacts of climate change on the Tone River basin, a distributed hydrologic model was composed using the OHyMoS. And future water resources condition was evaluated using this hydrologic system considering current reservoir operation rules, under an assumption that the current water usage pattern will be continued in the future.

One example of simulation results with dam reservoir operation using the given outflow regulations are presented in Fig. 14. Both simulation results for the present and the future are rather successfully following the designed outflow. Except several times of exceeding cases in April and shortage problem in summer season of the future, the day-by-day averaged outflow of the present (bold blue line) and future (bold red) are almost matched with the designed outflow (bold black).

The inflow in May becomes very low in the future comparing with the current inflow, and therefore the water volume (water level) will be significantly decreased (fell down) if there is big release as the current condition. If it is necessary to keep the current dam release pattern for some reason, such as downstream water demand and water intake in a certain season. However, reservoir water insufficiency in the summer season of the future should be carefully considered.

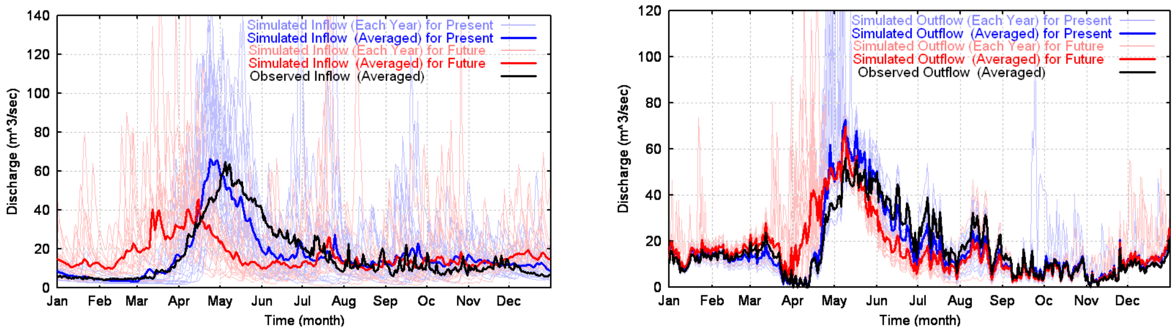

Fig. 14 Different dam inflow pattern of present and future (left), and regulated dam outflow to follow the given outflow conditions (right), example of Yagisawa Dam.

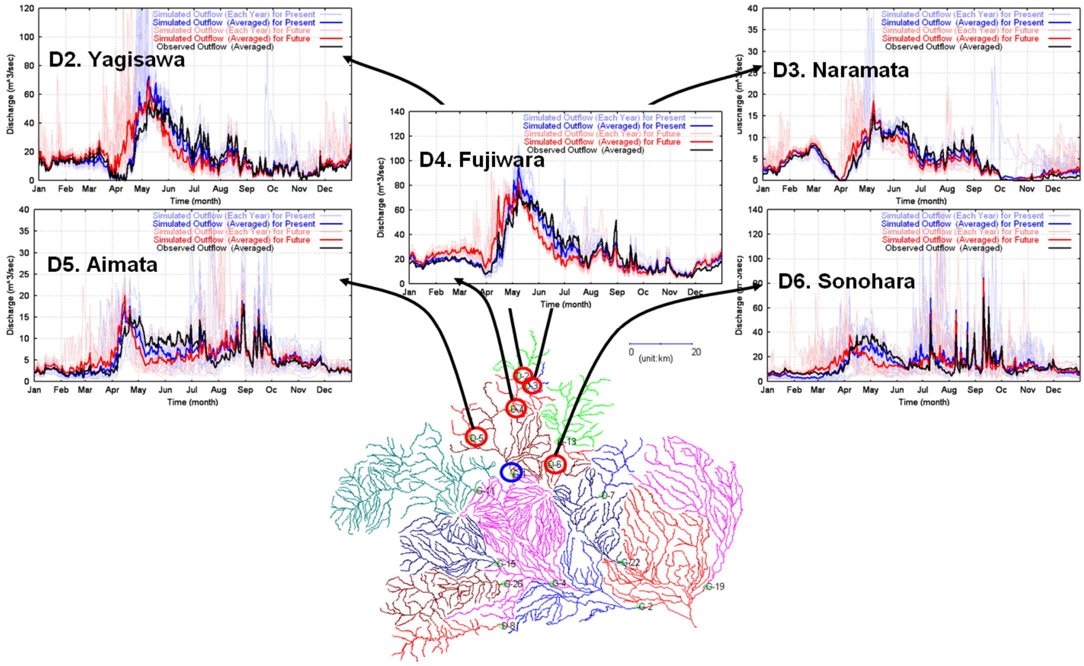

Fig. 15 Controlled outflows of five dam reservoirs in the upper Tone River basin. Reproducing current dam release pattern is able to realize the present dam release pattern even in the future. In this case, however, the water level regulations should be revised, and the shortage of the reservoir water in summer season should be carefully considered.

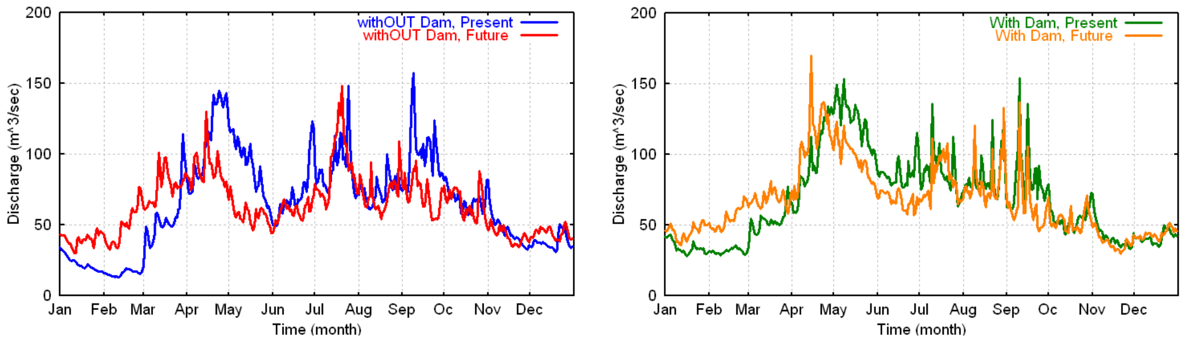

Fig. 16 Simulated annual discharge pattern of present and future without dam reservoir operations (left) and with the dam reservoir operations (right). It is able to see the changed flow pattern of future was regulated through the designed dam reservoir operation, and the future flow pattern got close to the present flow pattern (Yukatahara Outlet: 1677.5 km^2).

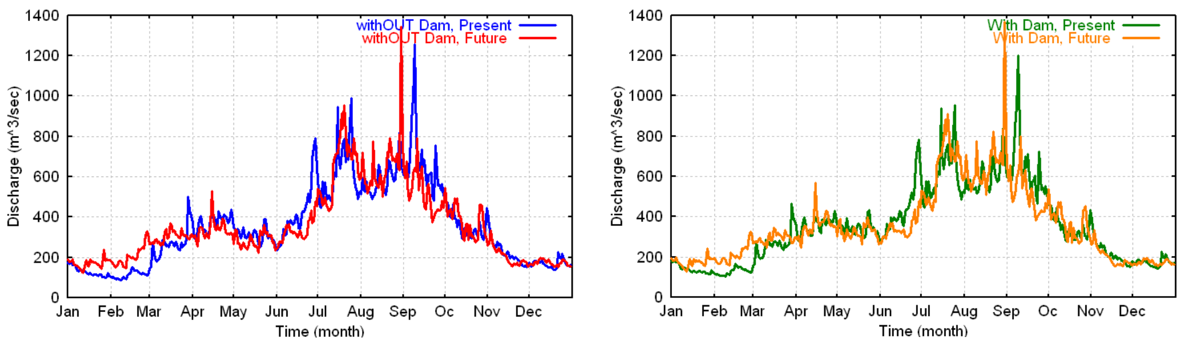

Fig. 17 Simulated annual discharge pattern of present and future without dam reservoir operations (left) and with the dam reservoir operations (right). The dam operation effect does not show enough to change the future flow pattern, because most of the dams are located in the upper part of the Tone River basin. Showing results are the annual discharge pattern at the Kurihashi Outlet (8772.2 km^2)

Changes in Steam Flows

With the same method to the Yagisawa Dam reservoir operation modeling, 6 other reservoirs' operation modeling was also carried out. The simulation results as shown in Fig. 15 present successful water release control for the most dam reservoirs. Even though the dam inflow seasonal pattern would be changed largely due to the shifted snowmelt season and amount, through the proper reservoir operation it is able to control the reservoir outflow same to the current outflow pattern. In other word, reproducing current dam release pattern is able to realize even in the future. In this case, however, the water level regulations should be revised, and the shortage of the reservoir water in summer season should be carefully considered.

The effect of the controlled dam outflow was also checked at the downstream of the dam reservoirs. First of all, the annual discharge pattern at the Yukatahara gauging station (blue circle point in Fig. 15) was evaluated and presented in Fig. 16. From the figure, it is able to see the changed flow pattern of future was regulated through the designed dam reservoir operation, and the future flow pattern got close to the present flow pattern at the Yukatahara station (1677.5 km^2). From the simulation result that does not consider dam reservoir operations, it was able to see that the annual runoff pattern at the Yukatahara will be changed in the future especially in spring season (February to May) mainly due to the shifted snowmelt season. This shifted snowmelt river flow, however, was able to be delayed and can be closed to the current runoff pattern as shown in the left hydrograph of Fig. 16. This means that the current water usage pattern can be sustained up to certain level even under the changed climate condition and hydrologic system in the future.

However, the controlled dam release effects was almost diminished and it is not able to see clear effects at the Kurihashi gauging station, which is the last output of the modeled basin in this study. Basin area of the Kurihashi Outlet is 8772.2 km^2, and snowfall is not a big portion of the annual precipitation in the southern part of the basin. Therefore, the shifted snowmelt season does not show up clearly at the Kurihashi outlet as shown in the left figure of Fig 17. Figure shows the simulated annual discharge pattern of present and future without dam reservoir operations (left) and with the dam reservoir operations (right). Because most of the dams are located in the upper part of the Tone River basin, the dam operation effect does not show enough to change the future flow pattern. From this study, it was able to see that the shifted snowmelt effect by the changed climate in the future may not big concern at the Kurishashi outlet.

Considering Uncertainties in the Analysis

It should be kept in mind that the hydrologic simulation of this study including dam reservoir operation was carried out with the output of the AGCM20, which was simulated following A1B scenario. This climate change scenario surely contains lots of uncertainty, and the hydrologic model simulation for the future also includes many uncertain factors.

Water usage pattern in the future would not be the same to the current one. Many social factors, such as population, agricultural and industrial conditions, and land usage type would be changed in the future. Because of these changed social factors in the future, desirable water demand would be different to the current one. To investigate climate change impact on the water resources more comprehensively, it is necessary to consider these kinds of possible social factors changes and reliable water demand scenarios in the subject basin.

At the same time, uncertainties induced from the model simulation following the climate change scenarios and the hydrologic modeling and simulation as well also carefully considered for a proper impact analysis. Without this kind of understanding on the model simulation conditions and the backgrounds, the impact analysis cannot provide persuadable information to decision makers and the publics as well. Further research under going is to include uncertainty analysis of the impact study.

6. Concluding Remarks

It is apparent that the risk of water problems may change and even increase due to variations in seasonal patterns and increased numbers of extreme events under future climate conditions. This paper shows comprehensive hydrologic impact analysis on the Tone River basin under climate change condition using the AGCM20 output and rainfall-runoff simulation through a distributed hydrologic model.

Tone River is the main water source to the metropolitan Tokyo, Japan, and upstream of the basin is in snow-dominated regions. The impact of climate change on the Tone River basin water resource should be viewed as a complex interaction between the natural system (e.g. climate, hydrology, etc) and the social system (e.g. dams, reservoirs, reservoir operation policies, etc) as well. To simulate these linkages and to investigate any possible hydrologic impacts on the Tone River basin (upper basin of Kurihashi gauging station, having 8772 km^2 of basin area), a distributed hydrologic model was composed to simulate the response of the climate/ hydrology/ water resources system.

Before the impact analysis of this study, AGCM20 output data evaluation was fulfilled in two aspects. Firstly, AGCM20 precipitation output for the present term (1979~2003, controlled simulation output) was evaluated with a comparison to the AMeDAS observation over the Japan Island. According to the AMeDAS observation, annual mean precipitation during 1979 and 2003 is 1684.3 mm, and the AGCM20 output data shows 1695.2 mm showing very good consistency. Annual mean of precipitation for three separate regions also show very good match. However, spatial distribution of annual precipitation from the AGCM20 shows little bit blurring pattern comparing to the AMeDAS observation one, which might be because of the specific topographic data in the AGCM20. 20-km resolution topographic data of AGCM20 has rather flattened topographic information while detailed topographic information is spatially averaged within the 20-km grid.

Secondly, the simulated discharges, which are converted river discharge information of the AGCM20 controlled simulation output data through the distributed hydrologic model, was also evaluated using the observed river discharge data of each sub-basin in the study area. Here, the current climate condition output should provide similar river flow pattern when it is converted into river discharge data to provide reliable model performance on the future climate condition simulation. There were various types of discrepancy of the simulation output to the observation of the small size catchments, however, this discrepancy diminished when the catchment size is over 5,000 km^2. Considering the AGCM20 output has 20-km spatial resolution equivalent to 400 km^2 of area, it was able to understand that the runoff simulation gives stable results when the analyzing data is wider than 3×3 grids.

After the characteristics of the simulation data was comprehensively investigated, the AGCM20 output for the present and future climate scenarios were translated into the river discharge information using the distributed hydrologic model, the simulated river discharge for the present and future climate was analyzed. There are seven dam reservoirs to control water resource in the basin, and every reservoir was also modeled to simulate its effects on the water resources management in the basin.

Rainfall-runoff simulation including dam reservoir operation presents successful water release control for the most dam reservoirs. Even though the dam inflow seasonal pattern would be largely changed due to the shifted snowmelt season and amount, through the proper reservoir operation it is able to control the reservoir outflow same to the current outflow pattern even in the future. In this case, however, the water level regulations should be revised, and the shortage of the reservoir water in summer season should be carefully considered.

The effect of the controlled dam outflow was also checked at the downstream of the dam reservoirs. First of all, the annual discharge pattern at the Yukatahara gauging station was evaluated, and it was able to see the changed flow pattern of future was regulated through the designed dam reservoir operation, and the future flow pattern get close to the present flow pattern at the Yukatahara station (1677.5 km^2). From the simulation result that does not consider dam reservoir operations, it was able to see that the annual runoff pattern at the Yukatahara will be changed in the future especially in spring season (February to May) mainly due to the shifted snowmelt season. This shifted snowmelt river flow, however, was able to be delayed and can be closed to the current runoff pattern. This means that the current water usage pattern can be sustained even under the changed climate condition and hydrologic system in the future.

The controlled dam release effects was almost diminished and it is not able to see clear effects at the Kurihashi gauging station, which is the last output of the modeled basin in this study. Basin area of the Kurihashi Outlet is 8772.2 km^2, and snowfall is not a big portion of the annual precipitation in the southern part of the basin. Therefore, the shifted snowmelt season does not show clear effect at the Kurihashi station. Because most of the dams are located in the upper part of the basin, the dam operation effect was not big enough to change the future flow pattern. From this study, it was able to see that the shifted snowmelt effect by the changed climate may not big concern at the Kurishashi outlet in the future.

However, it should be kept in mind that the hydrologic simulation of this study including dam reservoir operation was carried out with the output of the AGCM20, which was simulated following A1B scenario. This climate change scenario surely contains lots of uncertainty, and the hydrologic model simulation for the future also includes many uncertain factors.

Water usage pattern in the future would not be the same to the current one. Many social factors, such as population, agricultural and industrial conditions, and land usage type would be changed in the future. Because of these changed social factors in the future, desirable water demand would be different to the current one. To investigate climate change impact on the water resources more comprehensively, it is necessary to consider these kinds of possible social factors changes and reliable water demand scenarios in the subject basin.

At the same time, uncertainties induced from the model simulation following the climate change scenarios and the hydrologic modeling and simulation as well also carefully considered for a proper impact analysis. Without this kind of understanding on the model simulation conditions and the backgrounds, the impact analysis cannot provide persuadable information to decision makers and the publics as well. Further research under going is to include uncertainty analysis of the impact study.

Acknowledgements

This work was done within the framework of the “Integrated assessment of climate change impact on watersheds in a disaster environment (PM: Prof. Eiichi Nakakita, DPRI, Kyoto University)” supported by the Kakushin Program of the Ministry of Education, Culture, Sports, Science and Technology of Japan (MEXT).

References

Adam, J. C., Hamlet A.F. and Lettenmaier, D.P. (2009): Implications of global climate change for snowmelt hydrology in the twenty-first century, Hydrological Process. Vol. 23, pp. 962-972.

Akiyama, T. (1981): Time and Spatial Variations of Heavy Snowfalls in the Japan Sea Coastal Region, Journal of the Meteorological Society of Japan, Vol. 59, No. 4, pp. 578-590.

Andreadis K.M. and Lettenmaier, D.P. (2006): Trends in 20th century drought over the continental United States, Geophysical Research Letters, Vol. 33, L10403.

Barnett, T.P., Adam, J.C. and Lettenmaier, D.P. (2005): Potential impacts of a warming climate on water availability in snow-dominated regions, Nature, Vol. 438, pp. 303-309.

Betts, R.A., Boucher, O., Collins, M., Cox, P.M., Falloon, P.D., Gedney, N., Hemming, D.L., Huntingford, C., Jones, C.D., Sexton, D.M.H., and Webb, M.J. (2007): Projected increase in continental runoff due to plant responses to increasing carbon dioxide, Nature, Vol. 448, pp. 1037-1041.

Coupled Model Intercomparison Project (CMIP) of Program for Climate Model Diagnosis and

Intercomparison (PCMDI), http://www-pcmdi.llnl.gov/projects/cmip/index.php

Dettinger, D.D. Cayan, D.R. Meyer, M.K. and Jeton, A.E. (2004): Simulated hydrologic responses to climate variations and change in the Merced, Carson, and American River Basins, Sierra Nevada, California, 1900-2099, Climate Change, Vol. 62, pp. 283-317.

Dibike, Y.B. and Coulibaly, P. (2005): Hydrologic impact of climate change in the Saguenay watershed: comparison of downscaling methods and hydrologic models, Journal of Hydrology, Vol. 307, pp. 145-163.

Gedney, N., Cox, P.M., Betts, R.A., Boucher, O., Huntingford, C. and Stott, P.A. (2006): Detection of a direct carbon dioxide effect in continental river runoff records, Nature, Vol. 439, pp 835-838.

Ichikawa, Y., Tachikawa, Y., Takara, K. and Shiba, M. (2000): Object-oriented hydrological modeling system, Proc. of Hydroinformatics 2000, CD-ROM.

Intergovernmental Panel for Climate Change (IPCC, 1990): Climate Change: The IPCC Scientific Assessment, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Intergovernmental Panel for Climate Change (IPCC, 2007a): Climate Change 2007: The Physical Science Basis, Cambridge Univ. Press, Cambridge, U.K.

Intergovernmental Panel for Climate Change (IPCC, 2007b): Climate Change 2007b: Impacts, Adaptation and Vulnerability, Cambridge Univ. Press, Cambridge, U.K.

Iwamoto, K., Nakai, S. and Sato, A. (2008): Statistical Analysis of Snowfall Distribution in the Niigata Area and its Relationship to the Wind Distribution, Scientific Online Letters on the Atmosphere (SOLA), The Meteorological Society of Japan, Vol. 4, pp. 45-48.

Kim, S., Tachikawa, Y., Nakakita, E. and Takara, K. (2009): Reconsideration of Reservoir Operations Under Climate Change: Case Study with Yagisawa Dam, Japan, Annual Journal of Hydraulic Engineering, JSCE, Vol. 53, pp. 115-120.

Kitoh A. and Kusunoki, S. (2007): East Asian summer monsoon simulation by a 20-km mesh AGCM, Climate Dynamics, DOI 10.1007/ s00382-007- 0285-2.

Kusunoki S. and Mizuta, R. (2008): Future Changes in the Baiu Rain Band Projected by a 20-km Mesh Global Atmospheric Model: Sea Surface Temperature Dependance, Scientific Online Letters on the Atmosphere (SOLA), The Meteorological Society of Japan, Vol. 4, pp. 85-88.

Milly, P.C.D., Dunne, K.A., and Vecchia, A.V. (2005): Global pattern of trends in streamflow and water availability in a changing climate, Nature, Vol. 438, pp. 347-350.

Ministry of Land, Infrastructure and Transport, Japan (2007): Water Resources in Japan.

Mizuta, R., Oouchi, K., Yoshimura, H., Noda, A., Katayama, K., Yukimoto, S., Hosaka, M., Kusunoki, S., Kawai, H. and Nakagawa, M. (2006): 20-km-mesh global climate simulations using JMA-GSM model -Mean climate states. Journal of the Meteorological Society of Japan, Vol. 84, pp. 165-185.

Mote, P.W., Hamlet, A.F., Clark, M.P., and Lettenmaier, D.P. (2005): Declining mountain snow pack in western North America, Bulletin of American Meteorological Society, Vol. 86, pp. 39-49.

Nakicenovic, N., Alcamo, J., Davis, G., de Vries, B., Fenhann, J., Gaffin, S., Gregory, K., Grubler, A., et al. (2000): Special Report on Emissions Scenarios, Working Group III, IPCC, Cambridge University Press, Cambridge.

Nijssen, B., O'Donnell, G.M., Hamlet A.F. and Lettenmaier, D.P. (2001): Hydrologic Sensitivity of Global Rivers to Climate Change, Climatic Change, Vol. 50, pp. 143-175.

Oki T. and Kanae, S.(2006): Global hydrological cycles and world water resources, Science, Vol. 313, pp. 1068-1072.

Piao, S., Friedlingstein, P., Ciais, P., de Noblet-Ducoudre, N., Labat, D. and Zaehle, S. (2006): Changes in climate and land use have a larger direct impact than rising CO2 on global river runoff trends, Proceedings of the National Academy of Sciences, Vol. 104, No. 39, pp. 15242-15247.

Rayner, N. A., Parker, D. E., Horton, E. B., Folland, C.K., Alexander, L.V., Rowell, D.P., Kent, E.C. and Kaplan, A. (2003): Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century, Journal of Geophysical Research, Vol. 108, No. D14, 4407, doi:10.1029/ 2002JD002670.

Reed, S., Koren, V., Smith, M., Zhang, Z., Moreda, F., Seo, D. J., and DMIP Participants. (2004): Overall distributed model intercomparison projects results, Journal of Hydrology, Vol. 298, pp. 27-60.

Singh, V. P. (2001): Kinematic wave modelling in water resources: a historical perspective, Hydrological Processes, Vol. 15, pp. 671-706.

Tachikawa, Y., Nagatani, G. and Takara, K. (2004): Development of stage-discharge relationship equation incorporating saturated-unsaturated flow mechanism, Annual Journal of Hydraulic Engineering, JSCE, Vol. 48, pp. 7-12, (Japanese with English abstract).

Takara, K., Kim, S., Tachikawa, Y. and Nakakita, E. (2009): Assessing Climate Change Impact on Water Resources in the Tone River Basin, Japan, using Super-High-Resolution Atmospheric Model Output, Journal of Disaster Research, Vol. 4, pp. 12-23.

Takasao, T. and Shiiba, M. (1988): Incorporation of the effect of concentration of flow into the

Kinematic wave equations and its applications to runoff system lumping, Journal of Hydrology, Vol. 102, pp. 301-322.
Takasao, T., Shiiba, M. and Ichikawa, Y. (1996): A runoff simulation with structural hydrological modeling system, JHHE, Vol. 14, No. 2, pp. 47-55.
Vorosmarty, C.J., Green, P., Salisbury, J. and Lammers, R.B. (2000): Global water resources: Vulnerability from climate change and population growth, Science, Vol. 289, pp. 284-288.
UNESCO-IHP Regional Steering Committee for Southeast Asia and the Pacific (2002): Catalogue of Rivers for Southeast Asia and the Pacific, Volume IV, UNESCO-IHP Publication, R. Ibbitt, K. Takara, M.N.M. Desa and H. Pawitan (Eds.), pp. 95-109.

地球温暖化が利根川流域の水資源管理に与える影響評価

キム スンミン・立川康人*・中北英一・寶 馨

*京都大学都市環境工学科

要　旨

治水施設の能力や管理施策が将来に渡って有効に機能するかを分析するために, 温暖化時の水文気象予測情報を河川流量に変換するための分布型流出予測モデルを構築する。従来, 温暖化時の治水・利水リスク評価は, 降水量から得た統計量の変化を分析することに焦点が当てられてきた。しかし, 特に水工施設が高度に流況を制御している河川流域においては降水量の分析だけでは不十分で, 河川流量の変動を分析してはじめて温暖化が当該流域の治水や利水にどう影響する可能性があるかを分析することができる。本研究では, 水文モデルを用いて特に高度に流況が制御され, かつ地域社会・経済に大きなインパクトをもつ利根川流域（栗橋上流8, 588 km^2）を対象とする。

キーワード:　温暖化，超高解像度大気モデル，分布型流出予測モデル，インパクト評価