Hydrologic Evaluation on the AGCM20 Output Using Observed River Discharge Data

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Abstract:

The controlled simulation output of a super-high resolution atmospheric model (AGCM20) was evaluated from a hydrologic point of view, using a distributed hydrologic model and observed river discharge data. The AGCM20 output for the current climate condition should be able to provide a current flow pattern when it is converted into river discharge information using a reasonably well-prepared hydrologic model. For this evaluation, a distributed hydrologic model was composed for various basin scales ranging from 60 km² to 8,772 km² in the Tone River Basin, Japan, and calibrated in advance, using observed data of each sub-basin. Most sub-basins in the study area provide more than 25 years of observed discharge data, and the evaluations were conducted by comparing seasonal patterns of simulated and observed discharges. The result shows that the GCM output provides excellent discharge output when the basin scale is more than 5,000 km², while its utilization into a smaller basin remains limited. The proposed hydrologic evaluation method provides direct and comprehensive understanding to hydrologists in addition to the conventional evaluation method.

KEYWORDS AGCM20; hydrologic evaluation; river discharge; distributed hydrologic model

INTRODUCTION

The rapid evolution of general circulation models (GCMs) in the last three decades allows us to expect a reasonable hydrologic dataset from the model output. However, evaluating the simulated model output is indispensable to achieve reasonable confidence in the model performances and, thus, be able to expect considerable attention on the future projection analysis. Performances of GCMs have been continuously evaluated through verification of controlled run output by comparing them with observation of such factors as precipitation, temperature and other atmospheric variables. Much of climate change research efforts with GCMs have been on model output evaluation through several model intercomparison projects, e.g., the Atmospheric Model Intercomparison Project (AMIP; Gate et al., 1998) and the Coupled Model Intercomparison Project (CMIP; Covey et al., 2003).

Nevertheless, additional evaluation of the model output is necessary to properly utilize it for a designed purpose, such as assessing the impact of climate change on the hydrologic cycle. The purpose of GCM output usage in the hydrologic field is to analyze water-related problems, e.g., flood and water resources condition. Therefore, it would be more appropriate to evaluate GCM from a hydrologic viewpoint, namely basin scale and river discharge based standpoint. Here, the controlled simulation output of a GCM should provide a river flow pattern similar to the observation when it is converted into river discharge information through a well-prepared hydrologic model.

In this study, the output of a super-high-resolution global atmospheric general circulation model (hereafter AGCM20) was evaluated using a distributed hydrologic model and long-term observed river discharge data. The subject area is divided into 16 sub-basins in this study, and each sub-basin provides more than 25 years of observed discharge data (10 years of data for dam reservoir basins), which is a sufficient duration of data to evaluate the AGCM20 output. For the evaluation of this study, a distributed hydrologic model was prepared and calibrated in advance for various basin scales ranging from 60 km² to 8,772 km² within the Tone River Basin, Japan. Because the hydrologic model is well calibrated with the observed input (e.g. precipitation and evaporation) and output data (river discharges), it is possible to see the characteristics of the AGCM20 output into a river discharge format, which is more direct and easy-to-understand information for hydrologists.

The next section describes in more detail this evaluation procedure, introducing the AGCM20 and its output. The third section illustrates the details of the distributed hydrologic model and the modeling process on the subject basin. The Results and Discussion section provides the evaluation results in a way that also checks seasonal patterns of river discharge and flood peaks. The last section summarizes this study and offers conclusions.

DATA AND METHODOLOGY

Super-High Resolution Atmospheric Model

The Japan Meteorological Agency (JMA) and Meteorological Research Institute (MRI) of Japan have developed a prototype of the next generation of global atmospheric models for use in both climate simulations and weather predictions (Mizuta et al., 2006; Kitoh et al., 2009). AGCM20 is the state-of-the-art atmospheric general circulation model with super-fine resolution. The model conducts simulations 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 vertical, and provides hourly precipitation output. AGCM20 uses the HadISST1 dataset (Rayner et al., 2003) for observed monthly mean climatologic sea surface temperature (SST) for a boundary condition of controlled simulation. The 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. Test run output during the model development showed advantages in simulating orographic rainfall and frontal rain bands, as a result of its very fine spatial resolution. Refer to Mizuta et al. (2006) and Kitoh and Kusunoki (2007) for more details on the model characteristics.

Among the many components in the AGCM20 output, hydrologic values, such as rainfall, snowfall, transpiration and evaporation, were evaluated in this study. Those five components are precipi, prcsl, sn2sl, evpsl and trnsl. The prcsl indicates daily precipitation amount reaching the soil layer after extracting interception and evaporation loss in the canopy zone; the sn2sl is the daily snowmelt amount into the soil layer. During the rainfall-runoff simulation of this study, the daily prcsl and sn2sl data were downscaled into hourly resolutions, using the hourly precipitation data, precipi. The evpsl stands for the daily evaporation amount from the soil layer, and trnsl stands for the daily transpiration amount from the soil root zone.

The controlled simulation of the AGCM20 provides present term (1979–2003) output, and the projection simulation provides near future term (2015–2039) and future term (2075–2099) outputs. The AGCM20 finished producing its first run output in 2009, and was preparing for its second run at the time this paper was written. This study focused on evaluation of the controlled simulation output from the first run.

Hydrologic Evaluation

Traditionally, GCM output evaluations have been carried out by comparing them with corresponding observations of global or continental scale (e.g. Gates et al., 1999; Covey et al., 2003). The output of AGCM20 was also evaluated in this way since the developing stage of the model (Mizuta et al., 2006). Kim et al. (2010) showed the characteristic of the controlled simulation output of the AGCM20 by comparing the precipitation output with the observed precipitation over Japan. However, to utilize the GCM output information for hydrologic purposes, such as assessing climate change impact on water resources and flood disaster, the evaluation should be more comprehensive and concentrate on a smaller scale, such as a river basin scale.

Because the rainfall-runoff process relates to several atmospheric variables, the use of only precipitation data does not provide high quality simulated river discharges. Evaporation and transpiration play an important role in a long-term based runoff simulation. Snowfall and snowmelt is becoming critical if the subject basin is in a snow-dominated region. Because measurements of evapotranspiration, interception, snowfall and snowmelt are imprecise compared to precipitation measurement, it is not easy to evaluate each variable of a GCM output using observed data.

Given that the conventional evaluation method of GCM output was not sufficient to provide an acceptable level of confidence regarding hydrologic impact analysis, this study proposed an additional evaluation method using a hydrologic model and observed river discharge data. Few studies have tried to check the reproducibility of the global model output using river discharge information (e.g. Nakaegawa, 2008). It is the first trial of GCM output evaluation using observed river discharge from various basin scales. This study provides more direct and more comprehensive understanding of the AGCM20 controlled simulation output to hydrologists who want to use the GCM output in the hydrologic impact analysis.

The hydrologic evaluation process of this study is as follows. A distributed hydrologic model (hereafter DHM) was prepared in advance for the hydrologic evaluation, and it was calibrated using observed data (e.g. precipitation, evaporation, discharge) for the subject basin. Thus the DHM is believed to provide accurate river discharge information, when correct input data is fed in. The calibrated DHM performed runoff simulation using the AGCM20 output data to generate river discharge at every sub-basin outlet. Finally, the simulated river discharge was evaluated using the observed river discharges, especially for seasonal pattern of river flow and peak amounts.

DISTRIBUTED HYDROLOGIC MODEL

Kinematic Wave Model on OHyMoS

The DHM was built on an object-oriented hydrologic modeling system, OHyMoS (Takasao et al., 1996). For the hillslope rainfall-runoff simulation module in the DHM, the kinematic wave equation was utilized, which incorporates a stage-discharge relationship for sub-surface and surface flow (Tachikawa et al., 2004); channel flow simulation is also conducted by solving the kinematic wave equation. This type of modeling was successfully applied to the Yodo River Basin by Sayama et al. (2008) to estimate the impact of climate change on flood disasters in the future, including dam reservoir operation model for flood control. Figure 1 shows the location and shape of the Tone River Basin with 16 sub-basins, which were divided by the main gauging points in this study.

The DHM was calibrated manually for the 16 sub-basins...
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in the Tone River Basin using the observed rainfall, evaporation and river discharge data. Here, the observation data for the calibration procedure was limited to the summer season (July–October) of a recent five-year period (1994–1998). The rainfall observation is from the AMeDAS (Automated Meteorological Data Acquisition System) observation data, and the evaporation data was estimated by the records of Uehara and Sato (1983). There are five parameters to be optimized in the model: Manning’s roughness coefficient \( n \), soil depths \( d_s \) and \( d_c \), and hydraulic conductivities \( k_a \) and \( k_c \). These estimate the velocity of saturated and unsaturated subsurface flow, respectively. The model parameter set for each sub-basin was calibrated using the former three years of data (1994–1996) and validated using the later two years of data (1997–1998). However, parameter sets for some upper basins were revised after the validation procedure in order to provide more generalized performances for the whole five-year duration. More details on the model structure and the calibration procedure are found in Kim et al. (2009).

Dam Reservoir Operation Modeling

There are 7 multipurpose dam reservoirs in the Tone River Basin, and each reservoir has an optimized operation rule to maximize its role. The dam module in the DHM to simulate reservoir operations was designed for reproducing the current outflow pattern of each reservoir. As it was successfully used in the Yagisawa Dam Basin in the previous study by Kim et al. (2009), the pattern-reproducing method provides a very efficient algorithm for the long-term simulation of reservoir operation.

Regulation rules to reproduce the given outflow pattern are: (1) if the water level is between the lowest water level (LWL) of the reservoir and the surcharge water level or highest water level (HWL), store the inflow and release the designed outflow; (2) if the water level reaches the HWL, release the designed outflow and inflow as well; (3) if the water level is lower than the LWL, water release is not allowed until the water level is higher than the LWL; and (4) the relationship of the water level and the reservoir volume follows the H-V relationship of each dam reservoir. The average outflow of recent 10 years (1994–2003) becomes the designed outflow for each reservoir operation.

We also included water usage information in the Tone River Basin. Annual water usage data (mainly for living and agricultural use) of 5 main points in the basin were collected from the Dam Management Office of the Tone River Basin. However, it was found the water usage amount does not use a large portion of the river flow volume.

RESULTS AND DISCUSSION

Seasonal Pattern Reproducibility

Evaluation of the simulated river discharges was carried out by comparing it with the observed river discharges. First, the seasonal patterns of those two river discharge data set were compared in each sub-basin. Some observed discharge data in several basins was available only in daily resolution, while the hydrologic model produces hourly discharge output for every sub-basin outlet. Thus, the seasonal pattern was estimated by averaging the daily discharge figures of both data sets.

As shown in Figure 2 and summarized in Table I, simulated river discharges from smaller basins (referring to less than 1,000 km\(^2\) of basin area in this study) show noticeable discrepancies; this was also seen with several middle-size basin (referring 1,000 km\(^2\)~5,000 km\(^2\) of basin area in this study). Simulated discharges of several basins show similar annual patterns with different volumes, such as Yagisawa (167.4 km\(^2\), 55.3% of underestimation) and

![Figure 2](image_url)

Figure 2. Observed discharges and simulated discharges using the AGCM20 output (both are average of 25 years) at the Sonohara, Murakami and Yattajima stations.

<table>
<thead>
<tr>
<th>Basin Name</th>
<th>Area (km(^2))</th>
<th>NSC</th>
<th>Vol. Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aimata</td>
<td>110.8</td>
<td>0.54</td>
<td>−10.2%</td>
</tr>
<tr>
<td>Kusaki</td>
<td>154.0</td>
<td>0.39</td>
<td>+1.1%</td>
</tr>
<tr>
<td>Yagisawa</td>
<td>167.4</td>
<td>0.13</td>
<td>−55.3%</td>
</tr>
<tr>
<td>Sonohara</td>
<td>493.9</td>
<td>0.14</td>
<td>+39.6%</td>
</tr>
<tr>
<td>Takamatsu</td>
<td>557.4</td>
<td>0.14</td>
<td>+39.9%</td>
</tr>
<tr>
<td>Otome</td>
<td>873.7</td>
<td>0.39</td>
<td>+18.5%</td>
</tr>
<tr>
<td>Murakami</td>
<td>1249.2</td>
<td>−1.74</td>
<td>+49.2%</td>
</tr>
<tr>
<td>Yakatahara</td>
<td>1677.5</td>
<td>0.65</td>
<td>+26.1%</td>
</tr>
<tr>
<td>Yattajima</td>
<td>5133.6</td>
<td>0.49</td>
<td>+3.5%</td>
</tr>
<tr>
<td>Tone-Ozeki</td>
<td>6058.8</td>
<td>0.45</td>
<td>−7.3%</td>
</tr>
<tr>
<td>Kuriihashi</td>
<td>8772.2</td>
<td>0.59</td>
<td>−2.0%</td>
</tr>
</tbody>
</table>

* NSC: Nash-Sutcliffe Coefficient
Takamatsu (557.4 km², 39.9% of overestimation), while several basins, such as Sonohara (1249.2 km²) and Murakami (1249.2 km²), are showing very poor performance levels in comparison with the simulation results, demonstrating unreasonable Nash-Sutcliffe Coefficient (NSC) values. Although there are couple of basins showing good performances in both the annual discharge pattern and the volume, such as Kusaki (557.4 km²) and Otome (557.4 km²), the simulation results from most smaller and middle-size basins did not show reasonable performances.

However, the discrepancy level becomes smaller when the area of the analyzing basin increases. As shown in Figure 2, simulated discharges for the Yattajima Basin (5133.6 km²) show a reasonably good match with the observed discharge pattern. Simulation results at the Tone-Ozeki (6058.8 km²) and Kurihashi (8772.2 km²) showed better performance, compared to the results from the small- and middle-size basins. Considering the area covered by one grid of the AGCM20 output is around 400 km², high accuracy at a grid-scale level of the AGCM20 output is not likely. However, the AGCM20 output shows reasonable reproducibility when it is analyzed on a larger scale, which is larger than 5,000 km² of area in the case of the Tone River Basin. The model output evaluation by Mizuta et al. (2006) also reported the reasonable resolution to resolve the precipitation pattern was about 100 km with the TL959 model.

**Extreme Events Reproducibility**

The annual flood peak of each check point was also evaluated using the observed daily discharge data. The maximum daily peak of each year was selected from both the 25 years of observation and the simulation data. Then, as shown in Figure 3, scattergrams were plotted with observed peak discharges (x-axis) and simulated peak discharges (y-axis), after sorting those data in maximum order. As a way of estimating a regression coefficient of the scattergrams, it was able to check the overall performance level of the simulation results for extreme flood events. A regression coefficient of approximately 1.0 is our desirable value, and a coefficient of less than 1.0 means an underestimated simulation result and vice versa.

From Figure 3, which shows the regression coefficients of each sub-basin, it is possible to see that the simulated discharges show generally underestimated extreme values when compared to the observation. The underestimated daily peak flow is more apparent in a smaller basin, and the reproducibility of the simulated peak improved for the larger basin, showing the same reproducibility pattern of the seasonal river flow.

**Considering with Precipitation Reproducibility**

AGCM20 precipitation output from the controlled run was also evaluated using the AMeDAS observation in Japan. According to the AMeDAS observation, the annual mean precipitation over the Japan Island during the period 1979–2003 was 1684.3 mm, and the AGCM20 output data show 1695.2 mm, demonstrating very good consistency (see Kim et al., 2010 for more details on the AGCM20 precipitation output evaluation using the AMeDAS observation). However, annual mean precipitation over the Tone River Basin from the AGCM20 overestimated values by 24%, finding 1790.7 mm compared to the one observed by AMeDAS, 1444.5 mm. Annual daily maximums from AGCM20 are, however, lower than maximum historical observations (Takara et al., 2009).

Although a similar type of AGCM20 bias was found in the hydrologic evaluation results of this study, annual pattern of the river flow at the basin outlet was not significant as much as the overestimated precipitation (see Table I). Evaporation and transpiration output from the AGCM20 may also be overestimated than the real values, and thus net-amount of precipitation for the river discharge shows rather good match with the observed river discharge amount.

However, even observed precipitation data has much uncertainty in it as shown in the case of the Yagisawa Dam Basin (Kim et al., 2009). From the AMeDAS observation, annual precipitation over the basin is less than 2,000 mm, and AGCM20 output shows around 1,900 mm of annual precipitation for the area. However, the basin’s average precipitation should be more than 3,000 mm per year, according to the dam inflow observation. The reason for the smaller observed precipitation was underestimated snowfall observation in a highly mountainous area. Even with the very fine network of precipitation observations, it is still difficult to get reasonable precipitation data with high accuracy in some cases.

**CONCLUDING REMARKS**

The AGCM20 output for the present climate scenario was evaluated using a distributed hydrologic model and observed river discharge data. The distributed hydrologic model was developed on the Tone River Basin, and it was calibrated using observed data (e.g. precipitation, evaporation, discharge). The calibrated hydrologic model performed a runoff simulation using the AGCM20 output, and converted it into river discharge information. The simulated river discharges at the 16 checking points in the basin were
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evaluated in two aspects, seasonal variation and peak discharge.

While the simulated river discharges of small basins show various types of discrepancies to observed discharges, the discrepancy is diminished as the size of the examining basin area increases. The simulated discharges show improved performances for an area larger than the Yattajima Basin (5133.6 km²). It was able to understand that the AGCM20 output does not show high accuracy in a grid scale; however, the output shows reasonable reproducibility when it is analyzed on a larger scale, e.g., more than 5,000 km² of area in the case of the Tone River Basin. Daily peak flow also shows better performance for the larger basin, while retaining limitations on its utilization with smaller basins.

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SUPPLEMENTS

Supplement 1 Enlarged figure of figure 1 is included.
Supplement 2 Enlarged figure of figure 2 is included.
Supplement 3 Enlarged figure of figure 3 is included.

REFERENCES


