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Application of a Land Surface Model for Bias Correction of Runoff Generation Data from MRI-AGCM3.2S Dataset

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Abstract In climate change researches, general circulation models or global climate models (GCMs) have been the most promising tools to project future changes and associated impacts in the hydrological cycle. However, there are biases in GCM outputs due to the coarse spatial resolution, simplified physics processes, numerical schemes, etc. Those biases should be corrected before using GCM data in climate change impact studies.

In this study, runoff generation data from the MRI-AGCM3.2S dataset were fed into distributed flow routing model 1K-FRM to project river discharge under a changing climate. Flow routing model 1K-FRM was developed in the Hydrology and Water Resources Research Laboratory, Kyoto University. The MRI-AGCM3.2S is the latest version of super-high-resolution atmospheric general circulation model which was jointly developed by Japan Meteorological Agency (JMA) and Meteorological Research Institute (MRI). Two river basins located in Kyushu (Japan) were selected as study areas, the Chikugo river basin and the Oyodo river basin.

Since the observed runoff generation data is not available, the land surface model Simple Biosphere including Urban Canopy (SiBUC) was applied to reproduce runoff generation data to use in bias correction of the MRI-AGCM3.2S’s output. SiBUC model was developed in the Disaster Prevention Research Insitute, Kyoto University. Corrected runoff generation data were used to project river discharge and examine the changes in river discharge in those two basins under a changing climate.

Keywords
Land surface model, SiBUC, flow routing model, 1K-FRM, bias correction, MRI-AGCM3.2S

Introduction

Climate change is now widely accepted as a scientific fact. It is projected to have significant impacts on hydrology and water resources. The most common approach to assess the hydrological impacts of global climate change is to force hydrological models (HMs) or land surface models (LSMs) with output from general circulation models (GCMs). Therefore, the quality of hydrological impact investigations largely depends on the accuracy of GCMs in simulating climate data (Hagemann et al., 2011).

Although there are considerable improvements in the performance of GCMs in recent years, outputs of GCMs still suffer from systematic errors, or biases, which can be due to incomplete knowledge of climate system processes, numerical schemes, parameterizations of small scale (sub-grid scale) processes, and coarse spatial resolution.

Removing these biases in GCM outputs is therefore essential for improving the reliability of climate projections and hydrological simulations forced by climate model data. Several bias correction methods have been developed and received much attention in climate change impacts studies (e.g. Themeßl et al., 2011; Hagemann et al., 2011; Teutschbein and Seibert, 2012).

In this work, river discharge in two river basins in Kyushu area (Japan), Chikugo River basin and Oyodo River basin, were projected by feeding the MRI-AGCM3.2S runoff generation data into flow routing model 1K-FRM. To improve the projection of river discharge using 1K-FRM, bias correction is considered to apply to MRI-AGCM3.2S runoff generation data. Due to the unavailability of observed runoff generation data, an advanced land surface process model called Simple Biosphere including Urban Canopy (SiBUC; Tanaka, 2005) was applied to reproduce runoff generation data based on meteorological and phenological records. Output of SiBUC model was used as reference data for bias correction of MRI-AGCM3.2S runoff generation data. Biases in GCM runoff generation data were corrected using quantile-quantile mapping bias correction method (Leimer et al., 2011).

Projected river discharge in Chikugo River basin and Oyodo River basin from 1K-FRM using MRI-AGCM3.2S runoff generation data, SiBUC runoff

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generation data, and bias-corrected runoff generation data were compared to examine the performance of land surface process model and bias correction method in river discharge projection.

Study area

The analysis in this study was performed for two river basins in Kyushu area, Japan – Chikugo River basin and Oyodo River basin. Fig. 1 shows the location of these two river basins.

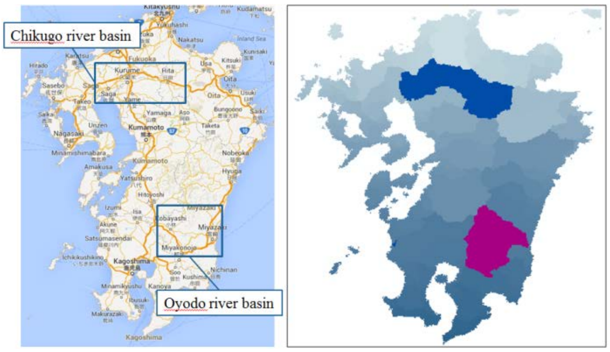

Fig. 1 Location of Chikugo River basin (blue) and Oyodo River basin (red) in Kyushu area, Japan

Chikugo River flows through Oita, Fukuoka, Kumamoto, and Saga prefectures in Kyushu area. With a total length of about 143 km, it is the longest river on Kyushu Island. The total basin area of Chikugo River is about 2,800 km^2.

Oyodo River runs through Kagoshima prefecture and Miyazaki prefectures with the basin area of about 2,230 km^2. The length of Oyodo River basin is about 107 km.

Flow routing model 1K-FRM

1K-FRM is a distributed flow routing model based on kinematic wave theory (Hunukumbura et al. 2012). It was developed by Hydrology and Water Resources Research Laboratory of Kyoto University. The kinematic wave model is applied to all slope units and runoff is routed according to the flow direction information. The basic form of the kinematic wave flow equation is:

$$\frac{\partial A}{\partial t}+\frac{\partial Q}{\partial x}=q_L(x,t) \qquad (1)$$

$$Q=\alpha A^m,\ \alpha=\frac{\sqrt{i_0}}{n}\left(\frac{1}{B}\right)^{m-1},\ m=\frac{5}{3} \qquad (2)$$

where, A(x, t) is the flow cross-sectional area, Q(x, t) is the flow discharge, $q_L(x, t)$ is the lateral inflow per unit length, i_0 is the slope, n is the Manning roughness coefficient, and B is the width of the flow.

Eq. (1) is the continuity equation. It is derived from the principle of mass conservation within a control volume. Eq. (2) is derived from Manning's laws which are flow resistance laws of open channel uniform flow.

Land surface model SiBUC

The land surface process model Simple Biosphere including Urban Canopy (SiBUC) was presented by Tanaka (2005) in Disaster Prevention Research Institute, Kyoto University. SiBUC model uses mosaic approach, which couples independently each land-use patch of the grid element to the atmosphere, to incorporate all kind of land-use to land surface scheme.

In SiBUC model, the surface of each grid cell is divided into three land-use categories including green area (vegetation canopy and ground), urban area (urban canopy and urban ground), and water body. Fig. 2 shows the schematic image of surface elements in SiBUC model.

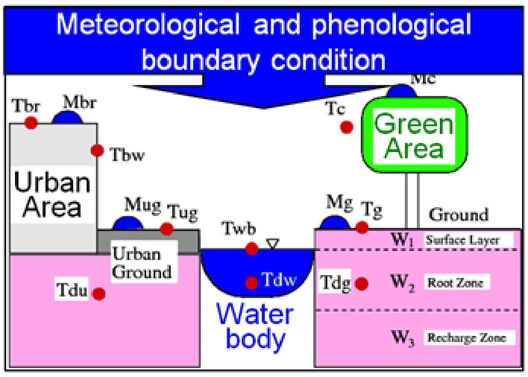

Fig. 2 Schematic image of SIBUC model

The fractions of these three land-use categories are fixed for each grid cell in SiBUC model. And surface fluxes are obtained by averaging the surface fluxes over each land-use weighted by its fractional area.

Data

Topographic data

The topographic data used in flow routing model 1K-FRM and land surface process model for two river basins in Kyushu area were the 30 arc-second (1-km) DEM and flow direction stored in HydroSHEDS (Lehner, 2006) for Asian regions. HydroSHEDS (Hydrological data and maps based on Shuttle Elevation Derivatives at multiple scales) provides hydrographic information for region and global-scale applications based on high-resolution elevation data obtained by NASA's Shuttle Radar Topography Mission.

GCM runoff generation data

GCM data used for flow routing model 1K-FRM is 3-hourly runoff generation data from super-high-resolution atmospheric general circulation model MRI-AGCM3.2S. It is the latest atmospheric GCMs based on a model jointly developed by the Japan Meteorological Agency (JMA) and the Meteorological Research Institute (MRI) (Mizuta et al., 2006). MRI-AGCM provides data for three climate experiments: present climate experiment (1979-2008), near future climate experiment (2015-2044), and future climate experiment (2075-2104). The data used for future projection were based on the Special Report on Emissions Scenarios (SRES) A1B scenario.

Meteorological data

Meteorological data to force land surface process model SiBUC include seven components: precipitation, air temperature, specific humidity, surface pressure, wind speed, long wave radiation, and short wave radiation. In this study, the product of the Japanese 55-year reanalysis (JRA-55) project was utilized to use as inputs for SiBUC. However, JRA-55 precipitation and surface radiation data are forecast data, not reanalysis data. Therefore, other data sources were considered to use as substitution. For precipitation data, the Asian Precipitation - Highly-Resolved Observational Data Integration Towards Evaluation of Water Resources (APHRODITE's Water Resources) project was selected. And the Surface Radiation Budget (SRB) dataset was used to process long wave radiation and short wave radiation data.

The Japanese 55-year Reanalysis (JRA-55) is the second reanalysis project conducted by Japan Meteorological Agency (JMA) (Ebita et al., 2011). In this project, a sophisticated data assimilation system based on the operational system as of December 2009 and newly prepared dataset of past observations were used to produce a high-quality homogeneous climate dataset. The analysis period covers 50 years from 1958, when regular radiosonde observation began on a global basis. Table 1 and Table 2 summary information about JRA-55 meteorological data used for land surface process model SiBUC.

Table 1 Parameters of surface analysis fields

Field parameter	Unit	Level
Pressure	Pa	Ground or water surface
Temperature	K	2m
Specific humidity	kg kg-1	2m
u-component of wind	m s-1	10m
v-component of wind	m s-1	10m

Table 6.2 Parameters of two-dimensional average diagnostic fields

Field parameter	Unit	Level
Total precipitation	mm day-1	Ground or water surface
Downward solar radiation flux	W m-2	Ground or water surface
Downward long wave radiation flux	W m-2	Ground or water surface

The spatial resolution of JRA-55 data is 0.5625 degree. Parameters of surface analysis fields have 6-hour temporal resolution. And parameters of two-dimensional average diagnostic fields have 3-hour temporal resolution.

The Asian Precipitation - Highly-Resolved Observational Data Integration Towards Evaluation of Water Resources (APHRODITE's Water Resources) project was conducted by the Research Institute for Human and Nature (RIHN) and the Meteorological Research Institute of Japan Meteorological Agency (MRI/JMA) from 2006 to develop state-of-the-art daily precipitation datasets on high-resolution grids covering the whole of Asia (Yatagai et al., 2012). The datasets are created primarily with data obtained from a rain gauge observation network. The APHRODITE's Water Resources dataset is the only long-term continental-scale daily product that contains a dense network of daily rain-gauge data for Asia, especially Japan.

Precipitation data to force land surface process model for Kuyshu area was extracted from the APHRO_JP V1207 (Kamiguchi et al., 2010) dataset with spatial resolution of 0.05 degree. Temporal resolution of APHRO_JP precipitation data is daily.

Surface Radiation Budget (SRB) dataset is produced and archived by the NASA Langley Research Center Atmospheric Sciences Data Center (NASA/GEWEX). It is produced on a 1 degree x 1 degree global grid using satellite-derived cloud parameters and ozone fields, reanalysis meteorology, and a few other ancillary datasets. The SRB dataset contains 3-hourly long wave and short wave radiative fluxes.

Soil, vegetation, and land use data

Phenological boundary conditions related to soil type, vegetation type and land use data for Kyushu area in SiBUC model were collected from Ministry of Land, Infrastructure, Transport and Tourism (MLIT, Japan) field survey data and satellite databases such as ECOCLIMAP product and GLASS Leaf Area Index product.

Land use data for Kyushu area collected from MLIT consist of 16 categories including paddy, farmland, fruit farm, other farm, forest, waste land, building A, building B, road, other land, lake, river A, river B, beach, and unknown. Surface parameters related to land use for green area, urban area, and water body in SiBUC model was set based on this category. The spatial resolution of MLIT land use data is 100 m.

Parameters for vegetation type were derived from the GLASS Leaf Area Index (LAI) product, which generated by the Center for Global Change Data Processing and Analysis of Beijing Normal University (Xiao et al., 2013). The GLASS product is available from 1982 to 2012 with temporal resolution of 8 days and spatial resolution of 0.05 degree.

Soil parameters in SiBUC model such as root depth, soil depth, soil texture class, etc. were set baed on ECOCLIMAP product (Masson et al., 2003). ECOCLIMAP is a database of surface parameters at 1-km resolution which was implemented in the METEO-FRANCE operation models.

Resolution and simulation period of SiBUC model

The output data grid of SiBUC was set in the same coordinate, spatial resolution as MRI-AGCM3.2S runoff generation data. Input data with finer spatial resolution such as soil and vegetation were aggregated to create 20-km spatial resolution data. For coarser spatial resolution data, value of the nearest grid was selected in calculation.

SiBUC model was set to simulate runoff in Kyushu area for 1982-2010 period based on the availability of input data.

Bias correction of GCM runoff generation data

To correct biases in GCM runoff generation data, quantile-quantile mapping (QQM) bias correction method was selected. QQM was first introduced by Brier and Panofsky (1968) as empirical transformation. Methods based on quantile mapping are getting more popular and widely used to correct climate model outputs (e.g. Leimer et al., 2011; Vidal and Wade, 2008). Themeßl et al. (2011) and Teutschbein and Seibert (2012) compared various bias correction methods and showed that QQM performs better than others.

In QQM bias correction method, GCM output and observations are sorted for the same historical base period to construct cumulative distribution functions (CDFs). These CDFs is used to define the quantiles of simulated values and observations. Then, GCM simulated values is substituted with those of the identical quantile from the observational dataset. Fig. 3 shows the schematic representation of quantile-quantile mapping.

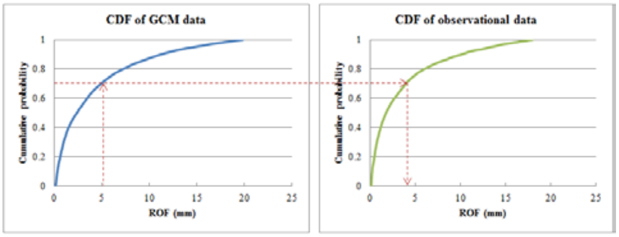

Fig. 3 Schematic representation of quantile-quantile mapping

In this study, runoff data simulated by SiBUC model were used as reference data to correct MRI-AGCM3.2S runoff generation data. Bias correction was applied to MRI-AGCM3.2S runoff generation data at each grid cell as follows:

Runoff generation data from MRI-AGCM3.2S dataset and SiBUC model at the same grid and in the same calendar month for the whole simulation period were sorted from smallest to largest to construct cumulative distribution functions.

Runoff generation data from MRI-AGCM3.2S dataset at each quantile was corrected by SiBUC runoff data at the equivalent quantile. MRI-AGCM3.2S corrected runoff generation data were rearranged following the original time order.

Results and discussions

Reproduction of runoff generation data using SiBUC

Two simulations for Kyushu area were carried out using SiBUC model with different precipitation data sources, JRA-55 and APHRO_JP. Fig. 4 shows the annual mean runoff in Kyushu area simulated by SiBUC model. Simulation using APHRO_JP precipitation data shows a higher value of annual mean runoff compared to the one using JRA-55 precipitation data.

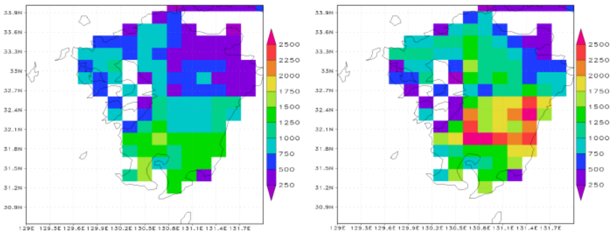

Fig. 4 Annual mean runoff in Kyushu area simulated using JRA-55 (left) and APHRO_JP precipitation data (right) from 1982-2008 (unit: mm/year)

To examine the reproduction of runoff generation data using land surface process model, river discharge in Kyushu area were simulated using runoff generation data given by SiBUC model. The runoff data simulated by SiBUC model using JRA-55 and APHRO_JP precipitation data hereinafter referred to as JRA-55 runoff data and APHRO_JP runoff data.

Flow duration curves for Oyodo River at Takaoka station and for Chikugo River at Senoshita station were constructed using the total-period method and the calendar-year method to compare simulated discharge with observations. Observational data at two stations mentioned above are available for 20 years period, from 1982 to 2001.

Fig. 5 and Fig. 6 show the total period and calendar-year flow duration curves for daily flow at Takaoka station, Oyodo River. Flow duration curves for Chikugo River at Senoshita are illustrated in Fig. 7 and Fig. 8 respectively.

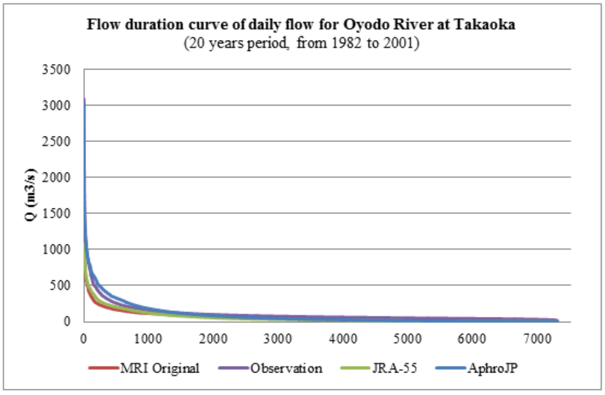

Fig. 5 Total period flow duration curve of daily flow for Oyodo Rirver at Takaoka

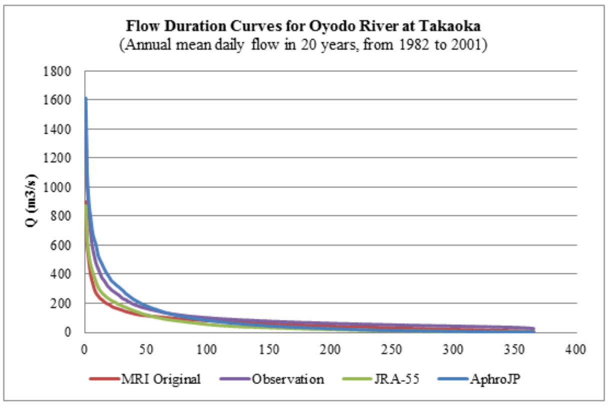

Fig. 6 Calendar-year flow duration curve of daily flow for Oyodo Rirver at Takaoka

As can be seen in Fig. 5, the flow duration curve from simulation using APHRO_JP runoff data was more close to observed data at Takaoka station, Oyodo River basin. River discharges simulated using original MRI runoff generation data and JRA-55 runoff data are lower than the observations. The calendar-year flow duration curves show the same pattern as the total-period flow duration curves (Fig. 6).

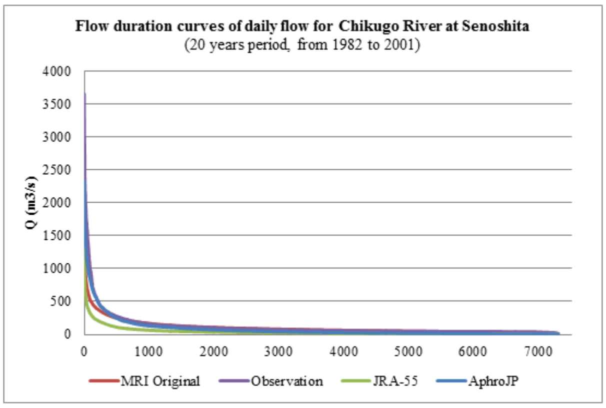

Fig 7 Total period flow duration curve of daily flow for Chikugo Rirver at Senoshita

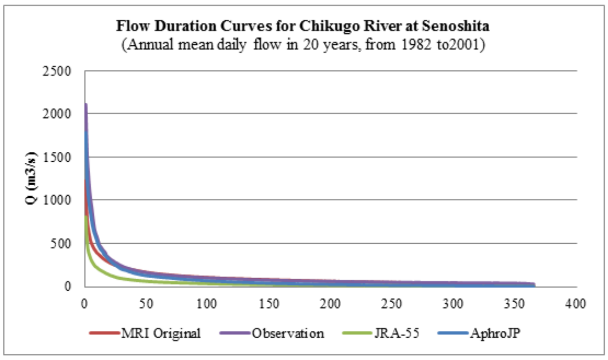

Fig. 8 Calendar-year flow duration curve of daily flow for Chikugo Rirver at Senoshita

At Senoshita station, Chikugo River basin, although all the simulation showed an underestimation of the simulated river discharges from the observation, the simulation using APHRO_JP runoff data still performs better than others (see Fig. 7 and Fig. 8). Therefore, in bias correction part, APHRO_JP runoff data were chosen as reference data to correct biases in MRI-AGCM3.2S runoff generation data.

Bias correction of runoff generation data

Biases in MRI-AGCM3.2S runoff generation data were corrected with APHRO_JP runoff data using quantile-quantile mapping method. Corrected MRI-AGCM3.2S runoff generation data were fed into flow routing model 1K-FRM to examine the effect of bias correction of runoff generation data on river discharge simulation.

Fig. 9 shows an example of the time series of MRI-AGCM3.2S runoff generation data, APHRO_JP runoff data, and corrected runoff generation data for 20 years period (1982-2001) at one grid upstream of Takaoka station, Oyodo River basin.

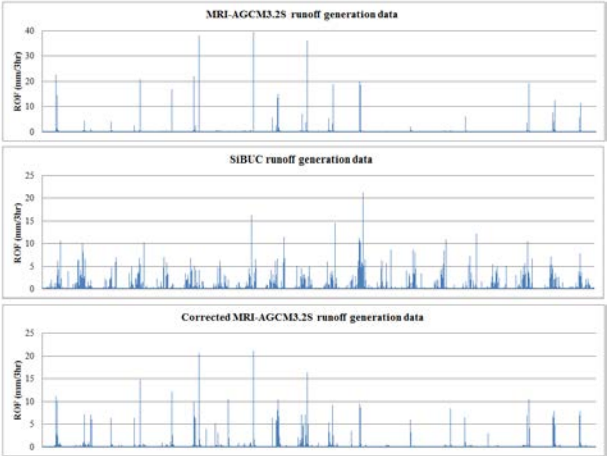

Fig. 9 An example of time series of runoff generation data for 20 years period (1982-2001)

It can be seen that, after bias correction, the temporal distribution pattern of corrected runoff generation data is similar to that of original MRI-AGCM3.2S data. However, comparing to reference data, the number of events with high runoff depth in the corrected runoff generation data is smaller but the density of high runoff depth in each event is higher. It may result in less flood events but higher peak discharge values.

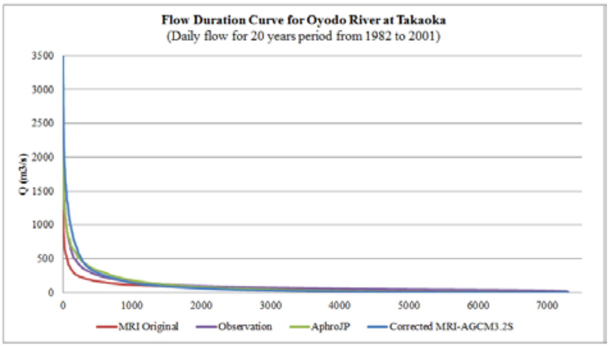

Fig. 10 Total period flow duration curve of daily flow for Oyodo Rirver at Takaoka

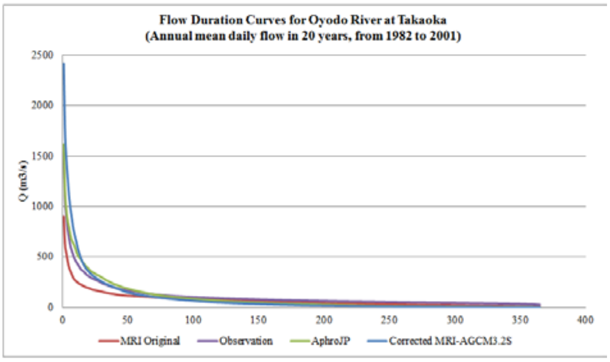

Fig. 11 Calendar-year flow duration curve of daily flow for Oyodo Rirver at Takaoka

Flow duration curves for river discharge simulated using corrected runoff generation data at Takaoka station, Oyodo River basin, are illustrated in Fig. 10 and Fig. 11. River discharge simulated using bias-corrected runoff generation data show an improvement comparing to original MRI-AGCM3.2S data. However, the peak discharge values are overestimated in comparison with simulation using reference runoff generation data. It may arise from the differences in temporal distribution pattern between corrected runoff generation data and reference data as mentioned above.

Conclusions

In this study, runoff generation data in the Kyushu area were simulated using a land surface process model SiBUC with reanalysis data. It was used as reference data to correct biases in MRI-AGCM3.2S runoff generation data.

SiBUC model showed a good performance in reproducing runoff generation data for Kyushu area. If high quality observed data are available, land surface process model will be a useful tool to reproduce runoff for a long-term period.

Bias correction of MRI-AGCM3.2S runoff generation data were also performed and showed an improvement in river discharge simulations. However, further works need to be done in bias correction of runoff generation data considering their temporal distribution pattern. The spatial correlation between neigbour grid-cells are also needed to be examined.

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