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Climate Change Assessment in Asian Water Cycle Initiative (AWCI) River Basins

Toshio Koike[1], Petra Koudelova[1], Patricia Ann Jaranilla-Sanchez, Cho Thanda Nyunt and Sixto Durran-Ballen
[1]Corresponding author
The University of Tokyo, Japan
Email: petra@hydra.t.u-tokyo.ac.jp

ABSTRACT: The AWCI countries represent a wide variety of geographical, climatic and hydrological conditions and thus various tools and methods are required for climate change impact assessment. This article introduces some of the tools developed as a part of the AWCI activities. A hydrological model for cold regions was developed by incorporating a multi-layer energy-balance based snowmelt scheme into the Water and Energy Budget Distributed Hydrological Model (WEB-DHM). A method was developed for estimating snow depth spatial distribution in mountain areas using a radiative transfer model and microwave radiometer observations (AMSR-E satellite data) and validated in the Puna Tsang basin in Bhutan. Moreover, an improved statistical method for GCM precipitation output bias correction was developed that covers extreme rainfall, normal rainfall and frequency of dry days, and was validated in the Pampanga basin in the Philippines. In addition, the bias correction method and WEB-DHM model were employed in a climate change impact assessment study in the Philippines, focusing on flood peaks and droughts. Results showed future flooding trends are virtually certain to increase while drought trends are likely not to increase in the uplands but very likely to increase in the flood plains.

KEYWORDS: *climate change impacts on water cycle, AWCI river basins, GCM bias correction, WEB-DHM, snow processes*

Introduction

The consequences of climate change that are unavoidable over the next several decades will have enormous impacts on a range of natural and socioeconomic systems. Therefore, it is very urgent to develop roadmaps for laying down proper adaptation strategies together with mitigation approaches. The Global Earth Observation System of Systems (GEOSS) Asian Water Cycle Initiative (AWCI) has been striving to develop and promote appropriate strategies for addressing issues associated with climate change impacts on water resources and their management in AWCI participating countries that include Bangladesh, Bhutan, Cambodia, India, Indonesia, Japan, Republic of Korea, Lao PDR, Malaysia, Mongolia, Myanmar, Nepal, Pakistan, Philippines, Sri Lanka, Thailand, Uzbekistan and Viet Nam. The APN-funded project "River Management System Development in Asia Based on Data Integration and Analysis System (DIAS) under the GEOSS" aims to develop an advanced river management system in member countries by exploiting and integrating data from earth observation satellites and *in situ* networks with other types of data, including numerical weather prediction model outputs, climate model outputs, geographical information, and socioeconomic data. The AWCI countries represent a wide variety of geographical, climatic and hydrological conditions and thus various tools and methods may be required, although the overall approach is common among the countries.

This article introduces some of the research outcomes of the AWCI activities related to the mentioned project including (i) snow processes, (ii) GCM bias correction and downscaling for climate change assessment, and (iii) impacts of changing climate on floods and droughts.

HIGHLIGHTS

- Development of a distributed hydrological model in AWCI basins by integrated *in situ* and satellite data and model outputs.
- Development and validation of WEB-DHM-S, a hydrological model for cold regions including an advanced, multilayer energy-balance based snowmelt scheme.
- Development and validation of a method for snow depth distribution estimation using satellite data.
- Development and validation of a GCM precipitation output bias correction method for use in climate change assessment studies.
- Application of developed methods in climate change impact analysis in AWCI basins.
- Dam operation optimization using forecast precipitation data and employing WEB-DHM in AWCI basins — ongoing.

Snow Modelling

Snow and glaciers are natural reserves of freshwater in a number of AWCI countries and thus tools and methodologies considering these phenomena are needed. From a hydrological point of view, the temporal and spatial variability of the snow distribution on a basin scale plays a key role in determining the timing and magnitude of snowmelt runoff. Considering the effect of snow on land and atmospheric processes, it is essential that hydrological models accurately describe seasonal snow evolution. For applications in the AWCI basins, such a model was developed by incorporating a multi-layer energy-balance based snow scheme into a distributed hydrological model (Shrestha et al., 2010, 2012). In addition, a method for estimating snow amount spatial distribution was developed using a microwave radiative transfer model (RTM) in mountain regions (Duran-Ballen et al., 2012).

WEB-DHM-S Model Description

The Water and Energy Budget Distributed Hydrological Model with improved snow physics (WEB-DHM-S; Shrestha et al., 2010, 2012) was developed by coupling the three-layer energy balance snow physics of the Simplified Simple Biosphere, version 3 (SSiB3) and the prognostic albedo scheme of the BATS into the Water and Energy Budget Distributed Hydrological Model (WEB-DHM; Wang et al., 2009a,b). The WEB-DHM realistically simulates the land surface and hydrological processes, providing a consistent description of water, energy, and CO_2 fluxes at a basin scale. WEB-DHM-S adds more features to the WEB-DHM for simulating the spatial distribution of snow variables such as the snow depth, snow water equivalent, snow density, liquid water and ice contents in each snow layer, snow albedo, snow surface temperature, and snowmelt runoff. Following the basic model structure (Wang et al., 2009a), the basin and sub-basins are delineated employing the Pfafstetter scheme, and sub-basins are divided into a number of flow intervals based on the time of concentration. All external parameters (for example, land use, soil type, hillslope properties and vegetation parameters) and a meteorological forcing data set including precipitation are attributed to each model grid, in which water, energy, and CO_2 fluxes are calculated. A hillslope-driven runoff scheme employing a kinematic wave flow routing method is adopted in calculating runoff. For snow-covered model grids, a three-layer energy-balance-based snow accumulation and melting algorithm is used when the simulated snow depth is greater than 5 cm; otherwise, a one-bulk-layer snow algorithm is used. Each model grid maintains its own prognostic snow properties (temperature, density and ice/water content) and/or land surface temperature and soil moisture content. The model was validated in the Dudhkoshi region of the Koshi basin, located in the northeast Nepal Himalayas (Shrestha et al., 2012).

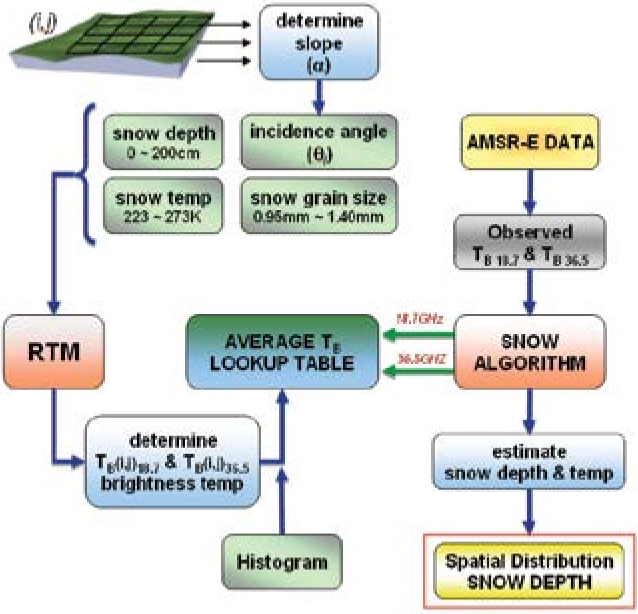


Figure 1. Framework of the snow depth spatial distribution estimation method

Snow Depth Spatial Distribution Using Microwave Remote Sensing at the Puna Tsang River Basin in Bhutan

Methodology

A new approach was developed to estimate snow amounts using a microwave radiative transfer model (RTM) in mountain regions, which takes into account local terrain slope and incidence angle of a radiometer scanner (Duran-Ballen et al., 2012). AMSR-E satellite observations of brightness temperature (Tb) at 18.7 GHz and 36.5 GHz frequencies were compared to calculated values of Tb in Lookup Tables generated by the RTM model. The snow algorithm used to derive the snow depth and temperature spatial distribution was validated in a flat region using *in situ* recorded snow depth data (Tsutsui & Koike, 2009a,b). However, remote sensing instruments are sensitive to the effects of the terrain slope, where the local incidence angle is different than the 55-degree incidence angle in case of a flat surface.

The terrain DEM is used to calculate the slope and aspect of each grid and the local incidence angle is computed with the geolocation of the satellite as it passes over. To overcome the difference of spatial resolution between the AMSR-E data (25x25 km) and the DEM (resolution 1x1 km to express appropriately the terrain), Tb for the both frequencies is estimated with the local incidence angle for each terrain grid and then averaged for the larger satellite footprint grid using a weighted average based on the occurrence of the same local incidence angle. A uniform snow depth and temperature is assumed within each satellite footprint.

The lookup tables are generated by inputting the snow depth and temperature into the RTM model for a range of local incidence angles (25°–80°), snow depths (1–200 cm), and snow temperatures (223–273 K). One 18.7 GHz Tb and one 36.5 GHz Tb are calculated for each combination of snow depth and temperature and for each terrain grid. Then, the observed Tb is compared to the calculated average Tb in the lookup tables and corresponding snow depth and temperature of each footprint grid is estimated (Figure 1).

Results and Conclusions

The algorithm was applied to the Puna Tsang river basin in Bhutan (Figure 2). Due to the lack of *in situ* snow observation, it was validated against the outputs of snow depth of the WEB-DHM-S (this model is described in sub-section 1 above by Shrestha et al. (2012)). WEB-DHM-S outputs of stream discharge and snow cover area were validated with measured flow discharge at 4 gauge stations and MODIS snow cover area, respectively. As indicated by comparison in Figure 3, the RTM successfully estimates the snow depth trend and seasonal behaviour of the snow cover areas. The best spatial correlation of 0.3 was for 26 February 2006.

The developed method is a useful tool for snow depth estimation from satellite observations in the snow-melt dependent basins. Together with the WEB-DHM-S model, these tools are essential for further research on climate change impacts on water cycle in AWCI countries with cold regions.

Bias Correction Method for Climate Change Impact Assessment

Realistic representation of precipitation fields in future projections from climate models is crucial for impact and vulnerability assessments. However, General Circulation Models (GCMs) often fail to simulate regional climate features required by basin-scale impact studies due to inadequate parameterization of several processes associated with cloud formation and land surface interactions with the atmosphere. To overcome this issue, a comprehensive statistical bias correction method for climate change assessment on the catchment scale was developed for applications in the AWCI basins (Nyunt et al., 2013). The method was applied and validated in the Pampanga,

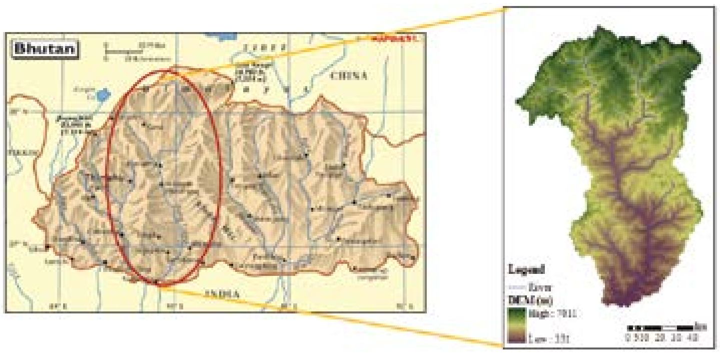


Figure 2. Puna Tsang river basin in Bhutan

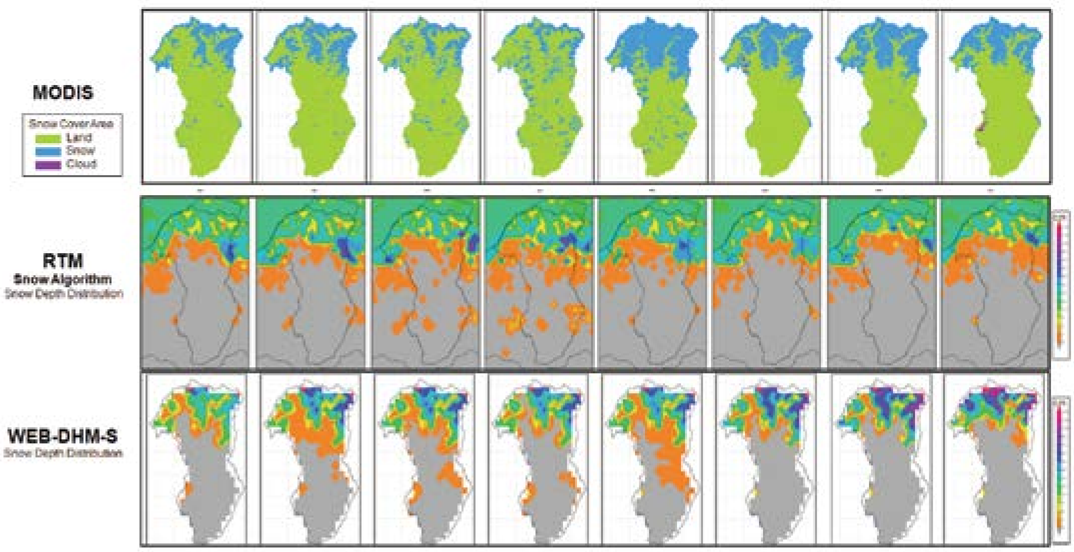


Figure 3. Snow depth spatial distribution over the target region from October 2005 to May 2006

Angat, and Kaliwa basins in the Philippines (Figure 4).

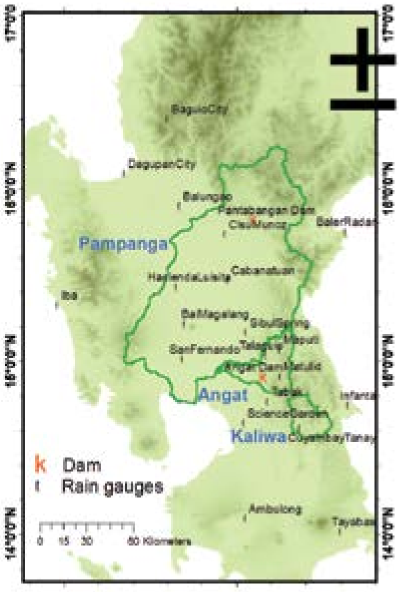


Figure 4. Location of Pampanga, Angat and Kaliwa Basins

Method Description

The method uses an ensemble of available GCM outputs (daily values) and begins with selection of suitable GCMs for a given region. Then the daily precipitation output is corrected in three steps including extreme rainfall correction, correction of frequency of wet days (no-rain-day threshold), and correction of frequencies between the no-rain-day threshold and extreme events. The GCM rainfall is corrected using historical *in situ* rainfall observation. The method is in details described in Nyunt et al., 2013).

GCM selection

GCM selection is based on historical simulation of daily rainfall and other atmospheric parameters of 24 GCMs from the Coupled Model Intercomparison Project 3 (CMIP3) project over a targeted area. The scores are determined from spatial correlation coefficient (Scorr) and root mean square error (RMSE), which are derived from comparison of model outputs with reference data sets. Reference data sets include Global Precipitation Climatology Project (GPCP) products for precipitation and Japanese 25-year Reanalysis Project (JRA-25) for other atmospheric parameters. The area of interest for GCM selection in this study covered the Bay of Bengal, Indian Ocean, Philippine Sea, Java Sea and part of Southeast Asia (80°E–160°E and 0°N–20°N), while a smaller window is used for precipitation (115°E–130°E and 10°N–20°N).

Rainfall Bias Correction

The analysis of extremes has traditionally been tested using annual maximum series (AMS), and adjusted to suitable distributions (Gupta & Duckstein, 1975). However, this causes a loss of further high rainfall events within one year that may be considered extremes and that may exceed the maximum rainfall of other years. Therefore a new approach is employed to correct both intensity and frequency of extreme events. It is based on partial duration series (PDS), which are constructed using values above a threshold regardless of their year of occurrence, and permit inclusion of more than one event per year (Hershfield, 1973). The generalized Pareto distribution (GPD), which is the limit distribution of excess over a threshold series, is used to model PDS (Bobee & Rasmussen, 1995). A major issue of using PDS is the selection of threshold rainfall value to fit GPD. In this study, the lowest AMS from observed rainfall is defined as the first trial threshold of the GPD series. The same number of extreme events is defined for GCM gridded series by ranking. Then, GCM series are fit to the GPD and bias-corrected GCM precipitation is calculated:

$$x'_{GCM} = F^{-1}_{OBS}\left(F_{GCM}\left(x_{GCM}\right)\right) \qquad (1)$$

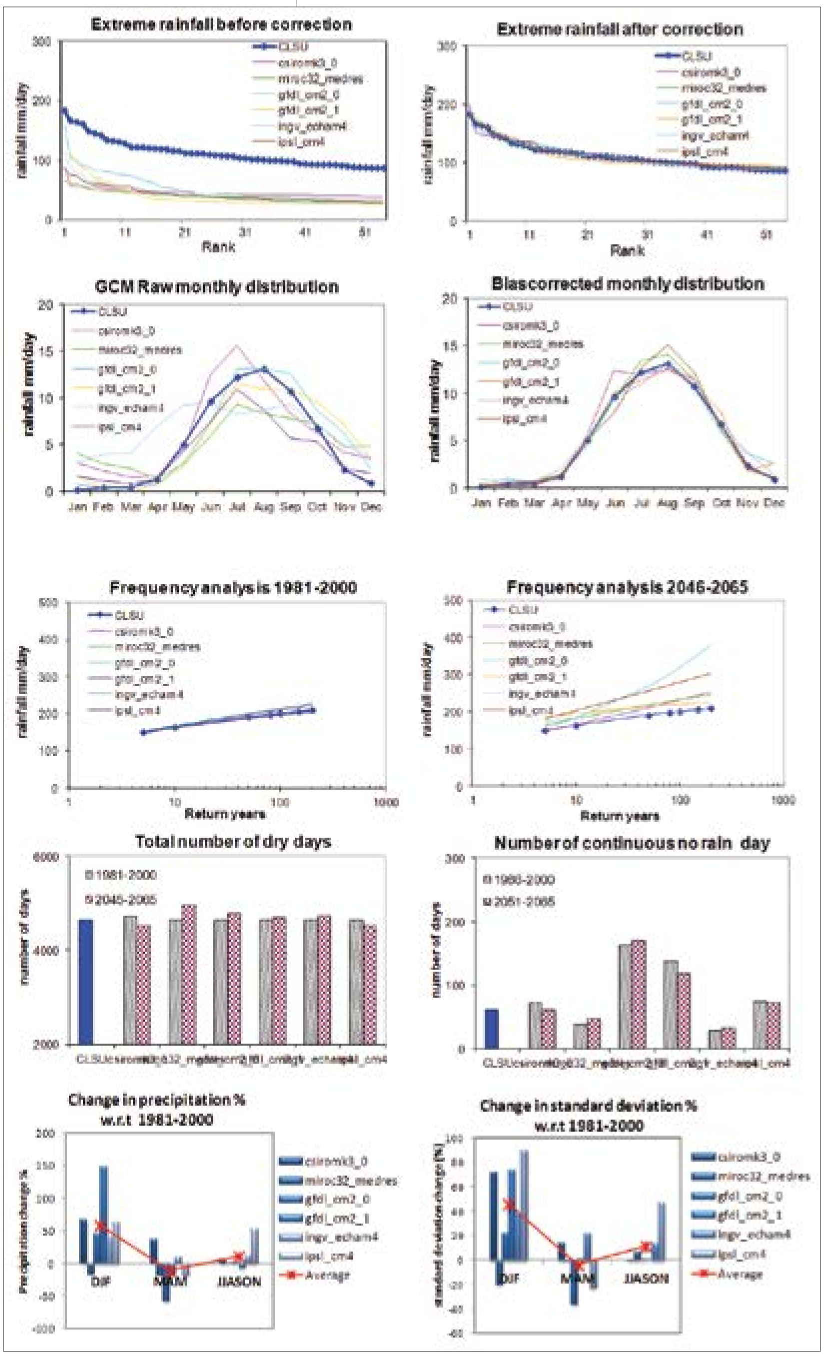
where x'_{GCM} is bias-corrected extreme rainfall, F^{-1}_{OBS} is the inverse function of GPD probability of observed rainfall, F_{GCM} is the GPD probability of GCM rainfall, and x_{GCM} is the raw GCM output. Moreover, the corrected extreme rainfalls are calibrated by tuning the different thresholds to minimize RMSE between the corrected GCM and the observed extreme. The future projection rainfall is corrected by applying the same transfer function between GCM and observations during the historical period:

$$x'_{GCM\_fut} = F^{-1}_{OBS}\left(F_{GCM\_past}\left(x_{GCM\_fut}\right)\right) \qquad (2)$$

where x'_{GCM_fut} is the future bias-corrected rainfall F_{GCM_past} is the GPD probability of GCM rainfall for historical period, and x_{GCM_fut} is the raw GCM future projection.

The next step is to correct the frequency of wet days because most GCMs generate unrealistic low-intensity rainfall during a large number of wet days. This issue is resolved by using the ranking order statistics of the entire time series. The total frequency of wet days in the observed data set is attained and applied to the GCM output to find the threshold rank and rainfall value, below which the GCM output is then considered zero, i.e. no-rain-day. For future projection, the same threshold for no-rain-day correction is used.

Figure 5. Results of the bias correction of six selected GCM rainfall outputs using *in situ* observations at the CSLU station in the Pampanga basin



Finally, rainfall intensities between the extreme and no-rain-day thresholds are classified as normal rainfall in both observed data and GCMs. A two-parameter gamma distribution is used to correct bias of normal rainfall. It is assumed that the cumulative distribution function (CDF) of normal daily rainfall at a certain grid point follows the gamma distribution function. The daily GCM and observed rainfall data are fitted to a two-parameter gamma distribution for 12 months. Then, the CDF of daily GCM rainfall is mapped to the CDF of observed data for each month. The corrected normal rainfalls are calculated by the fitted gamma CDF using Eq. 1. This procedure adjusts only the rainfall intensity at monthly scale; it does not correct any errors in monthly frequency. The same transfer function for future projection is used (Eq. 2).

Application at the Pampanga Basin

The method was applied and validated at the Central Luzon State University (CLSU) station in the Pampanga basin. The Philippine Atmospheric, Geophysical and Astronomical Services Administration (PAGASA) and MWSS provided the *in situ* data. CMIP3 GCM gridded daily precipitation was acquired from the DIAS server, developed at the University of Tokyo. The control historical period was 1981–2000 and the projected period was 2046–2065, under the Special Report on Emissions Scenarios (SRES) A1B.

Results and Conclusion

Six GCMs were selected according to their simulated performances over Luzon Island in the Philippines, to reduce the uncertainty of single GCM use. The results of bias correction are shown in Figure 5. The biases of extreme rainfall are successfully controlled by GPD fitting of their sorted ranks, not only in frequency but also in intensity of extremes. The method was validated through frequency analysis of extremes during the control period and then the trends in extreme intensities were identified (Figure 5, third row). It is important for deciaion-making and infrastructure design in future strategies. All GCMs show general increases in intensity in future, except the INGV_ECHAM4 which is the same as CLSU in high return years.

Frequencies of no-rain-days were corrected as described in the previous section. The analysis of future projections showed that four out of six GCMs predicted larger numbers of total dry days in the future, by nearly 70 to 80 days (Figure 5, fourth row). After correcting all the components including normal intensity rainfall, the seasonal variability was validated against observation, which was well captured (Figure 5, second row). Remaining small discrepancies originate from errors in the monthly frequency distribution. The future change in seasonal rainfall (%) and standard deviation change (%) for three seasons with respect to 1981–2000 was investigated (Figure 5, bottom row). DJF is December-January-February, MAM is March-April-May and JJASON is wet season from June to November. By averaging all GCM outputs, maximum increase in precipitation is indicated for winter, while there is a decrease during the monsoon season and a small increase during the rainy season.

The developed statistical bias correction method was validated for both intensity at a point and for long-term average seasonal rainfall climatology. It can be applied in further hydrological impact studies analysing river discharge and other hydrological parameters at the basin scale.

Impacts of Climate Change Assessment and Runoff Simulation in Philippine Basins

The study (Jaranilla-Sanchez et al., 2013) is an example of an analysis of possible impacts of climate change on water resources in an AWCI country using some of the tools introduced in previous sections. The objective is to assess these impacts in three river basins in the Philippines, including Angat, Kaliwa and Pampanga in terms of flooding trends and drought trends. To accomplish this, hydrometeorological parameters (rainfall, temperature, short wave and long wave radiation) from CMIP3 GCMs archived in DIAS were used as forcing data for a hydrological model to determine past and future climate change projections at the three river basins.

Method and Data

Selected GCM ensembles were incorporated into the Water and Energy Budget-Based Distributed Hydrological Model (WEB-DHM; Wang et al., 2009a,b) and 1981–2000 (past) versus 2046–2065 (future) impacts on floods and droughts were analysed by focusing on climate change effects on surface flow. However, large biases in GCM output (especially in precipitation) need to be reduced as well as the mismatch of grid resolution between GCM outputs and basin-scale hydrological model inputs. The three-step bias correction described in the previous section was used prior to GCM output utilization. Spatial downscaling by bias correcting on 21 gauges with observed data were employed while temporal downscaling by using specimen hourly rainfall distribution for different intensities were used. Analysis of flooding trends were based on the analysis of the 10th percentile of peak flow trends while for drought, low flow was analysed based on the second lowest of the 20-year past drought discharge (355th value descending order). Long-term drought intensity trends were analysed using the Standard Anomaly Index (SA; Jaranilla-Sanchez et al., 2011) applied to discharge flows in each basin to quantify (monthly scale) drought trends for the past versus the future. This index can be utilized to determine drought frequency and intensity using at least 20 years of monthly data sets from different hydrological parameters by fitting an appropriate distribution pattern to the monthly data and standardizing and categorizing the deviations from the mean with increasing dryness (if below -1).

The study included three river basins: Angat (1,085 km^2), Kaliwa (280 km^2) and Pampanga (10,981 km^2) (Figure 4). There are two dams (Angat and Pantabangan) and several water conveyance constructions in these basins including Umiray-Angat tunnel, Casecnan trans-basin tunnel, Aurora trans-basin channel and Masiway spillway outflow that are considered in the simulations. Digital elevation model was derived from 90 m SRTM data and re-sampled to 500x500 m grid size. The soil and land-use data were prepared from local maps and re-classified according to the FAO and SiB2 categories.

In situ meteorological forcing data used for calibration and historical simulations were taken from 12 local gauges and include: surface air temperature (K), relative humidity (%), total cloud cover (%), downward long wave and short wave radiation flux at surface (W/m^2). Rainfall was from daily data in 12 meteorological stations and 35 synoptic stations. These were spatially distributed and downscaled by inverse distance weighing interpolation (IDW). The Nash Coefficients (Nash; Nash & Sutcliffe, 1970) and relative errors (RE) were used in the WEB-DHM calibrations of the 3 basins.

GCM forcing data for future simulations include output of 6 models: gfdl_cm2_0, gfdl_cm2_1, ipsl_cm4, ingv_echam4 and miroc3_2_medres. The selection procedure (described in the previous section) considered seven parameters: precipitation, longwave radiation, sea surface temperature, sea level pressure, air temperature, meridional and zonal wind. The three-step bias correction method (described in the previous section) was used to correct rainfall while no bias correction was done for the other meteorological parameters (temperature, short wave and long wave radiation). Spatial downscaling was done by correcting the biases on each of 21 selected rain gauge data, temporally downscaling them using average hourly rainfall factors from several rain gauges and re-gridding the hourly rainfall data. Hence this method assumes that future rainfall will have similar climatology and distribution as that of past rainfall. Soil moisture verification in the basin for the WEB-DHM calibration used the Land Data Assimilation System developed by the University of Tokyo (LDAS-UT; Yang et al., 2007).

Results and Conclusions

Calibration of Angat dam inflow was done by comparing dam inflows for the year 2003 (Nash=0.72, RE=23%). Currently there are no installed streamflow gauges in the Kaliwa river basin. Hence calibration of this basin was done by assuming similar soil properties for the same soil types in Angat and Kaliwa. Calibration in the Pampanga river basin was done for 2002 upstream in Pantabangan dam (Nash=0.5, RE=3.8%), Cabanatuan (Nash=0.05, RE=83%), Zaragoza (Nash=0.35, RE=34%), San Isidro (Nash=0.22, RE=50%) and 2001 for Arayat streamflow gauge (Nash=0.31, RE=24%). Results showed that the temporal behaviour of soil moisture from basin scale hydrological modelling and larger scale estimation using LDAS-UT can be used to estimate large scale soil moisture of the area. RE was found to be 2.23%. The simulated soil moistures assimilated by LDAS-UT and simulated by WEB-DHM were not used to project future climate change effects on basin scale droughts since the focus of the study was mainly on the behaviour of discharge during extreme events.

Peak flow trends can be good indicators of future floods. Results after ranking (in descending order) the past and future 20 years daily discharge show that similar patterns can be expected in the near future. However, the 10th percentile peak daily discharges for Angat, Kaliwa and Pampanga river basins showed that all 6 models of each basin had higher peak discharges in the future (Figure 6). In all 3 basins, highest peak discharge can go from 1.5x to 6x increase from past values while the remaining 19 peak flows show only a slightly higher (1x) to double (2x) the past peak values. These simulations were under the assumption

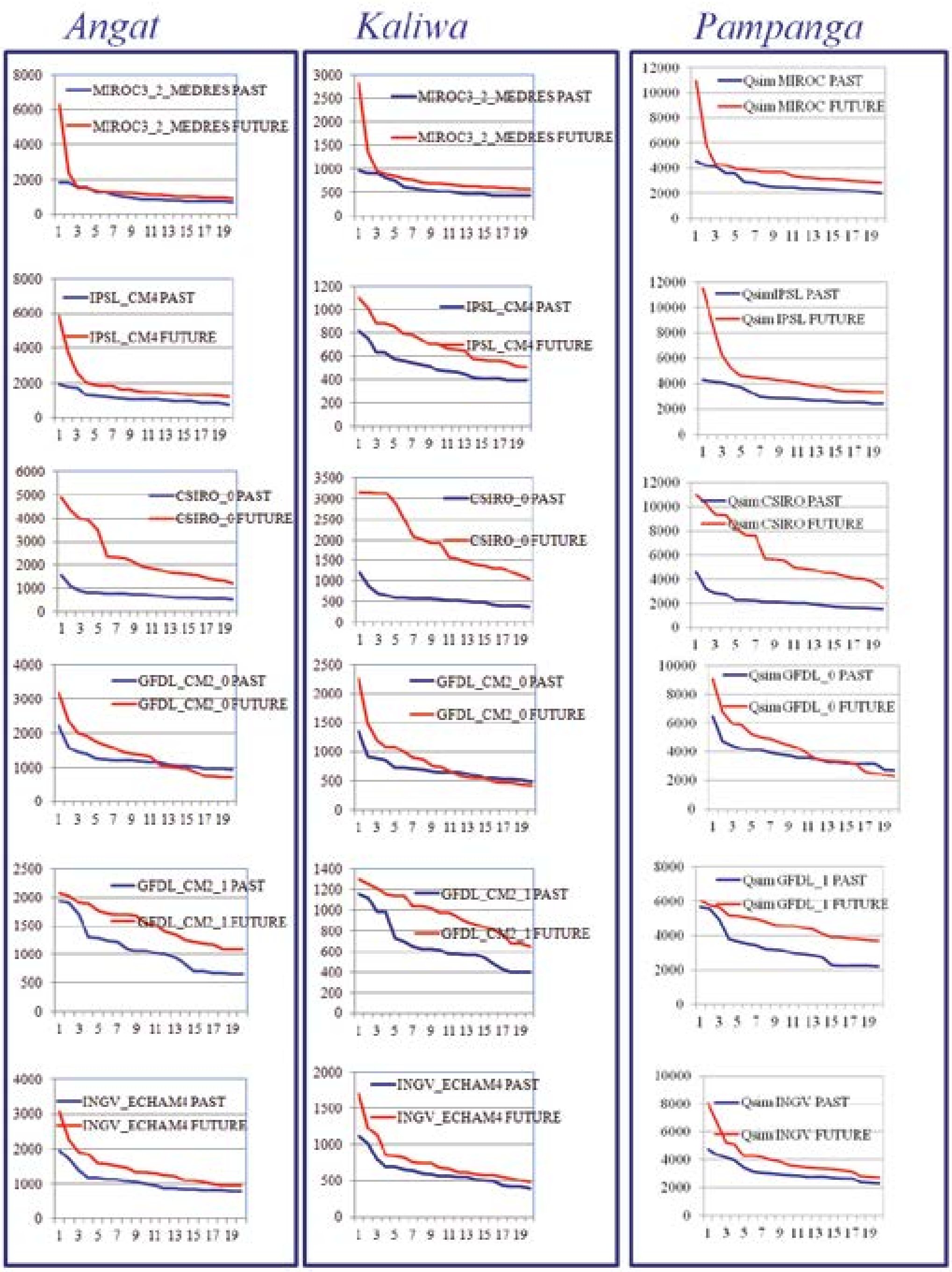


Figure 6. The 10th percentile peak flows for past (blue) and future (red) simulations in the Angat, Kaliwa and Pampanga basins

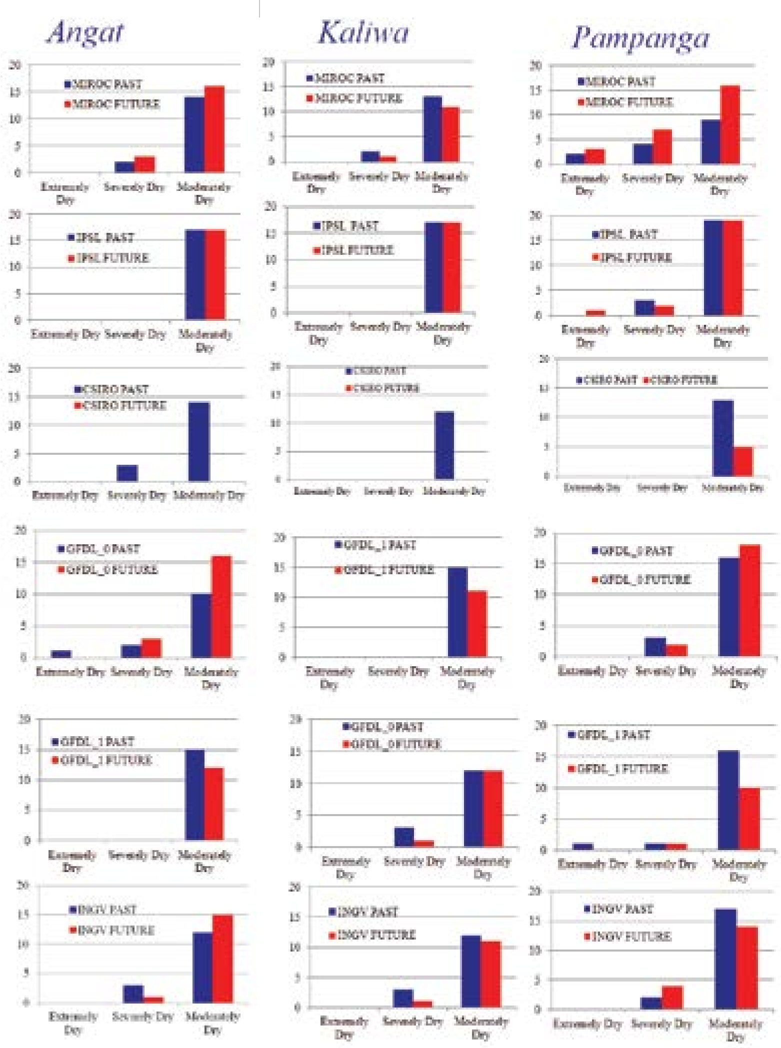
that climatology will be similar in the past and in the future. However, even after bias correction and temporal downscaling, only the intensities and frequency of the extreme events can be simulated. Further studies are still needed to improve the timing as to when the extreme events occur.

Base flow trends were used to determine drought trends in future. The 355th rank of the past climatologically averaged daily discharge simulation was used as the basis of drought discharge. The 10th percentile was additionally used to identify drought discharge for the 20 year simulation in past GCMs. The number of days that base flow was less than past drought discharge was identified as well as the longest number of days each year that is below average drought discharge. The Angat and Kaliwa river basin show a 50%–60% chance of drought in the future while a 90% chance of increasing drought conditions in the future is shown in the Pampanga river basin. This difference is due mainly to the local land-use and climatologic conditions (forest and higher rainfall in the two smaller basins vs. croplands and low rainfall in Pampanga). The SA drought index was used to project longer duration (at least one month) drying trends in the future (Figure 7). For Angat, 3 models increase, 2 models remain the same and 1 model decreased while for Kaliwa, 4 models decreased and 2 models remained the same. For Pampanga, only miroc model increased in all SA categories while the rest showed different degrees of increase and decrease in the categories.

Conclusion

This article introduced several outcomes of the research work carried out in the AWCI countries and contributing to the highlighted APN project. Advanced tools and methods were developed to enable climate change impact assessment on water cycle in basins in Asia, including WEB-DHM-S, a hydrological model addressing snow and glacier processes, a method for snow depth distribution estimation in mountain regions, and a GCM precipitation output bias correction technique. A comprehensive study on climate change impacts in three basins in the Philippines, employing some of the developed tools, was carried out and indicated a very likely increase in flood intensities and frequencies in all the basins. On the other hand, the results also suggested that severe droughts are very likely to occur in the Pampanga river basin but not as likely in Angat and Kaliwa basins, with local conditions playing a very important role in how floods and droughts affect them. Careful consideration of uncertainty should be considered for water resource management planning factoring in future climate changes in these basins.

Figure 7. Long-term drought intensity analysis using Standard Anomaly Index



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PROJECT TITLE

River Management System Development in Asia Based on Data Integration and Analysis System (DIAS) under the GEOSS

COUNTRIES INVOLVED

Bangladesh, Bhutan, Cambodia, India, Indonesia, Japan, Korea, Lao PDR, Malaysia, Mongolia, Myanmar, Nepal, Pakistan, Philippines, Sri Lanka, Thailand, Uzbekistan, Viet Nam

PROJECT DURATION

2 years

APN FUNDING

US$ 90,000

PROJECT LEADER

Prof. Toshio KOIKE

Department of Civil Engineering, School of Engineering, The University of Tokyo
Bunkyo-ku, Tokyo 113-8656, Japan

Tel: +81 3 5841 6106

Email: tkoike@hydra.t.u-tokyo.ac.jp

Website: http://aqua.t.u-tokyo.ac.jp/REEL/