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Impacts of climate change on streamflows under RCP scenarios: A case study in Xin River Basin, China

Yuqing Zhang [a], Qinglong You [a,*], Changchun Chen [b], Jing Ge [a]

[a] Key Laboratory of Meteorological Disaster, Ministry of Education (KLME)/Joint International Research Laboratory of Climate and Environment Change (ILCEC)/Collaborative Innovation Center on Forecast and Evaluation of Meteorological Disasters (CIC-FEMD), Nanjing University of Information Science and Technology (NUIST), Nanjing, 210044, China
[b] School of Geography and Remote Sensing, NUIST, Nanjing 210044, China

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ABSTRACT

Researchers often examine hydro-climatological processes via Global Circulation Model (GCM) and hydrological model, which have been shown to benefit water resources management and prediction, especially at the basin scale. In this study, the Soil and Water Assessment Tool (SWAT) and Statistical Downscaling Method (SDSM) were integrated and applied to estimate streamflows in the Xin River Basin, China, based on climate change scenarios downscaled from different GCMs (BCC-CSM1.1, CanESM2, and NorESM1-M) under three Representative Concentration Pathways (RCPs). Results confirmed that the calibrated SWAT model accurately depicts hydrological processes features at daily, monthly, and yearly scales. Three GCMs based on the calibrated SDSM showed that temperature is continually increasing in the region, however, future precipitation is highly complex and uncertain; there were significant differences among various GCM RCP scenarios. The average of the precipitation in three models showed slight and steady increase trends under RCP2.6 and RCP4.5, but a significant increase under the RCP8.5 scenario. The ensemble average of streamflow in GCMs demonstrated that many RCPs significantly decrease from May to June but increase from August to September relative to the baseline period. The ensemble mean of the multi-GCM indicated that future streamflows under RCP2.6 and RCP4.5 scenarios will be closer to the current streamflow volume. Many RCPs also revealed a significant increase in monthly streamflow dispersion coefficient in October, reflecting a tendency for drought and flood events in that month. The BCC-CSM1.1 and NorESM1-M models showed that streamflows are higher than the baseline with median probability in the future. The low monthly streamflow (10th percentile) processes for each GCM were altogether similar to the baseline, whereas the high monthly streamflows (90th percentile) showed various levels of disparity compared to the baseline.

1. Introduction

As mentioned in the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR5), the current global average surface temperature warmed by 0.85 °C from 1880 to 2012, and the beginning of the 21st century has been the warmest on record (IPCC, 2013). The increase in global temperature has caused higher evapotranspiration rates leading to changes in precipitation worldwide (Paparrizos et al., 2016; Urrutia and Vuille, 2009), and significantly impacted hydrological processes and the occurrence frequency of hydrological events (i.e., floods and droughts). Complex meteorological situations affect streamflow regimes, especially at the basin scale, which is the focus of the present study.

The general circulation model (GCM) is a type of climate model which mathematically represents the general circulation of a planetary atmosphere or ocean. The impact of climate change has been widely studied using GCMs, which are considered one of the most effective tools for exploring the physical processes of the earth's surface-atmosphere system; GCMs can provide very credible information in regards to historical, current, and future climate (Gonzalez et al., 2010; Jing et al., 2015). GCMs are limited to regional studies, however, because their spatial resolution is too coarse to be compatible with hydrological models necessary to simulate sub-grid or basin-scale hydrological processes, the downscaling method can be utilized to bridge these two different scales. The Coupled Model Intercomparison Project Phase 5 (CMIP5) established new climate change scenarios called Representative Concentration Pathways (RCPs) (Meinshausen et al., 2011; Taylor et al., 2012), which can depict a wide variety of possible future climate scenarios. Thus, RCP scenarios represent an attractive potential approach for further research and assessment, including emissions mitigation and impact analysis (Van Vuuren et al., 2011). Xin et al. (2013) pointed out that the BCC-CSM1.1 (Beijing Climate Center, Climate System Model, version 1.1) model provides a fairly accurate representation of climatology over East Asia despite some biases. The CanESM2 (Second Generation Canadian Earth System Model) model can also simulate

* Corresponding author.
E-mail address: yqingl@126.com (Q. You).

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the variability of surface air temperature over China quite well via a series of six statistical measurements (Chen and Frauenfeld, 2014). Siew et al. (2014) demonstrated that the NorESM1-M (Norwegian Earth System Model, version 1) model can also realistically simulate the climate over Southeast Asia and is suited to future climate projection. Considering the same atmospheric circulation predictors and period lengths among different GCMs, as well as their applicability to East Asia, we finally selected three well-suited GCMs to assess the effects of climate change on streamflows in China.

The SWAT hydrological model, a physical-based, semi-distributed, basin-scale hydrological model, is one of the most appropriate applications for investigating simulated streamflow response to climate change. Recently, the impact of climate change on hydrological processes has garnered considerable attention resulting in a wealth of numerical modeling studies in many regions throughout the world (Khoi and Suetsugi, 2012). For example, Musau et al. (2015) assessed the impact of climate change on the streamflow in Mt. Elgon watersheds using the 10-GCM Special Report on Emissions Scenarios (SRES) in combination with the SWAT model. To examine water resource shortage and salt water intrusion during dry seasons in Pearl River, China, Yan et al. (2015) evaluated the variations in low flow using the Variable Infiltration Capacity (VIC) model driven by bias-corrected results of five GCMs under scenarios RCP4.5 and 8.5. Alfieri et al. (2014) presented the current status of the European Flood Awareness System (EFAS) monitoring and evaluation framework based on the Lisflood model driven by outputs of the ECMWF (European Centre for Medium-Range Weather Forecasts).

The Poyang Lake Basin, which is characterized by the largest freshwater lake in China, has been affected by severe and frequent floods and droughts especially in the past two decades (Ye et al., 2015; Zhang et al., 2015). The Xin River Basin (XRB) is an important geographical region due to the fact that it has the second largest volume of runoff in the Poyang Lake Basin. Accurate assessment of the potential impact of climate change on hydrological processes, as mentioned above, is a highly valuable and urgent endeavor in terms of controlling and mitigating disaster events, managing water resources, and facilitating regional development. As of now, though several studies have investigated hydroclimatic changes in the Poyang Lake Basin, few have focused on future streamflow regimes' responses to climate change scenarios specifically by using multiple-GCM downscaling methods in a basin-scale hydrological model. In this study, we projected the future impact of climate change on runoff via SWAT using data from three GCMs archived in the CMIP5 and according to the Statistical Downscaling Method (SDSM). We compared streamflow characteristics in three future periods (2010–2039, 2040–2069, 2070–2099) of the RCP2.6, 4.5 and 8.5.

The primary objective of this study is to present a comprehensive analysis of streamflow response to climate change scenarios using SDSM and SWAT models in the XRB. The most notable aspects of this work include: 1) characteristics of temperature and precipitation as projected from three CMIP5 GCMs under RCP scenarios using a statistical downscaling model; 2) future streamflows as modeled by the calibrated SWAT model together with downscaling outputs; and 3) different streamflow indices analyzed for GCMs under different future scenarios. The findings presented here may provide a scientific reference for decision-making regarding basin-scale flood control, drought resistance, and water resources management in the XRB as well as other regions that share similar climatic characteristics.

2. Materials and methods

2.1. Study area

The XRB is located in the northeastern part of the Poyang Lake Basin, Southeast China (Fig. 1). The basin has an area of 15,535 km^2 dominated by a subtropical humid monsoon climate, which is governed by the East Asian monsoon. The average annual precipitation is approximately 1800 mm and annual temperature is about 18 °C. Nearly 60% of the annual total precipitation occurs during the rainy season from March to June; peak flow usually occurs during the rainy season and is often accompanied by severe floods. Mountainous regions and subordinate hilly areas occupy nearly 75% of the total basin area, and plains occupy the remaining 25%. Land use across the basin consists of forest (67%), agriculture (26%), and small areas of other types. Red soil is the most common soil type, covering more than 60% of the basin. The annual runoff is about 181.6×10^8 m^3, giving XRB the second-largest runoff volume in terms of streamflow in the Poyang Lake Basin.

2.2. Data

2.2.1. Hydro-meteorological data

Daily streamflow data for 1961–2012 at Meigang gauge station were provided by the Jiangxi Hydrological Bureau. These data were used to calibrate and validate our hydrological model. Meteorological data (1961–2013) including daily maximum (*Tmax*) and minimum (*Tmin*) temperature, precipitation, relative humidity, wind speed, and solar radiation were provided for nine meteorological stations by the China Meteorological Administration (CMA) and applied to build the SWAT weather generator database. Detailed information for these stations is listed in Table 1. Daily *Tmax*, *Tmin*, and precipitation records served as predictands in the downscaling model, as these high-quality data were sufficient to establish, calibrate, and validate the downscaling model.

2.2.2. Geospatial data

Geospatial data used in this study included digital elevation model (DEM), actual stream network information, soil type, and land use. The 90 × 90 m SRTM (Shuttle Radar Topography Mission) DEM, in raster format, came from the International Scientific and Technical Data Mirror Site (http://www.gscloud.cn). The DEM data were used to extract flow direction and accumulation, create streams, delineate the watershed, and calculate subbasin parameters. Land use data at 1:25,000 scale was provided by the Data Sharing Infrastructure of Earth System Science, and reclassified according to SWAT land use database requirements. Soil data with a 1:1 million scale was downloaded from the Environmental and Ecological Science Data Center for West China, which was originally established using the Harmonized World Soil Database (HWSD) from the International Institute for Applied System Analysis (IIASA), with the standard depths of 0–30 cm and 30–100 cm. More detailed information about the soil database can be found in our references (FAO et al., 2009). Hydrological attributes of each soil type were calculated using Soil–Plant–Atmosphere–Water model (SPAW) software and relevant empirical formulae.

2.2.3. NCEP reanalysis data

Daily reanalysis data for 1961–2013 was obtained from the NCEP/NCAR (National Center for Environmental Prediction/National Center for Atmospheric Research) (Kalnay et al., 1996). This data is usually regarded as a set of observed large-scale atmospheric variables with a resolution of 2.5° (longitude) × 2.5° (latitude), and includes many large-scale atmospheric variables such as geopotential height, horizontal wind, pressure, specific humidity, relative humidity, and others.

2.2.4. RCP scenario data

The RCP database (Moss et al., 2008) provides documentations of the emissions, concentrations, and land-cover change projections of the so-called RCPs. Three GCM outputs of CMIP5 under RCP2.6, 4.5, and 8.5 (representing a very low forcing scenario, medium stabilization scenario, and very high emission scenario, respectively) were utilized to project future climate scenarios. The RCP2.6 scenario (Van Vuuren et al., 2007) reflects very low greenhouse gas concentration levels, with a radiative forcing level that first reaches about 3.1 W/m^2 in the middle period of the 21st century before returning to 2.6 W/m^2 by the year 2100. In