.

THE ASSESSMENT OF CMIP5 MODELS IN THE CONTEXT OF COMPLEMENTARY RELATIONSHIP OF AREAL EVAPOTRANSPIRATION

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ABSTRACT

The moisture in the atmosphere implements a key role in evapotranspiration process among all meteorological variables governing hydrological energy and water cycle. In atmospheric dynamics, it functions to maintain the energy balance between land surface and atmosphere through precipitation process. Additionally, the evapotranspiration has significant effects on flow-duration curve of long-term streamflow particularly below ordinary and low flow regime. Most climate models have an evapotranspiration module, but lack of observations limits the validation of model performance. The purpose of this paper is to verify the simulation capability of the evapotranspiration module of the CMIP5 (Coupled Model Intercomparison Project Phase 5) climate models in the lack of observational data. The hypothesis of the complementary relationship between potential and actual evapotranspiration was verified in multi-purpose dam basin and then utilized for assessing the evapotranspiration outputs under reference scenario by the CMIP5 models. The 5 GCM datasets with the highest performance among the GCMs provided by CMIP5 in Korean region were collected and clipped into the study area of the Soyanggang dam basin in Han River, the South Korea. The actual evapotranspiration data of raw GCMs are shown to be overestimated during 1974~2000 of the reference period and the regional biases were corrected through the quantile mapping. The overall quantitative performance of individual GCM model was improved through the generic regional bias correction. However, the additional bias correction was required for balancing long-term mosture budget between precipitation and evapotranspiration expressed through the complementary relationship between the actual and potential areal evapotranspiration. In order to obtain representative scenario, the Bayesian multi-model ensemble averaging scheme was applied and resulted in sufficiently reliable performances in terms of absolute biases and reproducibility of complementary relationship. This methodology allowed reducing the uncertainty arising from the direct use of actual evapotranspiration of GCMs and consequently expected to contribute in improving reliability of the estimation of low flow during non-flood season for dam inflow projection.

Keywords: Complementary relationship, evapotranspiration, Bayesian model averaging, Low flow regime

1 INTRODUCTION

Evapotranspiration is an important factor that greatly affects the global water cycle, although its absolute amount is relatively small. It consists of evaporation, which evaporates through soil or water surface, and transpiration, which emits water vapor through the pores of vegetation. The transpiration is closely related to land use and vegetation coverage. Also, evapotranspiration is directly transformed into the moisture in the atmosphere and eventually occurred as precipitation to an extent after undergoing condensation process. From a global point of view, the 60% of global precipitation is directly transferred into atmosphere as the form of evapotranspiration (Trenberth et al., 2009). As such, evapotranspiration accounts for a large part of the total water budget in the hydrological cycle, which is an important factor to be considered in the management and planning of water resources.

Since it is technically limited to measure the actual evapotranspiration over the whole watershed or country for operational purposes, a method for estimating it through indirect calculation has been proposed. Bouchet (1963) first proposed the hypothesis of complementary relationship between potential evapotranspiration (ETP) and actual evapotranspiration (ETA).. This hypothesis has been used in a number of studies to estimate the exact runoff using evapotranspiration and has been applied to the watersheds with various spatial scales (Brutsaert and Parlange, 1998; Golubev et al., 2001; Ozdogan and Salvucci, 2004; Yang et al., 2006; Pettijohn and Salvucci, 2009). However, the above studies are only aimed at assessing the applicability of the Advection-Aridity (AA) model of Brutsaert and Stricker (1979) and Complementary Relationship of Areal Evapotranspiration (CRAE) model of Morton (1983). The first study by Hobbins et al. (2001a) compared the

ETA calculated by the CRAE and AA model with the same component estimated from the long-term water budget in the 120 watersheds in the United States. The results show that the CRAE model is overestimated and the AA model is underestimated and the parameter correction is necessary for applying the AA model to the dry area. In a second study by Hobbins et al. (2001b), the problem of the AA model's underestimating actual evapotranspirationby was improved by re-evaluating the parameter (α) of the Priestley-Taylor (1972) equation. The Ramirez et al. (2005) performed a number of CRE-related studies but presented a theoretical and conceptual study results due to lack of observational data sets that can validate CRE. The CRE hypothesis was validated by estimating CRE with the annual-scale observation data, defining ETP as pan evaporation and ETA as difference between annual precipitation and runoff. Recently, Ma et al. (2015) estimated the parameter (α) of Priestley-Taylor equation by comparing the ETA estimated by CRE with the observed ETA. Zuo et al. (2016) claimed that pan evaporation has asymmetrical complementary with actual evapotranspiration and asymmetrical complementary coefficient is linear with pan non-uniformity intensity. They found that the CRE proportional constant and ratio of the pan evaporation and the ETP calculated by Penman (1948) are linear.

The CRAE model has been experimented and confirmed in the area with continental scale expected advantageous in projecting interaction between evapotranspiration and precipitation.There are few studies to verify or improve CRE in the region of local scale. South Korea. In this study, statistical verification of the meteorological components and the CRE hypothesis is carried out using the observation data and the CMIP5 climate models for Soyanggang dam basin.

2 STUDY AREA AND DATASETS

2.1 Study area

The study area is the Soyanggang dam basin, which is located upstream of the Han river basin (Fig. 1). The Soyanggang dam basin is a multipurpose dam with a surface area of 70 km^2 and a total reservoir capacity of 2.9 billion tons. The total area of basin is 2,703.3 km^2, and the forest account for 89% of the total area. The average annual precipitation from 1974 to 2014 was 1255.2 mm/yr, of which 71.0%, 891.4 mm/yr, occurred during the flood season (June to September). The average annual temperature for the same period is 9.9 ℃, the annual minimum temperature is -5.5 ℃ (January) and the average maximum temperature is 23.0 ℃ (August).

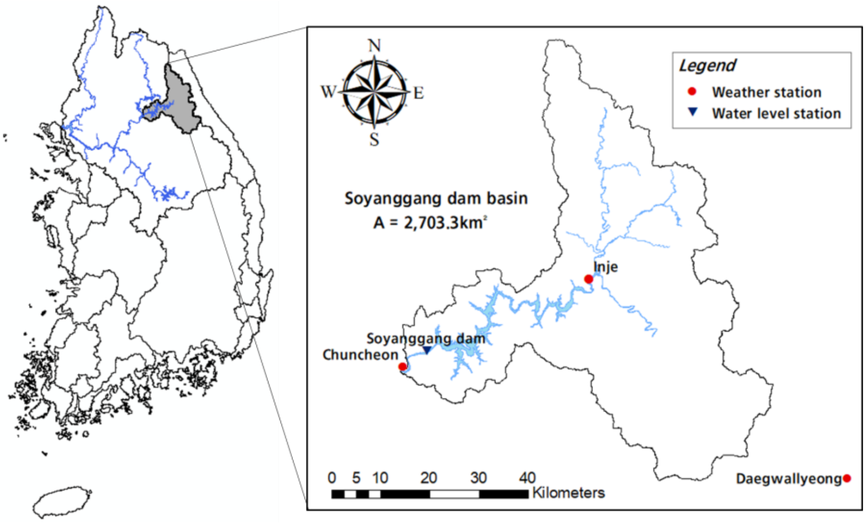


Figure 1. Soyanggang dam basin map and location of gauging stations

2.2 Datasets

2.2.1 Observation data

There are three weather stations (Chuncheon, Inje, Daegwallyeong) located in or around the Soyanggang dam basin managed by the Korea Meteorological Administration (KMA). The meteorological data in those stations include daily precipitation (mm), daily average temperature (℃), daily maximum temperature (℃), daily minimum temperature (℃), daily mean wind speed (m/s), daily average dew point temperature (℃), daily average relative humidity (%), day tide time (hr), day total sunshine duration (hr), and daily pan evaporation (mm). In addition, the monthly dam inflow data from 1974 to 2014 were obtained from the Water Resources Management Information System (WAMIS) of the Ministry of Environment of South Korea.

2.2.2 Global climate model

The output from Global climate model (GCM) can be categorized as atmospheric, oceanic, and terrestrial categories. In this study, the sum of 3 kinds of evapotranspiration; the evaporation from soil, the evaporation from canopy, and the transpiration was used as the actual evapotranspiration data of GCMs. The GCM data of this study is the results of CMIP5 (Coupled Model Intercomparison Project Phase 5) project provided by ESGF (Earth System Grid Federation). Among the CMIP5 GCMs, the output scenarios by ACCESS1.3 and CNRM-CM5 which were validated in the previous study Korea (Moon, 2014) with respect to the region in Korean peninsula have been selected for this study in the Han-river basin in South Korea. In addition, the CanESM2, GFDL-ESM2G, and HadGEM2-AO were included for this study. The GCM grids used for the analysis covering the Korean Peninsula were selected by confirming whether each grid contains terrestrial attribute (Fig. 2). The geometric location of each grid does not necessarily coincide with the geographic features. The layouts of the 5 selected GCMs' grids are shown in Table 1.

Figure 2. Grids located in the South Korea of 5 GCMs

Table 1. Information of the 5 selected GCMs

Modeling Center (or Group)	Resolution (lon × lat)	Institute ID	Model Name	Country
Commonwealth Scientific and Industrial Research Organization and Bureau of Meteorology, Australia	1.875 × 1.25	CSIRO-BOM	ACCESS1.3	Australia
Canadian Centre for Climate Modelling and Analysis, Canada	2.81 × 2.81	CCCMA	CanESM2	Canada
Centre National de Recherches Meteorologiques, Meteo-France, France	1.4 × 1.4	CRNM-CERFACS	CNRM-CM5	France
NOAA Geophysical Fluid Dynamics Laboratory	2.5 × 2.0	NOAA GFDL	GFDL-ESM2G	USA
Met Office, Hadley Centre, UK and Korea Meteorological Administration	1.87 × 1.24	MOHC	HadGEM2-AO	UK

3 METHODOLOGY

3.1 Bouchet's CRE hypothesis

Bouchet (1963) suggests that the CRE hypothesis is based on empirical observations and that potential evapotranspiration (ETP) and actual evapotranspiration (ETA) due to the interactive mechanism between land surface and atmosphere are complementary. From the viewpoint of the CRE hypothesis, the ETP is the water vapor flux under ideal conditions of complete ground cover by plants, uniform plant height and leaf coverage, and an unlimited water supply. The ETP cannot exceed free water evaporation under the same weather conditions. The ETA is the actual amount of evapotranspiration in the area of interest and converge to the wet environment evapotranspiration (ETW) under conditions where the environment is almost saturated and humid enough. In general, the CRE is expressed as Eq. [1].

$$\boldsymbol{ET_A + ET_P = 2ET_w} \quad [1]$$

If there is no water available for evapotranspiration along a surface-atmospheric boundary layer, the ETA will be minimized or not generated, and the ETP, which can be understood as the evaporative power, will be maximized. At this point the absolute rates of change of ETP and ETA are maximized. On the other hand, in an environment with sufficient water content required for evapotranspiration, ETA and ETP curves are symmetrical and converge to the ETW. At this the atmosphere is already almost saturated and the absolute rates of change will vanish. (Fig. 3).

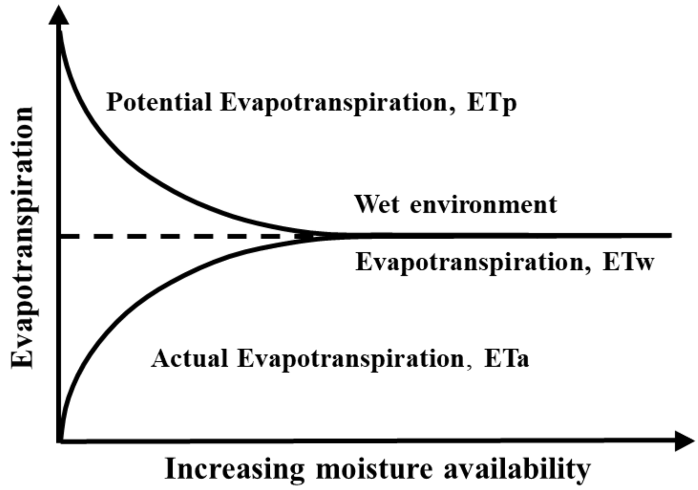


Figure 3. Complementary Relationship of between ETP and ETA (Hobbins et al., 2001a)

3.2 FAO-Penmann-Monteith

Evapotranspiration can vary under different climate and crop conditions. The FAO P-M equation is presented by the Food and Agriculture Organization of United Nations (FAO) to be used as a basis for evaluating the reference evapotranspiraztion (Walter et al., 2000; Droogers et al., 2002; Lage et al., 2003). Evapotranspiration rates of the various crops can be estimated from the evapotranspiration rate from the reference surface (ETO) by means of crop coefficients. The FAO accepted the following distinct definition for the reference surface as "A hypothetical reference crop with an assumed crop height of 0.12 m, a fixed surface resistance of 70 s m-1 and an albedo of 0.23". In other words, the reference surface refers to an extensive surface of green grass of uniform height, actively growing, completely shading the ground and with adequate water. The FAO P-M equation using the Penman-Monteith equation is shown in Eq. [2] (Allen et al, 1998).

$$\boldsymbol{ET_{PM}} = \frac{\mathbf{0.408}\,\Delta(\boldsymbol{R_n} - \boldsymbol{G}) + \boldsymbol{\gamma}\,\dfrac{\mathbf{900}}{\boldsymbol{T} + \mathbf{273}}\boldsymbol{u_2}(\boldsymbol{e_s} - \boldsymbol{e_a})}{\Delta + \boldsymbol{\gamma}(\mathbf{1} + \mathbf{0.34}\boldsymbol{u_2})} \qquad [2]$$

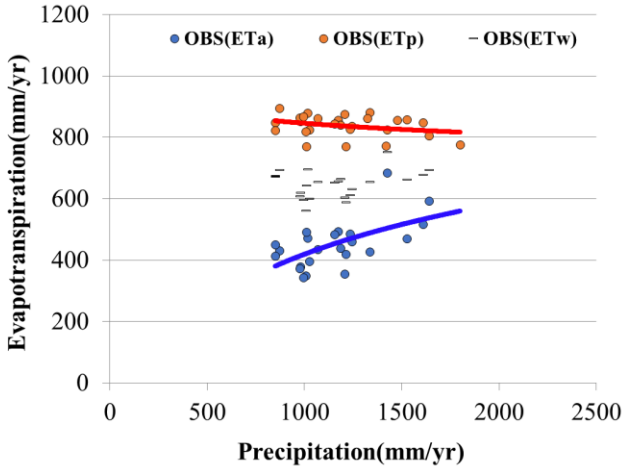
Where ET_{PM} is the Penman-Monteith reference evapotranspiration (mm/day), R_n is the net radiant energy (MJ/m^2/day) that is purely accumulated on the surface (or crop), G is the soil heat flux density (kPa), e_s is the saturated vapor pressure (kPa), e_a is the actual vapor pressure (kPa), Δ is the vapor pressure curve (kPa/℃), and γ is the humidity coefficient constant (kPa/℃). The difference between e_s and e_a is the saturation vapor pressure deficit (kPa).
In this study, the FAO P-M equation was used as the evapotranspiration under wet environment (ETW). and assumed to be. The Hargreaves equation were verified as the reference evapotranspiration and compared with the pan evaporation.

4 RESULTS

4.1 Validity of CRE hypothesis

In order to verify the CRE from the observed data, ETP is estimated as the calibrated pan evaporation value (ETPan(k_p)), ETA is regarded as the difference between annual precipitation and dam inflow, and the moisture availability in Figure 3 was defined as annual precipitation. The above setup can be reasonable under the annual long-term analysis. Figure 4 shows the CRE obtained through independently computed ETP and ETA using the observation data during 1974 - 2000. Generally, Figure 3 shows the maximum value of ETP and the minimum value of ETA under the minimum available moisture. At this state the rates of change of the ETP and ETA reveal to maximum values. As the moisture availability increases, the ETP decreases and the ETA increases. Under the wet condition the rates of change are minimized to zero.

In Figure 4, it was confirmed that the relationship between ETP and ETA follows the general CRE pattern as the moisture availability (annual precipitation) increases. Therefore, it can be regarded that the CRE is reproduced well in the annual data of the Soyanggang dam basin. This phenomenon means that the assumption of ETP for pan evaporation and ETA for difference between precipitation and runoff can be valid under the annual time scale.



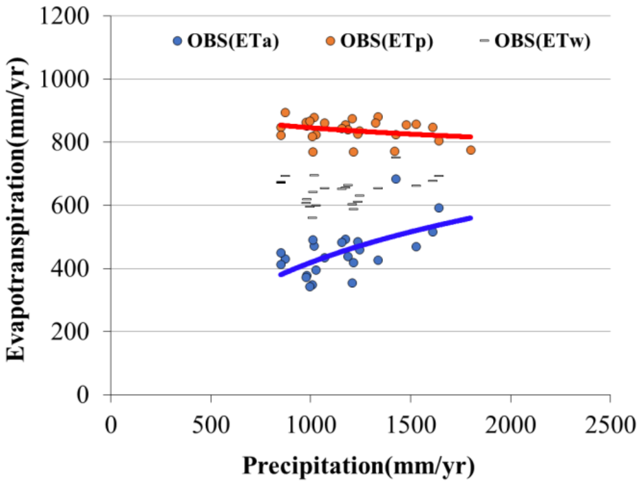


Figure 4. Complementary relationship using observation data in Soyang dam basinduring 1974~2000

4.2 GCM output validation with respect to CRE

The CRE can be used for assessing how well the GCM simulates or predicts the evapotranspiration, The CRE can be estimated using each individual or ensemble GCM data. The ETP was calculated by applying the relative humidity and temperature data from the raw GCM to the FAO P-M equation (Eq. [2]). ETA is direct product of GCM.Figure 5 shows the CREs for the five raw GCM outputs and their simple model average (SMA). Generally most GCM outouts do not follow the typical CRE pattern. The CNRM-CM5 showed the best convergence under the wet condition and the ETP and ETA are symmetrical. However, the ETA was over-estimated. The HadGM2-AO is symmetric and shows weak convergence, but ETA was over-estimated, too. The remaining GCMs of ACCESS1.3, Can-ESM2, GFDL-ESM2G showed high biases from the typical CRE, and the most ETAs were over-estimated with respect to the observed evapotranspiration. These problems were not improved through the simple averaging process for all GCM members.

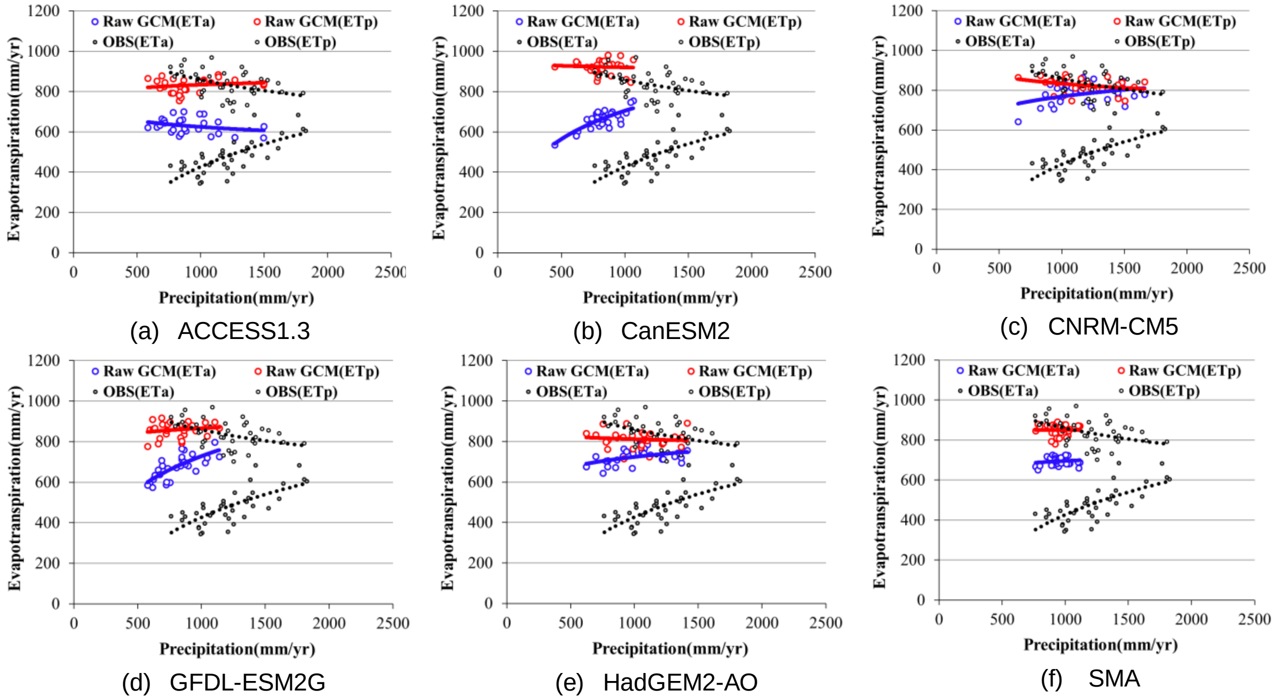


Figure 5. Complementary relationship using the Raw GCM during 1974~2000

To apply the quantile mapping (QM), a regional bias-correction method, a probability distribution should be assumed at first. In the case of the Korean peninsula, the flood season (June to September) is influenced by typhoons and seasonal monosoon called ‘Jangma’, so that about 70% of annual precipitation is concentrated during this period. The flood and nonflood seasons are climatically and statistically different, and the evapotranspiration can be affected by the difference in atmospheric thermo-dynamics. To consider these characteristics, the seasonal classification was made between the flood and non-flood season (October to May). In this study, the Gamma distribution was selected considering the verification results in previous study (Moon, 2014). The raw GCM was bias-corrected and downscaled for precipitation, ETA and ETP through the quantile mapping. The raw GCM data did not represent the unique seasonal meteorological characteristics in South Korea. However, as a result of the application of the stationary quantile mapping for the ET_{PM} and the ETA estimated from the raw GCM data, it was confirmed that the seasonal characteristics of the flood and non-flood season was restored and numerically improved. Figure 6 shows the observed values of simple average (SMA) of five GCMs and the result before and after regional bias-correction.

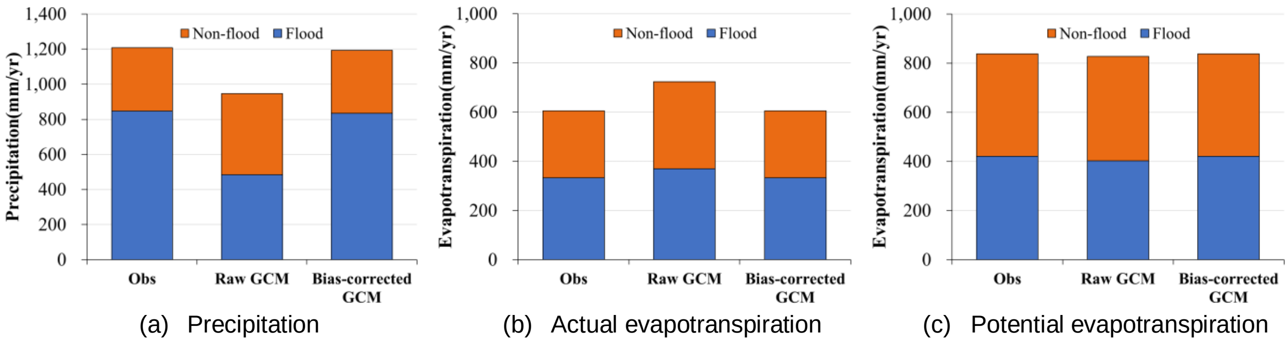
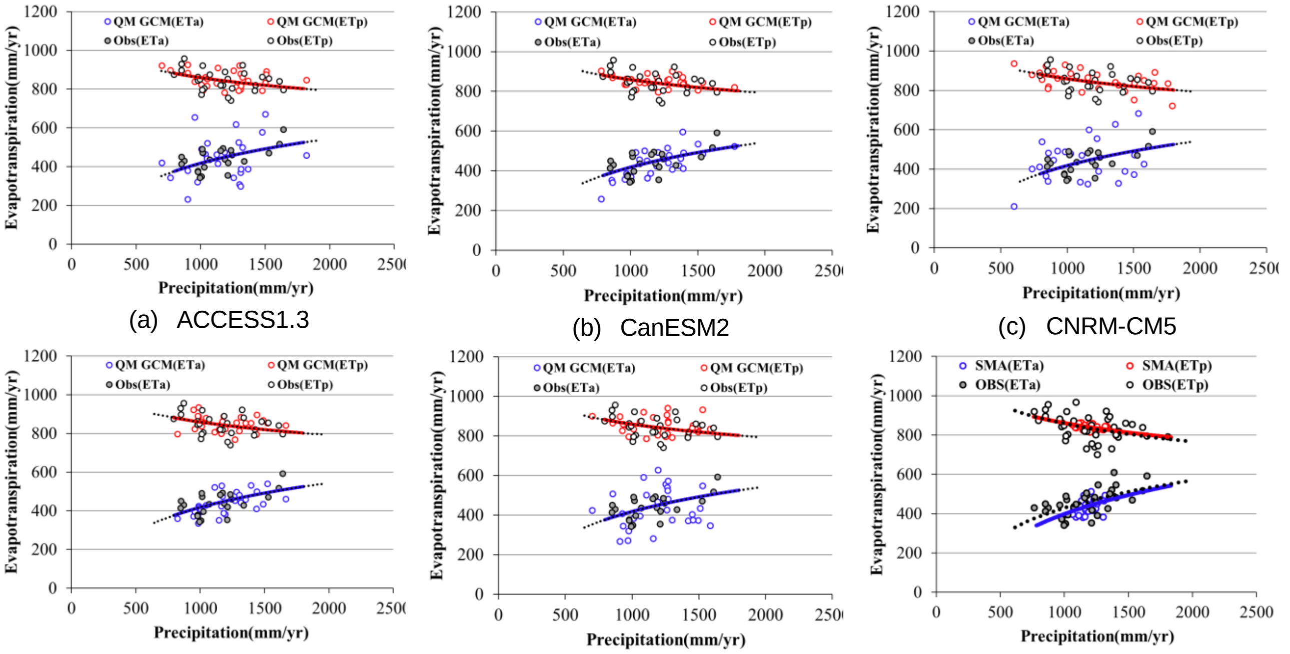


Figure 6. Comparison of flood/non-flood season results before and after the stationary quantile mapping of simple averaging 5 GCMs in Soyanggang dam basin during 1974~2000

Figure 7 shows the CRE of each model and the simple average (SMA) after regional bias-correction, and the remarkably improved results can be confirmed in comparison with the CRE in Figure 5 using the raw GCMs. The CRE of the five GCMs and SMA are almost identical to the typical CRE pattern in the observation time series. Especially, ACCESS1.3 and SMA have the most significant numerical improvement and the change of CRE pattern is most obvious. In the case of other four GCMs (CanESM2, CNRM-CM5, GFDL-ESM2G, HadGEM2-AO), the simulation results are improved and follow trends on observed values. The regional bias-correction processes for not only precipitation but temperature and evapotranpiration are effective for restoring and confirming the CRE hypothesis. when using GCM climate models.



(a) ACCESS1.3 (b) CanESM2 (c) CNRM-CM5

(d) GFDL-ESM2G (e) HadGEM2-AO (f) SMA

Figure 7. Complementary relationship of observation and GCMs after the stationary quantile mapping during 1974～2000

5 CONCLUSIONS

Due to the extreme drought that occurred in South Korea recently, there is a growing interest in forecasting the low flow for effective water resources management. Even though the evapotranspiration is critical component in estimating the low flow, the area where the actual evapotranspiration data (flux tower) are available is very limited. The effective validation of the evapotranspiration estimated by the GCM was not possible due to the limited observation density for the actual evapotranspiration. In the case of a climate model that can indirectly estimate evapotranspiration, especially potential evapotranspiration, there has not been enough studies on verification. In this study, we investigated the indirect way of verification of evapotranspiration outputs of in the CMIP5 GCM model using the CRE.

The evapotranspiration provided by the GCM meteorological variables is provided on a monthly basis and the effectiveness of the CRE hypothesis was verified using monthly observations and raw GCM data. ETP was calculated by the FAO P-M equation. ETA was estimated as the difference between the annual precipitation and the annual dam inflow. The annual precipitation was used for the moisture availability for the abscissa of CRE plot. Based on observational data of regional scale of the study area (2,703.3km^2) and annual time scale, the relationship between ETP and ETA follows a common pattern (except for ACCESS1.3) as the moisture availability increases. However, the values of ETA based on the GCMs tend to be overestimated from the observed ETA. The evapotranspiration, which is defined as the loss in the runoff relationship, is also subject to the regional bias-correction particularly if it is used for estimating streamflow regime under specific scenarios. We used the stationary quantile mapping for the GCM evapotranspiration, which is widely used for precipitation bias-correction, and as a result, the amount of evapotranspiration is effectively restored. Assessment of evapotranspiration and its reproducibility through verification of GCMs can be used as a useful methodology for monitoring soil moisture changes due to future land use changes and forecasting low flow for estimating the shortage of water due to extreme drought.

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