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The regional variation in climate elasticity and climate contribution to runoff across China

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SUMMARY

The climate elasticity of runoff is an important indicator that is used to quantify the relationship between changes in runoff and changes in climate variables. It is a function of both climate and catchment characteristics. Recently, Yang and Yang (2011) proposed an analytical derivation of climate elasticity (YY2011), in which a parameter n was used to represent the impact of the catchment characteristics. In China, both climate and catchment characteristics have large spatial variations. To understand the spatial variation of hydrologic response to climate change, this paper divided China into 210 catchments, further calculated the parameter n, and then estimated the climate elasticity and evaluated the contribution of climate change to runoff for each catchment. The results show that n ranges from 0.4 to 3.8 (with a mean of 1.3 and a standard deviation of 0.6), which has a logarithmic relationship with catchment slope; the precipitation elasticity ranges from 1.1 to 4.8 (with a mean of 1.9 and a standard deviation of 0.6), which shows a large regional variation, smaller values (1.1–2.0) mainly appearing in Southern China, the Songhua River basin and the Northwest, and larger values (2.1–4.8) mainly appearing in the Hai River basin, the Liao River basin and the Yellow River basin. In addition, climate contribution to runoff exhibits a large regional variation, the largest positive values (1.1–3.1%/a) occurring in the Northwest, the largest negative values (−1.0 to −0.5%/a) occurring in the Hai River basin and the middle reach of the Yellow River basin. In theory, the YY2011 method is a first-order approximation. The approximation underestimates the precipitation (P) contribution to runoff when P increases and overestimates that when P decreases, and the relative error has a median of ∼3% and a maximum of ∼20% when 10% precipitations change in those catchments of China.

1. Introduction

In the past five decades, significant climate change has been widely reported (IPCC, 2007), which has observably impacted the hydrologic cycle. As a consequence, a simple question – What is the impact on runoff from a 10% annual change in precipitation? – Has attracted the attention of hydrologists and geoscientists (Roderick and Farquhar, 2011). To answer this question, Schaake (1990) defined the climate elasticity of runoff (R) to precipitation (P) as:

$$\varepsilon_P(P,R) = \frac{dR}{dP}\cdot\frac{P}{R}. \tag{1}$$

Since that time, climate elasticity, as an important indicator quantifying the sensitivity of runoff to climatic variables, has been widely used to evaluate the hydrologic response to climate change (Dooge et al., 1999; Dooge, 1992; Fu et al., 2007; Ma et al., 2010; Milly and Dunne, 2002; Sankarasubramanian et al., 2001; Schaake, 1990; Yang and Yang, 2011; Zheng et al., 2009).

Many previous researches estimated climate elasticity of runoff in China towards understanding hydrologic response to climate change. Xu et al. (2013) estimated precipitation elasticity as 2.6 in the Luan River basin. Ma et al. (2010) calibrated precipitation elasticity as 2.4 in the Chao–Bai Rivers basin. Zheng et al. (2009) calculated precipitation elasticity as 2.1 in the headwater catchments of the Yellow River basin. Yang and Yang (2011) reported precipitation elasticity ranging from 1.3 to 3.9 in 89 catchments of the Hai River and Yellow River basins. Sun et al. (2013) used two different methods to estimate climate elasticity for four rivers into the Poyang Lake, precipitation elasticity ranging 1.4–1.9 and 1.4–1.7. Although those researches generally focused on a special region or basin, a large regional variation in precipitation elasticity can be glimpsed. In fact, China has a larger regional variation in climate types and catchment characteristics (such as landscape, soil and vegetation), which can lead to a large regional variation in

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climate elasticity. Consequently, it is required to estimate climate elasticity and explore its regional variation over the whole China, which helps to understanding the regional variation of changes in hydrologic cycle and water resources under climate change.

There are many methods for estimating climate elasticity, which can be classified into five categories (Sankarasubramanian et al., 2001). Among these methods, an analytical method, i.e., deriving climate elasticity of runoff based on the Budyko hypothesis is clear in theory and does not depend on a large amount of historical climate and runoff data (Yang and Yang, 2011). Consequently, this method has been applied in many studies to evaluate the impact of climatic variables on runoff (Arora, 2002; Dooge et al., 1999; Zheng et al., 2009). The Budyko hypothesis has several formulae, called the Budyko-type formulae, as shown in Table 1. Schaake (1990) derived the precipitation elasticity of runoff (Eq. (1)) according to one Budyko-type formula. Arora (2002) derived the elasticity of runoff to changes in precipitation and potential evaporation according to five different formulae, namely, the Schreiber equation (Schreiber, 1904), the Ol'dekop equation (Ol dekop, 1911), the Budyko equation (Budyko, 1958), the Turc–Pike equation (Pike, 1964; Turc, 1954), and the Zhang et al. equation (Zhang et al., 2001) (with $w = 1$) as $\frac{\Delta R}{R} = \left[1 + \frac{\phi F_0'(\phi)}{1-F_0(\phi)}\right]\frac{\Delta P}{P} - \frac{\phi F_0'(\phi)}{1-F_0(\phi)}\frac{\Delta E_0}{E_0}$ where $\phi = E_0/P$, $F_0(\phi)$ is one Budyko-type formula and $F_0'(\phi)$ is the derivative with respect to ϕ. Large differences were found among the derived climate elasticity indices when using the different formulae. In addition, Zheng et al. (2009) estimated the climate elasticity of runoff for the headwaters of the Yellow River Basin using the Schreiber equation, the Ol'dekop equation, the Budyko equation, the Turc–Pike equation, the Zhang et al. equation (with $w = 1$), and the Fu equation (with $m = 2.5$), respectively. For the continental United States, Sankarasubramanian et al. (2001) drew a contour map of precipitation elasticity based on the Turc–Pike equation (Pike, 1964; Turc, 1954). In those studies, one curve was applied to the water balance in different catchments, which ignores the effects of the catchment characteristics on the climate elasticity. Therefore, Yang and Yang (2012) and Roderick and Farquhar (2011) derived climate elasticity theoretically based on an analytical formula for the Budyko hypothesis, i.e. the Mezentsev–Choudhury–Yang (M–C–Y) equation (Mezentsev, 1955; Choudhury, 1999; Yang et al., 2008):

$$E = \frac{E_0 P}{(P^n + E_0^n)^{1/n}}, \tag{2}$$

where n represents the integrated effects of the catchment characteristics, such as the average slope (Yang et al., 2007, 2009), vegetation cover (Eagleson, 2002; Li et al., 2013; Donohue et al., 2010), vegetation type or land use (Zhang et al., 2001), and climate seasonality (Woods, 2003; Yang et al., 2012).

Both the climate and catchment characteristics (such as landscape, soil and vegetation) have large spatial variations in many regions of the world, especially China, which will lead to a spatial variation in climate elasticity. Therefore, this study prepares to divide China into 210 catchments, calibrate n for each catchment, and estimate the climate elasticity to further understand its spatial variation and reveal the impacts of climate change on hydrology. In addition, this study plans to explore the relationship of n with catchment slope and vegetation coverage.

Table 1
Different formulae for the Budyko hypothesis.

Formula	Parameter	References
$E = P[1 - \exp(-E_0/P)]$	Non	Schreiber (1904)
$E = E_0 \tanh(P/E_0)$	Non	Ol dekop (1911)
$E = P/\left[1 + (P/E_0)^2\right]^{0.5}$	Non	Pike (1964) and Turc (1954)
$E = \{P[1 - \exp(-E_0/P)]E_0 \tanh(P/E_0)\}^{0.5}$	Non	Budyko (1958)
$E = P + E_0 - [P^m + E_0^m]^{1/m}$	m	Fu (1981)
$E = P/[1 + (P/E_0)^n]^{1/n}$	n	Mezentsev (1955), Choudhury (1999) and Yang et al. (2008)
$E = P[1 + w(E_0/P)]/[1 + w(E_0/P) + P/E_0]$	w	Zhang et al. (2001)

2. Data and method

2.1. Study area and data

Daily meteorological data, including precipitation, surface air temperature (mean, maximum, and minimum air temperature), sunshine hours, relative humid, and wind speed, were collected from 736 stations during 1961–2010 from the China Meteorological Administration (CMA). In addition, daily solar radiation was collected from 118 stations during the period 1961–2010. Catchment information data set, including catchment boundary and runoff ratio, was from the Ministry of Water Resources (MWR) of the People's Republic of China (Water Resources and Hydropower Planning and Design General Institute, 2011). In the data set, the first-level basins are the 10 large river basins in China, such as the Yangtze River basin and the Yellow River basin (shown in Fig. 1); the second-level basins are tributary basins of the 10 large ones; the third-level basins are tributary basins of the second-level basins. In the data set, basin information includes area, catchment average slope, and runoff ratio; therein, the runoff ratio was estimated according to precipitation observations and natural runoff data, in which the impacts of water intake and reservoir regulation have been restored. The catchment average slope (Fig. 2) was calculated based on the 1:1,000,000 topographic map of China from the National Fundamental Geographic Information System (http://nfgis.nsdi.gov.cn/). According to the third-level basins, we divided China into 210 catchments with areas ranging from 3100 to 682,700 km^2. No observation data over the Taiwan Island was collected, and two catchments in the inland Xinjiang Province have no runoff. Therefore, 207 catchments were chosen for this study.

To calculate the average daily climatic variables in each catchment, the procedure was designed as follows: (a) a 10 km grid data set covering the study area was interpolated from the observations of the meteorological stations and then (b) the catchment average (or national average) values were calculated. The air temperature was interpolated using an inverse-distance weighted technique that considers the effect of elevation. The other variables were interpolated using an inverse-distance weighted technique. Because only 118 meteorological stations directly measure solar radiation, we estimated it using the Angstrom equation (Allen et al., 1998):

$$R_s = \left(a_s + b_s \cdot \frac{n}{N}\right) R_a, \tag{3}$$

where n is the actual sunshine hours, N is the maximum possible sunshine hours, R_a is the extra-terrestrial radiation, and a_s and b_s are parameters. In this study, the parameters (a_s and b_s) were calibrated using the observed data for each month at the 118 stations with solar radiation observations, and their values for each grid were obtained from the nearest station (Yang et al., 2006). The potential evaporation E_0 (mm/day) can be calculated for each 10 km grid using the Penman equation (Penman, 1948):

$$E_0 = \frac{\Delta}{\Delta + \gamma}(R_n - G)/\lambda + \frac{\gamma}{\Delta + \gamma} \cdot 6.43(1 + 0.536U_2)(1 - \mathrm{RH})e_s/\lambda, \tag{4}$$

where Δ is the slope of the saturated vapour pressure versus air temperature curve (kPa/°C), γ is a psychometric constant (kPa/°C), λ is the latent heat of vaporisation of water (MJ/kg), R_n and G are