

**The effect of water storage change on annual evapotranspiration  
estimation in humid catchments based on the Budyko framework**

Tingting Wang<sup>1,2</sup>, Fubao Sun<sup>1,2,3\*</sup>, Hong Wang<sup>1</sup>, Wenbin Liu<sup>1</sup>, Hao Wang<sup>4</sup>

1. Key Laboratory of Water Cycle and Related Land Surface Processes, Institute of  
Geographic Science and Natural Resources Research, Chinese Academy of Sciences,  
Beijing, China

2. College of Resources and Environment, University of Chinese, Academy of  
Sciences, Beijing, China

3. Ecology Institute of Qilian Mountain, Hexi University, Zhangye City, Gansu  
Province, China

4. China Institute of Water Resources and Hydropower Research, State Key  
Laboratory of Simulation and Regulation of Water Cycle in River Basin, Beijing,  
China

**Corresponding Author:** Fubao Sun ([Sunfb@igsnr.ac.cn](mailto:Sunfb@igsnr.ac.cn)), from Key Laboratory of  
Water Cycle and Related Land Surface Processes, Institute of Geographic Sciences  
and Natural Resources Research, Chinese Academy of Sciences

2017/06/09

**Keywords:** evapotranspiration, humid catchments, water storage change, water  
balance, the Budyko hypothesis

## Abstract

An accurate estimation of annual evapotranspiration ( $ET$ ) in humid catchments is essential in water-energy budget research and water resource management. Attempts on improving the estimated annual  $ET$  are made to meet  $ET$  from water balance equation, i.e.,  $ET_{wb}=P-Q-\Delta S$  where  $\Delta S \sim 0$ , as common practice. While this improvement is not significant. Here we first presented the poorly estimated annual  $ET$  in 102 humid catchments over China based on commonly used Fu's type of Budyko equation ( $ET_{budyko}$ ) and hydrological models: abcd model and Xin'anjiang model, in comparison with  $ET_{wb}$ . We then provided the possible explanation: the neglecting of annual water storage change ( $\Delta S$ ) in the water balance. Almost no improvement has been made in annual  $ET$  estimation based on the extended Budyko equation, which uses  $P-\Delta S$  as equivalent precipitation at monthly timescale through high  $R^2$  achieved, which is due to the seasonal pattern within the year. Then we set out from the effect of ignoring variation of annual  $\Delta S$  in water balance equation. Much improvement has been made when comparing  $ET_{budyko} + \Delta S$  with  $ET_{wb}$ . And ignoring the variation of annual  $\Delta S$  increases the variability of real  $ET$  and leads to large deviation in modelled  $ET$  assessment in humid region. This provides a possible explanation for the poorly estimated annual  $ET$  and reveals the important role of annual  $\Delta S$  in  $ET$  estimation and validation in humid catchments. We highlight that the common practice of ignoring annual  $\Delta S$  in water balance, can lead to larger deviation in estimated  $ET$  assessment. Without reliable  $\Delta S$ ,  $ET$  estimation in humid catchments remains a challenge in bridging

44 our gap in our knowledge of the hydrologic cycle.

45

46

## 1 Introduction

Evapotranspiration ( $ET$ ) over terrestrial surface is the second largest component of the global water cycle because it returns about two thirds of precipitation ( $P$ ) that falls over the land back into the atmosphere. Considering the conservation of mass and energy under steady state conditions, the Budyko hypothesis (Budyko, 1963; Budyko, 1974; Fu, 1981; Zhang et al., 2001; Zhang et al., 2004) is able to characterise the relations between precipitation ( $P$ ) and runoff ( $Q$ ); and that between evapotranspiration ( $ET$ ) and the ratio of potential evapotranspiration ( $PET$ ) to precipitation ( $PET/P$ , aridity index) into a consistent framework. (Milly, 1994; Yang et al., 2006; Donohue et al., 2007; Tekleab et al., 2011; Roderick et al., 2014). It is constrained by physical limits, namely, the limitation of available water ( $ET < P$ ) in non-humid catchments and available energy ( $ET < PET$ ) in humid catchments (Fu, 1981; Milly and Dunne, 2002). It has been widely applied in  $ET$  estimation in arid and semiarid catchments at inter- and intra-annual timescales around the globe (Ukkola and Prentice, 2013; Xu et al., 2013), e.g., America (Chen et al., 2013; Wang et al., 2009), Australia (Zhang et al., 2004; O'Grady et al., 2011) and China (Yang et al., 2006; Yang et al., 2007; Liang et al., 2015).

The Budyko hypothesis has also been used for  $ET$  estimation (hereafter denoted as  $ET_{budyko}$ ) in humid catchments ( $PET/P < 1$ ) (Xu et al., 2013; Tekleab et al., 2011; Zhang et al., 2012; Carmona et al., 2016; Gudmundsson et al., 2016), typically at intra-annual timescale (Chen et al., 2013; Ye et al., 2015; Zeng and Cai, 2015; Greve et al.,

2015;Zhang et al., 2016;Peter et al., 2016;Moussa and Lhomme, 2016). To improve  $Q$  prediction (Vogel et al., 2015) and water resources management (Bierkens, 2015) at seasonal/monthly timescales, the Budyko framework has been extended to account for the concept of ‘equivalent’ precipitation, i.e., the difference between precipitation and water storage change (hereafter  $\Delta S$ , including soil moisture change and ground water change), in intra-annual  $ET$  estimation(Chen et al., 2013;Moussa and Lhomme, 2016) and thus  $Q$  prediction and water resources management(Liang et al., 2015). Satisfactory results have been achieved and some kind of relationship are built with hydrologic relevant factors, e.g., vegetation(Chen et al., 2013;Ye et al., 2015), soil moisture(Feng et al., 2012;Gentine et al., 2012),  $\Delta S$  (Chen et al., 2013;Zeng and Cai, 2015). Recent advance include an analytically derived a two-parameter Budyko function(Peter et al., 2016), which explicitly representing additional water availability, i.e.,  $P-\Delta S$ , to better estimate intra-annual  $ET$ .

However, there are some limitations in annual  $ET$  estimation in humid catchments. First, most inter- and intra-annual  $ET$  estimation research are focusing on areas containing both humid and non-humid catchments(Xu et al., 2013;Zhang et al., 2008;Zeng and Cai, 2015;Ye et al., 2015), while there is currently limited research containing humid catchments only(Zhang et al., 2012). Second, studies have showed that the annual  $ET$  estimation generally yield poor results in humid catchments when assessed against  $ET$  from water balance equation (hereafter denoted as  $ET_{wb}$ ). Zhang et al. (Zhang et al., 2012) evaluated the ability of some commonly used approaches (PML

model (Leuning et al., 2008;Zhang et al., 2012), products from Jung(Jung et al., 2010) and the Budyko framework (Fu, 1981)) and found that none of them accurately captured the  $ET_{wb}$  across 110 humid catchments distributed worldwide. Whilst Carmona et al. (Carmona et al., 2016) demonstrated that the introduction of scaling approach into the Budyko framework could improve the estimation of ET in the Amazon River basin, it remains unclear whether such approach would also produce reliable outcomes elsewhere. The effect of vegetation(Li et al., 2013;Donohue et al., 2010;O'Grady et al., 2011), soil moisture (Gentine et al., 2012;Feng et al., 2012), catchment topography (Shao et al., 2012) and climate change(Patterson et al., 2013) has been explored and considered in the Budyko framework in order to better estimate  $ET$ .

Third, while performing model validation at an annual timescale, it is common to assume steady state conditions ( $\Delta S \sim 0$  at annual and multiannual timescales) and compare the estimated  $Q$  ( $=P-ET_{budyko}$ ) against the observed  $Q$ . However, previous studies have shown that  $\Delta S$  do not always approximate zero in humid catchments at annual timescale(Zhang et al., 2008;Wang, 2012;Bai et al., 2016;Tekleab et al., 2011;Wang and Alimohammadi, 2012;Wang and Zhou, 2015;Mao et al., 2016;Fang et al., 2016;Liu et al., 2016;Pan et al., 2016). And the  $\Delta S$  has been considered to be one important factor that can affect inter- and intra-annual  $ET$  estimation in humid catchments. Milly (Milly, 1994) discussed the effect of soil moisture on  $ET$  theoretically and indicated a mediating effect on  $ET$  based on the Budyko framework. Istanbulluoglu et al.(Istanbulluoglu et al., 2012) presented the effect of groundwater storage, which

built a climate memory in the hydrologic system, causing persistence and statistically significant trends in annual  $Q$  and thus  $ET$ . Moreover, the  $\Delta S$  can affect the variability of  $ET$  in humid catchment as well. (Wang and Alimohammadi, 2012; Chen et al., 2013; Ye et al., 2015; Zeng and Cai, 2015) Zeng and Cai (Zeng and Cai, 2015) pointed out that the variability of  $\Delta S$  made some contribution to the variability of  $ET$  in humid catchments, through it is much smaller than that in non-humid catchments (Wang et al., 2009; Wang and Zhou, 2015).

In this study, we present the fact of annual  $ET$  estimation, and consequence of neglecting annual  $\Delta S$  in both Budyko equation and water balance equation in humid catchments over China. We aim to (1) present the annual  $ET$  estimation based on the commonly used Fu's type of Budyko equation and hydrological models, i.e., abcd model and Xin'anjiang model, when assessed against annual  $ET_{wb}$  on the ground that the  $\Delta S$  is approximately zero, as common practice, in 102 humid catchments over China, and (2) examine how much improvement can  $\Delta S$  make in annual  $ET$  estimation based on the extended Budyko equation, i.e., using  $P-\Delta S$  as equivalent  $P$  at monthly timescale and then aggregated to annual timescale, (3) understand the consequence of neglecting annual  $\Delta S$  in  $ET_{wb}$  and assessment of  $ET_{budyko}$ . Section 2 summarises the methods used in  $ET$  estimation for humid catchments, and section 3 documents the data sources and selected catchments used in this study. Results and analysis are presented in section 4, followed by the conclusion and summary in section 5.

## 2 Methodology

The water balance equation has been widely used in *ET* calibration/validation for its simplicity. When *P* and *Q* are obtained from reliable measurement and  $\Delta S$  is assumed to be zero in steady state,  $ET_{wb}$  is more widely used as stand *ET* to make assessment of the modelled *ET*. (Milly and Dunne, 2002; Yang et al., 2006; Wang et al., 2009; Roderick and Farquhar, 2011; Liang et al., 2015). For any time period, the water balance equation can be written as:

$$ET_{wb} = P - Q - \Delta S \quad (1)$$

Here, we first use  $ET_{wb}$  as standard *ET* to assess the modelled *ET* in humid catchments.

### 2.1 Hydrological models: abcd and Xin'anjiang models

In practice, application of water balance equation is often limited by the availability of reliable observations. Hence hydrologic models are indispensable tools in catchment hydrology studies. Here we apply two models, i.e., abcd and Xin'anjiang models, for their simplicity and adequate representation of runoff in humid catchments.

Briefly, the abcd model is a conceptual hydrological model with four parameters (*a*, *b*, *c*, and *d*) (Thomas, 1981). Whilst the model was originally developed for application at annual timescale, it was later evaluated and found applicable at monthly timescale (Alley, 1984). It has been used for water resources assessment (Martinez and Gupta, 2010) and climate change impact study (Sankarasubramanian and Vogel,



2002). It is relatively simple compared to many existing water balance models. The model inputs are monthly  $P$  and  $PET$ , and its outputs are monthly  $Q$ , soil moisture, groundwater storage and  $ET$ .

The partitioning of monthly  $P_t$ , which is determined by  $PET_t$  and the initial storages in soil moisture and groundwater,  $Sm_{t-1}$  and  $G_{t-1}$ , into  $Q_t$ ,  $ET_t$ , soil moisture storage  $Sm_t$ , and groundwater storage  $G_t$  is as follows:

$$Y_t(W_t) = \frac{W_t + b}{2a} - \sqrt{\left(\frac{W_t + b}{2a}\right)^2 - \frac{W_t b}{a}} \quad (2)$$

where  $Y_t$  is the sum of monthly evapotranspiration and soil moisture storage at the end of the month, namely evapotranspiration opportunity, and  $W_t$  is the sum of monthly precipitation plus initial soil moisture, named as available water. The soil moisture at the end of period  $t$  is written as:

$$Sm_t = Y_t \exp(-PET_t/b) \quad (3)$$

the  $ET$  at the period  $t$  is the difference between evapotranspiration opportunity and soil moisture ( $Y_t - Sm_t$ ). The  $G_t$  and  $Q_t$  are computed based on:

$$G_t = G_{t-1} + c(W_t - Y_t) - dG_t \quad (4)$$

$$Q_t = (1 - c)(W_t - Y_t) + dG_t \quad (5)$$

the four parameters:  $a$ , the propensity for  $Q$  to occur before the soil is saturated to capacity,  $b$ , the upper bound of  $Y_t$ .  $c$  is equal to the fraction of  $Q$ , which arises from groundwater, equivalent to the base flow index and  $d$  is proportional to the base flow recession constant (Thomas, 1981).

We adopt the abcd model to provide monthly  $ET$  (hereafter  $ET_{abcd}$ ) and  $\Delta S$  in this

study. The  $\Delta S$  is the soil moisture change plus groundwater change, and includes all other possible water loss except  $Q$  and  $ET$  in a catchment.

The Xin'anjiang model is a widely used lumped rainfall-runoff model developed by Zhao et al. (Zhao et al., 1980) and Zhao (Zhao, 1992) consisting three sub-models, a three layer evapotranspiration sub-model, a runoff generation sub-model and a runoff routing sub-model (Zhao, 1992). The parameters and schematic diagram can be found in many references (Li et al., 2009;Zhao, 1992) so we won't give any unnecessary details. It has been widely used in runoff simulation and hydrological processes modelling in humid and semi-humid regions (Rui et al., 2012). Here we use the Xin'anjiang model in annual  $ET$  estimation in one selected typical humid catchment and to support the results from Budyko equation and abcd model.

## 2.2 The Budyko framework

The widely used Budyko framework, derived by Budyko(Budyko, 1963;Budyko, 1974) based on findings of Schreiber (Schreiber, 1904) and Ol'Dekop (Ol'Dekop, 1911), describes the water-energy balance status of a catchment using the well-known "Budyko curve", which is empirically derived based on energy supply (represented by  $PET$ ) and water availability (represented by  $P$ ) on  $ET$ . Fu (Fu, 1981) gave the differential forms and achieved the analytical solutions of the Budyko hypothesis, providing a theoretical basis for the Budyko framework. Subsequently analysis on

annual water-energy balance have proofed that the Fu's equation can be used in both long-term and annual water-energy balances in non-humid catchments (Yang et al., 2007) and humid catchments as well (Tekleab et al., 2011; Xu et al., 2013). The Fu's type of equation is as:

$$\frac{ET}{P} = f\left(\frac{PET}{P}\right) = 1 + \frac{PET}{P} - \left(1 + \left(\frac{PET}{P}\right)^w\right)^{1/w} \quad (6.1)$$

where  $w$  is a dimensionless parameter related to the local factors.

Some have further extended the Budyko framework to  $ET$  estimation at seasonal (Chen et al., 2013) and monthly (Du et al., 2016) timescales by defined effective precipitation, which is taken as available water supply and is the difference between  $P$  and  $\Delta S$ , i.e.,  $P - \Delta S$ . Well results have been achieved around the world (Ye et al., 2015; Zeng and Cai, 2015). So the monthly water-energy balance is redefined the ratios of  $\frac{ET}{P - \Delta S}$  and  $\frac{ET}{P - \Delta S}$ . They are described as follows:

$$\frac{ET}{P - \Delta S} = f\left(\frac{PET}{P - \Delta S}\right) = 1 + \frac{PET}{P - \Delta S} - \left(1 + \left(\frac{PET}{P - \Delta S}\right)^w\right)^{1/w} \quad (6.2)$$

Among which, the  $PET$  is estimated based on the widely used FAO-Penman equation (Allen et al., 1998):

$$PET = \frac{0.408\Delta(R_n - G_s) + \gamma \frac{900}{T_a + 273} u_2 e_s (1 - Rh / 100)}{\Delta + \gamma(1 + 0.34u_2)} \quad (7)$$

where  $R_n$  is net radiation ( $\text{MJ}/(\text{m}^2 \text{ day})$ ),  $\Delta$  is slope of the vapor pressure curve in  $\text{kPa}/^\circ\text{C}$ ,  $G_s$  is soil heat flux ( $\text{MJ}/(\text{m}^2 \text{ day})$ ),  $u_2$  ( $\text{m/s}$ ) is the wind speed at 2 m height,  $\gamma$  ( $\text{kPa}/^\circ\text{C}$ ) is the psychrometric constant,  $e_s$  ( $\text{kPa}$ ) is saturation vapor pressure at a given air temperature ( $T_a$ ),  $Rh$  is the relative humidity.

We adopt the Budyko framework as one major approach to estimate annual and

213 monthly  $ET$  in humid catchments.

## 214 **3 Data**

215 We select 102 humid catchments ( $PET/P < 1$ ) in Southern China (Figure 1) with  
216 continuous monthly  $P$ ,  $PET$  and observed  $Q$  (hereafter as  $Q_{obs}$ ). The dataset is  
217 concentrated in 1960-2013, and some catchments miss several years of  $Q_{obs}$  during this  
218 period whilst the earliest data could trace back to 1950s.  $P$  is observed and obtained  
219 from daily meteorological dataset from China Meteorological Data Network  
220 (<http://data.cma.cn/>).  $PET$  is calculated using equation 7 based on daily meteorological  
221 datasets (containing the surface air temperature, sunshine duration, wind speed and the  
222 relative humidity) obtained from China Meteorological Data Network as well. And  $Q_{obs}$   
223 is obtained from the Annual Hydrological Report P. R. China: hydrological data from  
224 Yangtze River Basin, Pearl River Basin and Southeast Rivers Basin. While the  $\Delta S$ , is  
225 obtained from the output of abcd model. Both  $P$  and  $PET$  are interpolated and extracted  
226 at catchment scale and then form the monthly and annual time series along with  $Q_{obs}$   
227 and  $\Delta S$  in the following estimation and analysis.

228 The daily  $P$ ,  $PET$  and  $Q_{obs}$  for the selected typical catchment (black bold line  
229 defined and railed out by hydrological station *Dongbei* in Figure 1) over 2001-2012 are  
230 used for parameters calibration in Xin'anjiang model. And then we simulate daily  $Q$   
231 (hereafter  $Q_{XAJ}$ ) and  $ET$  (hereafter  $ET_{XAJ}$ ) for 1957-2013 (with available monthly  $Q_{obs}$   
232 for this period as validation). The Xin'anjiang model is chosen for its reliable runoff

simulation in humid catchment in order to further verify the results from abcd model, which requires monthly inputs instead of that for the Xin'anjiang model at daily timescale.

<Figure 1>

## 4 Results and discussion

We adopt the commonly used Fu's type of Budyko equation (equation 6.1) and hydrological models: abcd model and Xin'anjiang model in  $ET$  estimation in humid catchments. The estimated  $ET$  is comparison to  $ET_{wb}$  (assuming that the  $\Delta S$  is approximately zero) at both multiannual and annual timescales. The results are in sections 4.1 and 4.2 for multiannual and annual time scales, respectively, and analysis of the effect of  $\Delta S$  are shown in sections 4.3 and 4.4.

### 4.1 $ET$ estimation at multiannual timescale

First, we plot the multiannual averages of  $PET/P$  and  $ET/P$  in 102 humid catchments in Figure 2a. The relationship between aridity index and the evaporative ratio fits the Budyko hypothesis, showing a clear feature of energy control in these humid catchments. Then we calibrate the parameter  $w$  in Fu's equation using annual  $P$ ,  $PET$ , and  $Q_{obs}$  of each catchment (Figure 1), respectively. Then The value of parameter

$w$  varies greatly with maxima and minima of 4.16 and 1.33 and the majority distributed around 1.8~2.4 (25%~75% percentile), which indicating more about terrestrial feature (Figure S1).

We use these  $w$  values and the Fu's type of Budyko equation to estimate annual  $ET_{budyko}$  in these 102 humid catchments over China. The comparison of multi-year averages between  $ET_{budyko}$  and corresponding  $ET_{wb}$  are shown in Figure 2b. Good agreement has been achieved with very high determination coefficient ( $R^2 \approx 1.0$ ) and slope of 0.95 when using the Budyko equation at multiannual timescale. Hence, the Budyko equation is suitable for  $ET$  estimation in humid catchments at steady state since its reliability is greatest when applied using long-term averages in both non-humid and humid catchments.

<Figure 2>

## 4.2 $ET$ estimation at annual timescale

Reasonable estimation of annual  $ET$  provides invaluable information support for hydropower reservoirs (Kistenmacher and Georgakakos, 2015; Rheinheimer et al., 2016) and sustainable management and optimization of water resources (Oki and Kanae, 2006; Bierkens, 2015) etc. Hence, we adopt the Fu's equation first to estimate annual  $ET$  in those humid catchments since it works well at multiannual timescale. However,

poor results are achieved with  $R^2$  in more than 80 humid catchments lower than 0.1 and only a few higher than 0.3 (Figure 3a). These results concur Zhang et al. (Zhang et al., 2012) that the commonly used Budyko equation is not sufficiently accurate to estimate annual  $ET$  in humid regions.

Then we make attempt to estimate annual  $ET$  based on abcd model. The inputs include the monthly  $P$ ,  $PET$  and the outputs are simulated monthly runoff (donate as  $Q_{abcd}$ ),  $ET$  (donate as  $ET_{abcd}$ ) and  $\Delta S$  (soil moisture change plus ground water change). The  $R^2$  between annual  $Q_{abcd}$  and  $Q_{obs}$  in these 102 selected humid catchments are all higher than 0.65, and the majority are around 0.8 (Figure S2), showing that abcd model can well simulate  $Q$  in humid region. However, when we compare the annual  $ET_{abcd}$  with corresponding  $ET_{wb}$ , the results are still unsatisfactory (Figure 3b and Figure S2). The  $R^2$  in all 102 catchments are smaller than 0.4, and about 60% of these humid catchments have  $R^2 < 0.1$ . This shows that the abcd model fails to quantify annual  $ET$  in humid catchments as well.

<Figure 3>

To further verify the results above, we adopt the Xin'anjiang model, which is famous for its well  $Q$  simulation in humid region. We select one typical catchment, which is governed by hydrological station *Dongbei* (shown in Figure 1), as case study to estimate annual  $ET$  and to support the results from Budyko equation and abcd model

The inputs for Xin'anjiang model are including continuously daily  $P$  and  $PET$  over 2001-2012 for model calibration since we have accessed to the daily  $Q_{obs}$ . To validate the model effectiveness, we first compare the  $R^2$  between daily  $Q_{obs}$  and  $Q_{XAJ}$ , which is 0.792 and shows satisfactory estimation of  $Q$  in humid region. We then use the calibrated parameters to run Xin'anjiang model for 1957-2013 since monthly  $Q_{obs}$  is available for this period. Together with the results from abcd model, the  $R^2$  between observed and simulated monthly  $Q$  over the whole period are 0.905 (Figure 4b), and 0.875 (Figure 4c). Moreover, the  $R^2$  between annual  $Q_{obs}$  and  $Q_{XAJ}$  are 0.899 and 0.781 based on Xin'anjiang and abcd models, respectively. Hence, both two hydrological models work well in  $Q$  simulation in humid catchments and the Xin'anjiang model achieves better. However, very small  $R^2$  have been achieved with 0.056 for annual  $ET_{XAJ}$ , and 0.002 for  $ET_{abcd}$  when comparing against  $ET_{wb}$  in this catchment. Therefore, the hydrological models work poorly in annual  $ET$  estimation in this humid catchment as well, through they can well simulate  $Q$ . And we can further concluded that the Xin'anjiang model would not work well in annual  $ET$  estimation in other humid catchments.

<Figure 4>

In summary, both the Budyko equation and the commonly used hydrological models do not accurately estimate in  $ET$  in humid catchments at annual timescale. An



accurate  $ET$  estimation in humid catchments remains to be a universal challenge for bridging the gap in hydrologic cycle. Hence, causal analysis should be conducted in explaining the poorly annual  $ET$  in humid catchments.

#### **4.3 The effect of $\Delta S$ on annual $ET$ estimation based on the Budyko framework**

Some have addressed the role of  $\Delta S$  in the Budyko equation, and used  $P-\Delta S$  as equivalent  $P$  at intra-annual timescale (Chen et al., 2013; Du et al., 2016). So we assess the impact of  $\Delta S$  on Budyko equation (using equation 6.2) at monthly timescale, and aggregate to annual timescale for 102 humid catchments. The  $\Delta S$  is adopted from the  $abcd$  output. The newly calibrated parameter  $w$  varies with average of 2.63 and 10<sup>th</sup>~90<sup>th</sup> percentile of 1.52~2.50 when using monthly dataset (Figure S1), and it is similar to the results based on annual dataset.

We first compare the results at monthly timescale, and the  $R^2$  between  $ET_{budyko}$  and  $ET_{wb}$  for each month in 102 humid catchments are shown in Figure 5. Much improvement has been made in relatively dry months (Oct ~ Feb), and some in March, April, May, August and September. Little improvement has been made in June and July, when they are relatively humid within a year in South China. This shows that the monthly  $ET$  based on the extended Fu's equation can better estimate  $ET$  in dry season than that in wet season.

<Figure 5>

<Figure 6>

We aggregate the monthly  $ET_{budyko}$  and  $ET_{wb}$  to annual timescale for 102 humid catchments. Their  $R^2$  are shown in Figure 6a along with the  $R^2$  between  $ET_{budyko}$  and  $ET_{wb}$  at monthly timescale. Although much improvement has been made at monthly timescale, the aggregated annual ET are poorly estimated. We then present the  $R^2$  of this annual result in comparison with the original one in section 4.2 (Figure 6b). There is nearly no improvement at all in aggregated annual  $ET$  when we account for  $\Delta S$  in the Budyko equation at monthly timescale. Similar result can be achieved when taking  $\Delta S$  from VIC output (obtained from <http://hydro.igsnrr.ac.cn/>, (Zhang et al., 2014)) (Figure S5.1) or from GLDAS product (Figure S5.2) when using the extended Budyko equation.

In addition, the annual  $\Delta S$  is quite small when comparing with annual  $P$  in humid catchments, and using annual  $P-\Delta S$  as equivalent  $P$  in Fu's equation would not change the annual  $ET$  estimation much. We test this and there is almost no improvement this way (Figure S5), which is concur with some previous work (Gudmundsson et al., 2016; Greve et al., 2015).

One explanation for the relative higher  $R^2$  at monthly timescale is the seasonal pattern within the year. And when aggregated to annual timescale, this seasonal pattern has been eliminated and strong correlation has been removed from the comparison. Hence, the  $\Delta S$  hardly affects the annual  $ET$  estimation based on the Budyko equation.

356

#### 357 **4.4 The effect of $\Delta S$ on annual $ET$ validation based on water balance** 358 **equation**

359 From another perspective, the neglecting annual  $\Delta S$  in water balance has prone to  
360 errors associated with ungauged subsurface runoff transfer in humid catchments.  
361 Therefore it produces relatively unreliable  $ET_{wb}$  as real  $ET$  in hydrology and the  
362 assessment of modelled  $ET$ . Hence, unreliable input of annual  $\Delta S$  in  $ET_{wb}$  could  
363 probability be one possible reason that leads to the estimated results above.

364 As a matter of fact, the majority of selected catchments in the southwest China are  
365 distributed in karst region, and are more or less with ungauged subsurface  $Q$  transfers  
366 (Figure 1). And the catchments in the east and southeast are experiencing urbanization  
367 expansion, which is accompanied by groundwater extraction, inter-basin water transfer  
368 like South-to-North Water Transfer Project in China, etc, which might have introduced  
369 large bias in annual  $\Delta S$ . Hence, the unreliable  $ET_{wb}$  may thus lead to irresponsible real  
370  $ET$ , and further poorly modelled  $ET$  assessment in humid catchments. Therefore, a  
371 probable explanation based on the role of the  $\Delta S$  in annual  $ET_{wb}$  is launched.

372

##### 373 **4.4.1 Analytical explanation of the effect of neglecting $\Delta S$ on annual $ET_{wb}$**

374 The annual  $\Delta S$  is often seen as zero in arid and semiarid catchments since most of  
375 annual  $P$  turns into  $ET$ , leaving the majority of the rest  $P$  turn to annual  $Q$  and very

small proportion to  $\Delta S$  (Yang et al., 2007; Wang et al., 2009). Therefore it would be acceptable to neglect annual  $\Delta S$  in  $ET_{wb}$  calculation and calibration/validation in arid and semiarid catchments. While it is uncertain whether it is applicable in humid catchments. The above comparison between  $ET_{budyko}$  and  $ET_{wb}$ , i.e., roughly seen as  $ET_{budyko} + \Delta S$ , is shown in Figure 7. Extra deviation would emerge when annual  $\Delta S$  is not zero. And the larger the annual  $\Delta S$  is, the larger this deviation could be. Besides, the low  $R^2$  between  $ET_{budyko}$  and  $ET_{wb}$  in humid catchments above can to some extent, reflect the effect of annual  $\Delta S$  on  $ET_{wb}$ .

<Figure 7>

<Figure 8>

We first adopt the analytical explanation to explain the effect of  $\Delta S$  on annual  $ET_{wb}$ . There is no available observed annual  $\Delta S$  at catchment scale, and inaccuracy and uncertainty exists in almost all models output so far. So it would be acceptable to make simple assumption that annual  $\Delta S$  is linearly related to  $P$  as well, since clear linear relation exists between  $P$  and  $Q_{obs}$  in humid catchments (Figure S6). Hence, the relation between annual  $P$  and  $\Delta S$ ,  $Q$  are assumed as,

$$Q = \alpha P \quad (8.1)$$

$$\Delta S = \beta P \quad (8.2)$$

where  $\alpha$  and  $\beta$  are both dimensionless parameters, and  $\alpha$  is the runoff coefficient.

397 The ratio of estimated  $ET$  against  $ET_{wb}$  is as,

$$\frac{ET}{ET_{wb}} = \frac{ET}{ET + \Delta S} = \frac{1 - \alpha - \beta}{1 - \alpha} \quad (9)$$

399 which indicates the effect of  $\Delta S$  on annual  $ET_{wb}$  and thus modelled  $ET$  estimation and  
400 calibration/validation. We set the range of parameter  $\beta$  to be -0.5~0.5 and  $\alpha$  to be 0~1.

401 We plot the change of this ratio in Figure 8a with both the change of parameter  $\beta$   
402 in the range of (-0.5, 0.5) and parameter  $\alpha$  in the range of (0, 1). The ratio varies greatly,  
403 which indicates the various effect of  $\Delta S$  on  $ET_{wb}$  with the change of  $\Delta S$ . The smaller  
404 this  $\Delta S$  is, the more approaching to 1.0 this ratio could be, and thus indicating more  
405 insignificant effect of  $\Delta S$  on  $ET_{wb}$  estimation and assessment.

406 We choose a few typical values of parameter  $\beta$ , representing different proportional  
407 of  $\Delta S$ , and the changes of ratio are shown in Figure 8b. Apart from the various effects  
408 of  $\Delta S$  on  $ET_{wb}$ , the runoff coefficient can affect this ratio as well. We choose two runoff  
409 coefficient, 0.57 (average of runoff coefficients over 102 humid catchments here, blue  
410 dash in Figure 8b) and 0.11 (average of runoff coefficients over 108 non-humid  
411 catchments in China, red dash, the relevant data are provided by Fubao Sun(Yang et al.,  
412 2007)). The results show that the larger the runoff coefficient is, the greater effect of  $\Delta S$   
413 on  $ET_{wb}$  under the same proportional of  $\Delta S$ . Hence, it is worth noticing that the  
414 neglecting of annual  $\Delta S$  would increase uncertainty in  $ET_{wb}$  in humid catchments than  
415 that in arid and semiarid catchments. And this can therefore, lead to inaccurate real  $ET$   
416 based on water balance equation in humid catchments.

417

#### 4.4.2 The effect of $\Delta S$ on $ET_{wb}$ in humid catchments over China

We adopt the annual  $ET_{budyko}$ , the  $\Delta S$  from abcd output, and make the following comparison to verify the speculation above. First, we use the selected typical catchment as case study, and the annual time series of  $ET_{wb}$ ,  $ET_{budyko}$  and  $ET_{budyko} + \Delta S$  for 1957-2013 in the selected typical catchment are shown in Figure 9a. Through the  $ET_{wb}$  and  $ET_{budyko}$  are both fluctuated around their multiannual average (about 761.8 mm/yr, 755.8 mm/yr), the  $ET_{wb}$  fluctuates more severe with variability of about 12518 mm<sup>2</sup>/yr<sup>2</sup> than the variability of  $ET_{budyko}$ , which is only about 745 mm<sup>2</sup>/yr<sup>2</sup>. Interestingly, the  $ET_{budyko} + \Delta S$  can better capture its fluctuates with variability of 10611 mm<sup>2</sup>/yr<sup>2</sup> and multiannual averages of 757.2 mm/yr. Moreover, the original  $R^2$  between  $ET_{wb}$  and  $ET_{budyko}$  of 0.02 has improved to 0.58 when comparing  $ET_{budyko} + \Delta S$  with  $ET_{wb}$  in this catchment (Figure 9b). This shows that the annual  $\Delta S$  plays an important role in water balance equation and it should not be seen as zero in this humid catchment. The exclusion of annual  $\Delta S$  can increase the fluctuations of annual  $ET_{wb}$ , and therefore, lead to small  $R^2$  in modelled  $ET$  assessment.

<Figure 9>

<Figure 10>

<Figure 11>

Using similar approach, we make the comparison in all 102 humid catchments,

which are divided into 3 categories based on their area (Figure 10). We found that improvement can be made when we take annual  $\Delta S$  into consideration in  $ET$  validation in humid catchments. The averaged  $R^2$  between  $ET_{wb}$  and  $ET_{budyko}$  are smaller than 0.1 for both small sized (41 catchments with the area all smaller than 5000 km<sup>2</sup>) and moderate sized catchments (33 catchments, and the area greater than 5000 km<sup>2</sup> but smaller than 10000 km<sup>2</sup>), and about 0.12 for large sized catchments (28 catchments with area greater than 10000 km<sup>2</sup>). And the  $R^2$  within 10%~90% percentile, the small and moderate sized catchments are around 0~0.15, and large catchments varies around 0~0.4. In comparison, the  $R^2$  between  $ET_{wb}$  and  $ET_{budyko}+\Delta S$  promisingly shows that, their averages improve to 0.18, 0.33 and 0.48 for three categories, respectively. In particular, the  $R^2$  within 10%~90% percentile, all showing satisfactory improvements with about 0.02~0.38 for small sized catchments, 0.11~0.50 for moderate sized catchments and 0.25~0.65 for large sized catchments.

For further interpretation, we present the spatial distribution of variabilities of  $ET_{budyko}$ ,  $ET_{wb}$  and  $PET$  in 102 humid catchments (Figures 11a~11c), and the statistical information of variabilities of  $P$ ,  $PET$ ,  $ET_{wb}$ ,  $ET_{budyko}$  and  $ET_{budyko}+\Delta S$  (Figure 11d). The variability of  $P$  varies greatly around 20,800~97,000 mm<sup>2</sup>/yr<sup>2</sup> within 10%~90% percentile for 102 humid catchments. While the variability of  $PET$  is only about 1,465~4,008 mm<sup>2</sup>/yr<sup>2</sup>, which shall limit the variability of  $ET$  in humid catchments since it is controlled by  $PET$ (Fu, 1981). The variability of  $ET_{budyko}$  meets this limitation with min-max of 186~2,414 mm<sup>2</sup>/yr<sup>2</sup>, and 10%~90% percentile of 412~1355 mm<sup>2</sup>/yr<sup>2</sup>.

While the variability of  $ET_{wb}$  (min-max of 2,835~50,114 mm<sup>2</sup>/yr<sup>2</sup> and 10%~90% percentile of 7,161~26,142 mm<sup>2</sup>/yr<sup>2</sup>) goes far beyond this limitation

The above shows that when using  $ET_{wb}$  as real  $ET$  in humid region, the ignoring annual  $\Delta S$  can directly affect the  $ET_{wb}$  calculation, and more importantly, affect the of simulated  $ET$  calibration and validation. It increases the variability of real  $ET$  and leads to large deviation in modelled annual  $ET$  assessment. And above all, this inaccurate  $ET_{wb}$  in humid region would lead to biased effort in hydrological model correction.

## 5 Conclusion and summary

Attempts on improving the annual  $ET$  estimation in humid catchments based on the Budyko framework and some commonly used hydrological models have been made to meet the  $ET_{wb}$  on the ground that  $\Delta S$  is zero at annual timescale. While this improvement is not significant and an accurate estimation of annual  $ET$  in humid catchments remains to be a huge challenge in hydrology. In this research, we adopt the commonly used Fu's type of Budyko equation and hydrological models, i.e., the abcd model and Xin'anjiang model in annual  $ET$  estimation in 102 humid catchments over China. We are motivated to explore the possible explanation of poorly annual  $ET$  estimation in humid catchments.

We estimated  $ET$  in humid catchments and assessed against  $ET_{wb}$  on the ground that the  $\Delta S$  is approximate zero at multiannual and annual timescales, as common



practice. At multiannual timescale, the Budyko equation works well and is well recommended in  $ET$  estimation in humid catchments. At annual time scale, neither the Budyko equation nor these hydrological models performed satisfactorily.

To explore the possible explanation for the poorly estimated annual  $ET$  in humid catchments, we set out from the effect of neglecting  $\Delta S$ , and took monthly  $P-\Delta S$  as equivalent  $P$  in the extended Budyko equation first. However, almost no improvement has been made when comparing the aggregated annual  $ET_{budyko}$  with  $ET_{wb}$  at annual timescale, through relatively high  $R^2$ , which is due to the seasonal pattern within the year, has been achieved between monthly  $ET_{budyko}$  and  $ET_{wb}$ . Then we began with the effect of neglecting annual  $\Delta S$  in water balance equation, which would add more inaccuracy and uncertainty in  $ET_{wb}$  in humid catchments than that in arid and semiarid catchments. We adopted  $ET_{budyko}$  and the  $\Delta S$  from abcd output, and made comparison with  $ET_{wb}$ . The results show that much improvement could be made when comparing  $ET_{budyko}+\Delta S$  with  $ET_{wb}$ . And the neglecting of annual  $\Delta S$  in  $ET_{wb}$  increases the variability of real  $ET$  greatly. Hence, the neglecting of annual  $\Delta S$  in  $ET_{wb}$  can directly affect the reliability of real  $ET$  calculation, and more importantly, the simulated  $ET$  calibration and assessment seriously in humid region. And above all, the inaccurate  $ET_{wb}$  would lead to biased effort in hydrological model correction, especially in humid region.

Above all, we highlight that the common practice of ignoring variation of annual  $\Delta S$  in water balance, can lead to significant deviation in modelled  $ET$  assessment. Without reliable  $\Delta S$ ,  $ET$  estimation in humid catchments remains an important scientific

challenge.

## **Acknowledgements**

This research was supported by the National Key Research and Development Program of China (2016YFA0602402 and 2016YFC0401401), the CAS Pioneer Hundred Talents Program (Fubao Sun), an Open Research Fund of State Key Laboratory of Desert and Oasis Ecology in Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences (CAS), and the International Science and Technology Cooperation Program of China (2014DFA71910), the CPSF-CAS Joint Foundation for Excellent Postdoctoral Fellows and National Science Foundation of China (41601035 and 41401037)

## **Reference**

- Allen, R. G., Pereira, L. S., Raes, D., and Smith, M.: Crop evapotranspiration - Guidelines for computing crop water requirements - FAO Irrigation and drainage paper 56, FAO, 56, 1998.
- Alley, W. M.: On the Treatment of Evapotranspiration, Soil Moisture Accounting, and Aquifer Recharge in Monthly Water Balance Models, *Water. Resour. Res.*, 20, 1137-1149, 1984.
- Bai, P., Liu, X., Yang, T., Li, F., Liang, K., Hu, S., and Liu, C.: Assessment of the influences of different potential evapotranspiration inputs on the performance of monthly hydrological models under different climatic conditions, *J Hydrometeorol*, 17, 2259-2274, 10.1175/JHM-D-15-0202.1, 2016.
- Bierkens, M. F. P.: Global hydrology 2015: State, trends, and directions, *Water*.

525        Resour. Res., 51, 4923-4947, 10.1002/2015WR017173, 2015.  
 526    Budyko, M. I.: Evaporation under natural conditions, 1963.  
 527    Budyko, M. I.: Climate and life, Academic Press, 1974.  
 528    Carmona, A., Poveda, G., Sivapalan, M., Vallejo-Bernal, S., and Bustamante, E.: A  
 529        scaling approach to Budyko's framework and the complementary relationship of  
 530        evapotranspiration in humid environments: case study of the Amazon River  
 531        basin, Hydrology and Earth System Sciences, 20, 589-603, 10.5194/hess-20-589-  
 532        2016, 2016.  
 533    Chen, X., Alimohammadi, N., and Wang, D.: Modeling interannual variability of  
 534        seasonal evaporation and storage change based on the extended Budyko  
 535        framework, Water. Resour. Res., 49, 6067-6078, 10.1002/wrcr.20493, 2013.  
 536    Donohue, R., Roderick, M., and McVicar, T. R.: On the importance of including  
 537        vegetation dynamics in Budyko's hydrological model, Hydrology and Earth  
 538        System Sciences Discussions, 11, 983-995, 2007.  
 539    Donohue, R., Roderick, M., and McVicar, T. R.: Can dynamic vegetation information  
 540        improve the accuracy of Budyko's hydrological model?, Journal of Hydrology,  
 541        390, 23-34, 10.1016/j.jhydrol.2010.06.025, 2010.  
 542    Du, C., Sun, F., Yu, J., Liu, X., and Chen, Y.: New interpretation of the role of water  
 543        balance in an extended Budyko hypothesis in arid regions, Hydrology and Earth  
 544        System Sciences, 20, 393-409, 10.5194/hess-20-3673-2016, 2016.  
 545    Fang, K., Shen, C., Fisher, J. B., and Niu, J.: Improving Budyko curve - based  
 546        estimates of long - term water partitioning using hydrologic signatures from  
 547        GRACE, Water. Resour. Res., 5537-5554, 10.1002/2016WR018748, 2016.  
 548    Feng, X., Vico, G., and Porporato, A.: On the effects of seasonality on soil water  
 549        balance and plant growth, Water. Resour. Res., 48, W05543,  
 550        10.1029/2011WR011263, 2012.  
 551    Fu, B.: On the calculation of the evaporation from land surface, Chinese Journal of  
 552        Atmospheric Sciences, 1, 002, 1981.

553 Gentine, P., D'Odorico, P., Lintner, B. R., Sivandran, G., and Salvucci, G.:  
554 Interdependence of climate, soil, and vegetation as constrained by the Budyko  
555 curve, *Geophys Res Lett*, 39, L19404, 10.1029/2012GL053492, 2012.

556 Greve, P., Gudmundsson, L., Orlowsky, B., and Seneviratne, S. I.: Introducing a  
557 probabilistic Budyko framework, *Geophys Res Lett*, 42, 2261-2269, L19404,  
558 2015.

559 Gudmundsson, L., Greve, P., and Seneviratne, S. I.: The sensitivity of water  
560 availability to changes in the aridity index and other factors—A probabilistic  
561 analysis in the Budyko space, *Geophys Res Lett*, 43, 2016.

562 Istanbuluoglu, E., Wang, T., Wright, O. M., and Lenters, J. D.: Interpretation of  
563 hydrologic trends from a water balance perspective: The role of groundwater  
564 storage in the Budyko hypothesis, *Water. Resour. Res.*, 48, W00H16,  
565 10.1029/2010WR010100, 2012.

566 Jung, M., Reichstein, M., Ciais, P., Seneviratne, S. I., Sheffield, J., Goulden, M. L.,  
567 Bonan, G., Cescatti, A., Chen, J., and De Jeu, R.: Recent decline in the global  
568 land evapotranspiration trend due to limited moisture supply, *Nature*, 467, 951-  
569 954, 2010.

570 Kistenmacher, M., and Georgakakos, A. P.: Assessment of reservoir system variable  
571 forecasts, *Water. Resour. Res.*, 51, 3437-3458, 2015.

572 Leuning, R., Zhang, Y. Q., Rajaud, A., Cleugh, H., and Tu, K.: A simple surface  
573 conductance model to estimate regional evaporation using MODIS leaf area  
574 index and the Penman-Monteith equation, *Water. Resour. Res.*, 44, 652-655,  
575 2008.

576 Li, D., Pan, M., Cong, Z., Zhang, L., and Wood, E.: Vegetation control on water and  
577 energy balance within the Budyko framework, *Water. Resour. Res.*, 49, 969-976,  
578 10.1002/wrcr.20107, 2013.

579 Li, H., Zhang, Y., Chiew, F. H. S., and Xu, S.: Predicting runoff in ungauged  
580 catchments by using Xinanjiang model with MODIS leaf area index, *Journal of*

Hydrology, 370, 155-162, 2009.

Liang, W., Bai, D., Wang, F., Fu, B., Yan, J., Wang, S., Yang, Y., Long, D., and Feng, M.: Quantifying the impacts of climate change and ecological restoration on streamflow changes based on a Budyko hydrological model in China's Loess Plateau, *Water. Resour. Res.*, 51, 6500-6519, 10.1002/2014WR016589, 2015.

Liu, W., Wang, L., Zhou, J., Li, Y., Sun, F., Fu, G., Li, X., and Sang, Y. F.: A worldwide evaluation of basin-scale evapotranspiration estimates against the water balance method, *Journal of Hydrology*, 538, 82-95, 2016.

Mao, Y., Wang, K., Liu, X., and Liu, C.: Water storage in reservoirs built from 1997 to 2014 significantly altered the calculated evapotranspiration trends over China, *Journal of Geophysical Research: Atmospheres*, 121, 10097-10112, 10.1002/2016JD025447, 2016.

Martinez, G. F., and Gupta, H. V.: Toward improved identification of hydrological models: a diagnostic evaluation of the "abcd" monthly water balance model for the conterminous United States, *Water. Resour. Res.*, 46, W08507, 10.1029/2009WR008294, 2010.

Milly, P.: Climate, soil water storage, and the average annual water balance, *Water. Resour. Res.*, 30, 2143-2156, 1994.

Milly, P., and Dunne, K.: Macroscale water fluxes 2. Water and energy supply control of their interannual variability, *Water. Resour. Res.*, 38, 1206-1229, 10.1029/2001WR000760, 2002.

Moussa, R., and Lhomme, J.-P.: The Budyko functions under non-steady-state conditions, *Hydrology and Earth System Sciences*, 20, 4867-4879, 2016.

O'Grady, A., Carter, J., and Bruce, J.: Can we predict groundwater discharge from terrestrial ecosystems using existing eco-hydrological concepts?, *Hydrology and Earth System Sciences*, 15, 3731-3739, 10.5194/hess-15-3731-2011, 2011.

Oki, T., and Kanae, S.: Global hydrological cycles and world water resources, *Science*, 313, 1068-1072, 2006.

609 Ol'Dekop, E. M.: On evaporation from the surface of river basins, Transactions on  
610 meteorological observations, 4, 1911.

611 Pan, Y., Zhang, C., Gong, H., Yeh, P. J. F., Shen, Y., Guo, Y., Huang, Z., and Li, X.:  
612 Detection of Human - induced Evapotranspiration using GRACE Satellite  
613 Observations in the Haihe River Basin of China, Geophys Res Lett, 44, 190-199,  
614 10.1002/2016GL071287, 2016.

615 Patterson, L. A., Lutz, B., and Doyle, M. W.: Climate and direct human contributions  
616 to changes in mean annual streamflow in the South Atlantic, USA, Water. Resour.  
617 Res., 49, 7278-7291, 2013.

618 Peter, G., Lukas, G., Boris, O., and Sonia, S.: A two-parameter Budyko function to  
619 represent conditions under which evapotranspiration exceeds precipitation,  
620 Hydrology and Earth System Sciences, 20, 2195–2205, 10.5194/hess-20-2195-  
621 2016, 2016.

622 Rheinheimer, D. E., Bales, R. C., Oroza, C. A., Lund, J. R., and Viers, J. H.: Valuing  
623 year - to - go hydrologic forecast improvements for a peaking hydropower  
624 system in the Sierra Nevada, Water. Resour. Res., 52, 2016.

625 Roderick, M. L., and Farquhar, G. D.: A simple framework for relating variations in  
626 runoff to variations in climatic conditions and catchment properties, Water.  
627 Resour. Res., 47, W00G07, 10.1029/2010WR009826, 2011.

628 Roderick, M. L., Sun, F., Lim, W. H., and Farquhar, G. D.: A general framework for  
629 understanding the response of the water cycle to global warming over land and  
630 ocean, Hydrology and Earth System Sciences, 18, 1575-1589, 10.5194/hess-18-  
631 1575-2014, 2014.

632 Rui, X., Ling, Z., Liu, N., and Liang, X.: Origin of Xin'anjiang Model and its Further  
633 Development, Advances in Science and Technology of Water Resources, 32, 1-5,  
634 2012.

635 Sankarasubramanian, A., and Vogel, R. M.: Annual hydroclimatology of the United  
636 States, Water. Resour. Res., 38, 19-11-19-12, 10.1029/2001WR000619, 2002.

637 Schreiber, P.: Über die Beziehungen Zwischen dem Niederschlag und der  
 638 Wasserführung der Flüsse in Mitteleuropa, Meteorologische Zeitschrift, 21, 1904.  
 639 Shao, Q., Traylen, A., and Zhang, L.: Nonparametric method for estimating the effects  
 640 of climatic and catchment characteristics on mean annual evapotranspiration,  
 641 Water. Resour. Res., 48, W03517, 10.1029/2010WR009610, 2012.  
 642 Tekleab, S., Uhlenbrook, S., Mohamed, Y., Savenije, H., Temesgen, M., and  
 643 Wenninger, J.: Water balance modeling of Upper Blue Nile catchments using a  
 644 top-down approach, Hydrology and Earth System Sciences, 15, 2179-2193,  
 645 10.5194/hess-15-2179-2011, 2011.  
 646 Thomas, H. A.: Improved methods for national water assessment, Report  
 647 WR15249270, US Water Resource Council, Washington, DC, 1981.  
 648 Ukkola, A., and Prentice, I.: A worldwide analysis of trends in water-balance  
 649 evapotranspiration, Hydrology and Earth System Sciences, 17, 4177-4187,  
 650 10.5194/hess-17-4177-2013, 2013.  
 651 Vogel, R. M., Lall, U., Cai, X., Rajagopalan, B., Weiskel, P. K., Hooper, R. P., and  
 652 Matalas, N. C.: Hydrology: The interdisciplinary science of water, Water. Resour.  
 653 Res., 51, n/a-n/a, 2015.  
 654 Wang, D.: Evaluating interannual water storage changes at watersheds in Illinois  
 655 based on long - term soil moisture and groundwater level data, Water. Resour.  
 656 Res., 48, W03502, 10.1029/2011WR010759, 2012.  
 657 Wang, D., and Alimohammadi, N.: Responses of annual runoff, evaporation, and  
 658 storage change to climate variability at the watershed scale, Water. Resour. Res.,  
 659 48, W05546, 10.1029/2011WR011444, 2012.  
 660 Wang, T., Istanbuluoglu, E., Lenters, J., and Scott, D.: On the role of groundwater  
 661 and soil texture in the regional water balance: an investigation of the Nebraska  
 662 Sand Hills, USA, Water. Resour. Res., 45, W10413, 10.1029/2009WR007733,  
 663 2009.  
 664 Wang, X. S., and Zhou, Y.: Shift of annual water balance in the Budyko space for a

665 catchment with groundwater dependent evapotranspiration, *Hydrology & Earth*  
 666 *System Sciences Discussions*, 12, 11613-11650, 10.5194/hess-20-3673-2016,  
 667 2015.

668 Xu, X., Liu, W., Scanlon, B. R., Zhang, L., and Pan, M.: Local and global factors  
 669 controlling water - energy balances within the Budyko framework, *Geophys Res*  
 670 *Lett*, 40, 6123-6129, 10.1002/2013GL058324, 2013.

671 Yang, D., Sun, F., Liu, Z., Cong, Z., and Lei, Z.: Interpreting the complementary  
 672 relationship in non - humid environments based on the Budyko and Penman  
 673 hypotheses, *Geophys Res Lett*, 33, L18402, 10.1029/2006GL027657, 2006.

674 Yang, D., Sun, F., Liu, Z., Cong, Z., Ni, G., and Lei, Z.: Analyzing spatial and  
 675 temporal variability of annual water - energy balance in nonhumid regions of  
 676 China using the Budyko hypothesis, *Water. Resour. Res.*, 43, W04426,  
 677 10.1029/2006WR005224, 2007.

678 Ye, S., Li, H. Y., Li, S., Leung, L. R., Demissie, Y., Ran, Q., and Blöschl, G.:  
 679 Vegetation regulation on streamflow intra - annual variability through adaption to  
 680 climate variations, *Geophys Res Lett*, 42, 10,307-310,315,  
 681 10.1002/2015GL066396, 2015.

682 Zeng, R., and Cai, X.: Climatic and terrestrial storage control on evapotranspiration  
 683 temporal variability: Analysis of river basins around the world, *Geophys Res*  
 684 *Lett*, 43, 185-195, 10.1002/2015GL066470, 2015.

685 Zhang, D., Liu, X., Zhang, Q., Liang, K., and Liu, C.: Investigation of factors  
 686 affecting intra-annual variability of evapotranspiration and streamflow under  
 687 different climate conditions, *Journal of Hydrology*, 2016.

688 Zhang, L., Dawes, W., and Walker, G.: Response of mean annual evapotranspiration  
 689 to vegetation changes at catchment scale, *Water. Resour. Res.*, 37, 701-708, 2001.

690 Zhang, L., Hickel, K., Dawes, W., Chiew, F. H., Western, A., and Briggs, P.: A rational  
 691 function approach for estimating mean annual evapotranspiration, *Water. Resour.*  
 692 *Res.*, 40, 2004.



- Zhang, L., Potter, N., Hickel, K., Zhang, Y., and Shao, Q.: Water balance modeling over variable time scales based on the Budyko framework—Model development and testing, *Journal of Hydrology*, 360, 117-131, 10.1016/j.jhydrol.2008.07.021, 2008.
- Zhang, X.-J., Tang, Q., Pan, M., and Tang, Y.: A long-term land surface hydrologic fluxes and states dataset for China, *J Hydrometeorol*, 15, 2067-2084, 2014.
- Zhang, Y., Leuning, R., Chiew, F. H. S., Wang, E., Zhang, L., Liu, C., Sun, F., Peel, M. C., Shen, Y., and Jung, M.: Decadal Trends in Evaporation from Global Energy and Water Balances, *J Hydrometeor*, 13, 379-391, 10.1175/JHM-D-11-012.1, 2012.
- Zhao, R., Zuang, Y., Fang, e., Liu, X., and Zhang, Q.: The Xinanjiang model, *Hydrological Forecasting Proceedings Oxford Symposium*, IASH 129, 351-356, 1980.
- Zhao, R. J.: The Xinanjiang model applied in China, *Journal of Hydrology*, 135, 371-381, 1992.

## Figure captions

Figure 1 Spatial distribution of humid catchments ( $PET/P < 1$ ) over southern China along with their corresponding parameter  $w$  in Fu' equation, and one selected typical catchment used as case study accompanied with its controlling hydrological station: Dongbei Station.

Figure 2 The Budyko framework for 102 humid catchments over China in (a), and (b) the comparison of  $ET_{wb}$  (ET calculated based on water balance equation) against  $ET_{budyko}$  (ET estimated based on Fu's equation) at multi-annual timescale for these humid catchments.

Figure 3 The statistical information of catchments grouped by  $R^2$  between annual  $ET_{Budyko}$  and  $ET_{wb}$  in (a), and the same for  $ET_{abcd}$  (ET estimated based on abcd model) in (b).

Figure 4 The monthly time series of  $P$  over 1957-2013 for the selected typical catchment in (a), and (b) the corresponding observed runoff ( $Q_{obs}$ ) and simulated one based on the Xin'anjiang model ( $Q_{XAJ}$ ), along with output from the abcd model ( $Q_{abcd}$ ) in (c).

Figure 5 The box plot of  $R^2$  between monthly  $ET_{wb}$  and  $ET_{budyko}$  using the extended

Budyko equation, i.e.,  $P-\Delta S$  as equivalent  $P$ , and  $\Delta S$  is obtained from abcd model.

Figure 6 The  $R^2$  between  $ET_{wb}$  and  $ET_{Budyko}$  at monthly timescale and that aggregated to annual timescale in (a), and (b) the boxplot of  $R^2$  of this aggregated annual  $ET_{budyko}$  and the original  $R^2$  of annual  $ET_{budyko}$  and  $ET_{wb}$  (same as Figure 3a).

Figure 7 The schematic of  $\Delta S$  in Budyko equation and water balance equation in humid catchments (energy limited). ET is estimated based on given  $P$  and  $PET$ , and validated against  $ET_{wb}$ , i.e.,  $P-Q_{obs}-\Delta S$  where  $\Delta S \sim 0$ .

Figure 8 The effect of  $\Delta S$  to  $ET_{wb}$  on various proportion of  $Q$  and  $\Delta S$ . (a) The changes of ratio ( $ET/(ET+\Delta S)$ ) with the change of parameter  $p1$  in range of (-0.5, 0.5) in vertical axis, and parameter  $p2$  of (0, 1) in horizontal axis (parameters  $p1$  and  $p2$  are in equations 10 and 11, respectively). The value of ratio ( $ET/(ET+\Delta S)$ ) in range of (0, 2) are colored as color bar, and value greater than 2 in right-bottom triangle area is set as wine red. (b) The changes of ratio with the change of runoff coefficient (i.e., parameter  $p2$ ) in several selected typical proportion of  $\Delta S$  (i.e., parameter  $p1$ ), the red dash is the chosen runoff coefficient representing the effect of  $\Delta S$  to ET in non-humid ( $PET/P > 1$ ) region, and blue dash for humid ( $PET/P < 1$ ) region.

Figure 9 The annual time series of  $PET$ ,  $ET_{wb}$ ,  $ET_{budyko}$  and  $ET_{Budyko} + \Delta S$  over 1957-

753 2013 for the selected typical catchment (a), and (b) the comparison between  $ET_{budyko}$ ,  
754  $ET_{Budyko} + \Delta S$  against  $ET_{wb}$  in this catchment.

755

756 Figure 10 The box plot of  $R^2$  between  $ET_{budyko}$ ,  $ET_{budyko} + \Delta S$  against  $ET_{wb}$  for 102  
757 humid catchments, which are categorized by catchment area.

758

759 Figure 11 The spatial distribution of variabilities of  $ET_{Budyko}$ ,  $ET_{wb}$  and  $PET$  in humid  
760 catchments over China in (a), (b) and (c), respectively, and their statistics information  
761 accompanied by the variabilities of annual  $P$  and  $ET_{budyko} + \Delta S$  for 102 humid catchments  
762 in (d), the left blue y-axis is for variability of  $P$ , and the right black y-axis is for the  
763 variabilities of  $PET$ ,  $ET_{wb}$ ,  $ET_{Budyko}$ , and  $ET_{budyko} + \Delta S$ .

764

Figure

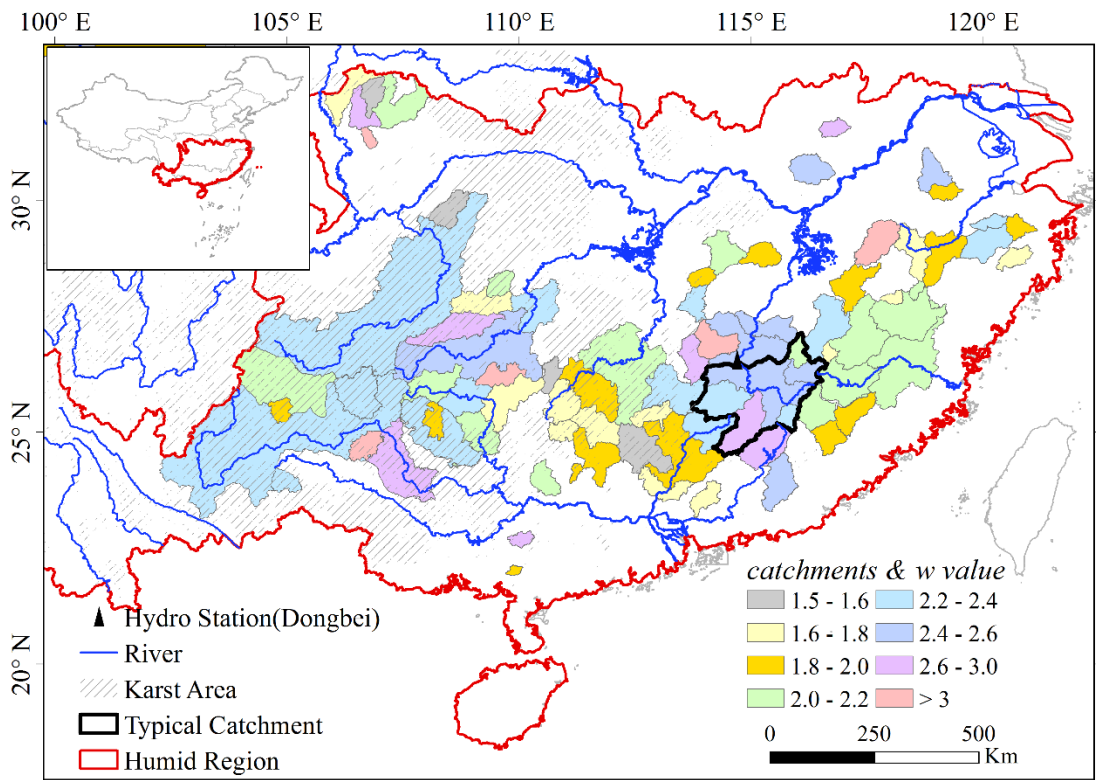


Figure 1 Spatial distribution of humid catchments ( $PET/P < 1$ ) over southern China along with their corresponding parameter  $w$  in Fu' equation, and one selected typical catchment used as case study accompanied with its controlling hydrological station: Dongbei Station.

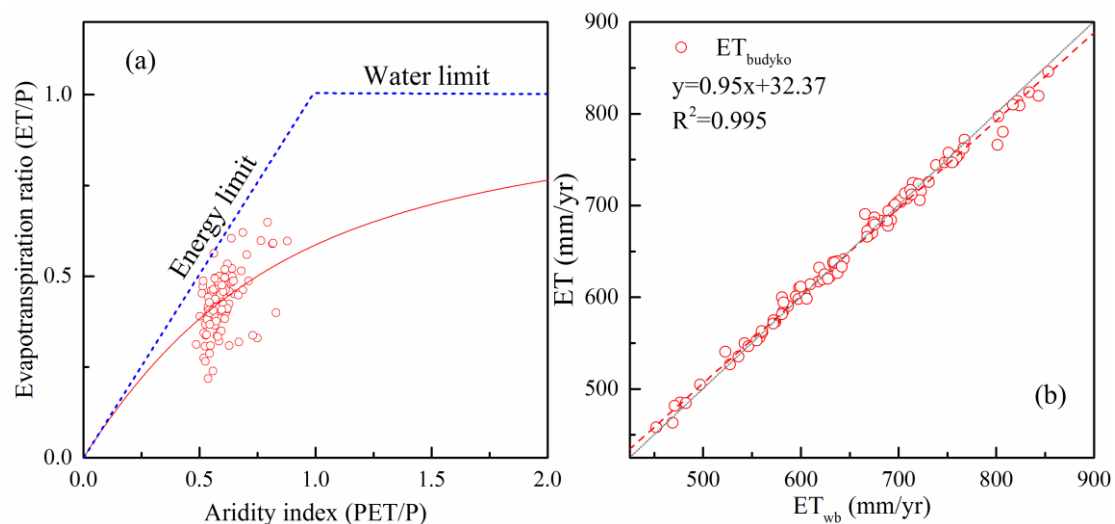


Figure 2 The Budyko framework for 102 humid catchments over China in (a), and (b) the comparison of  $ET_{wb}$  ( $ET$  calculated based on water balance equation) against  $ET_{budyko}$  ( $ET$  estimated based on Fu's equation) at multi-annual timescale for these humid catchments.

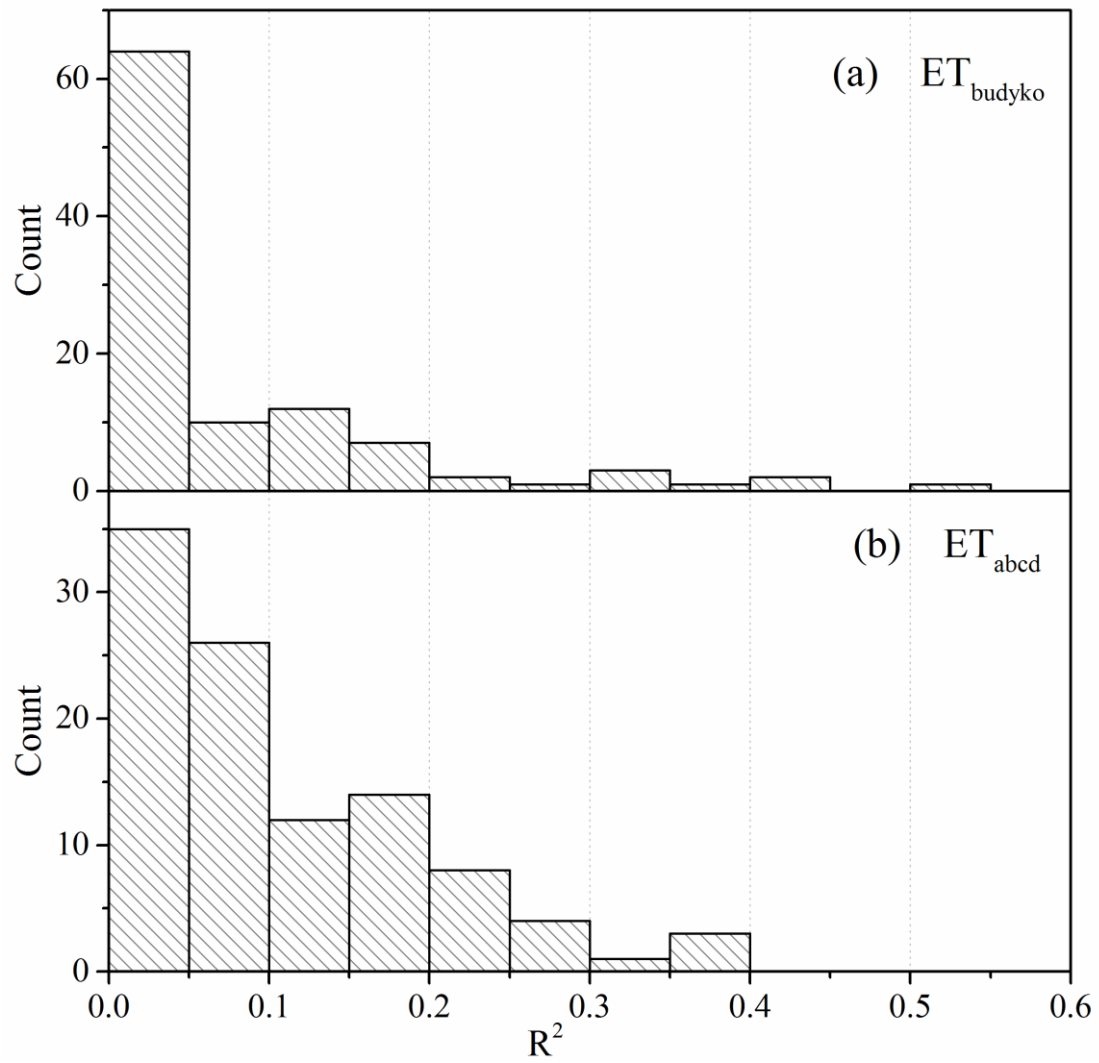


Figure 3 The statistical information of catchments grouped by  $R^2$  between annual  $ET_{Budyko}$  and  $ET_{wb}$  in (a), and the same for  $ET_{abcd}$  ( $ET$  estimated based on abcd model) in (b).

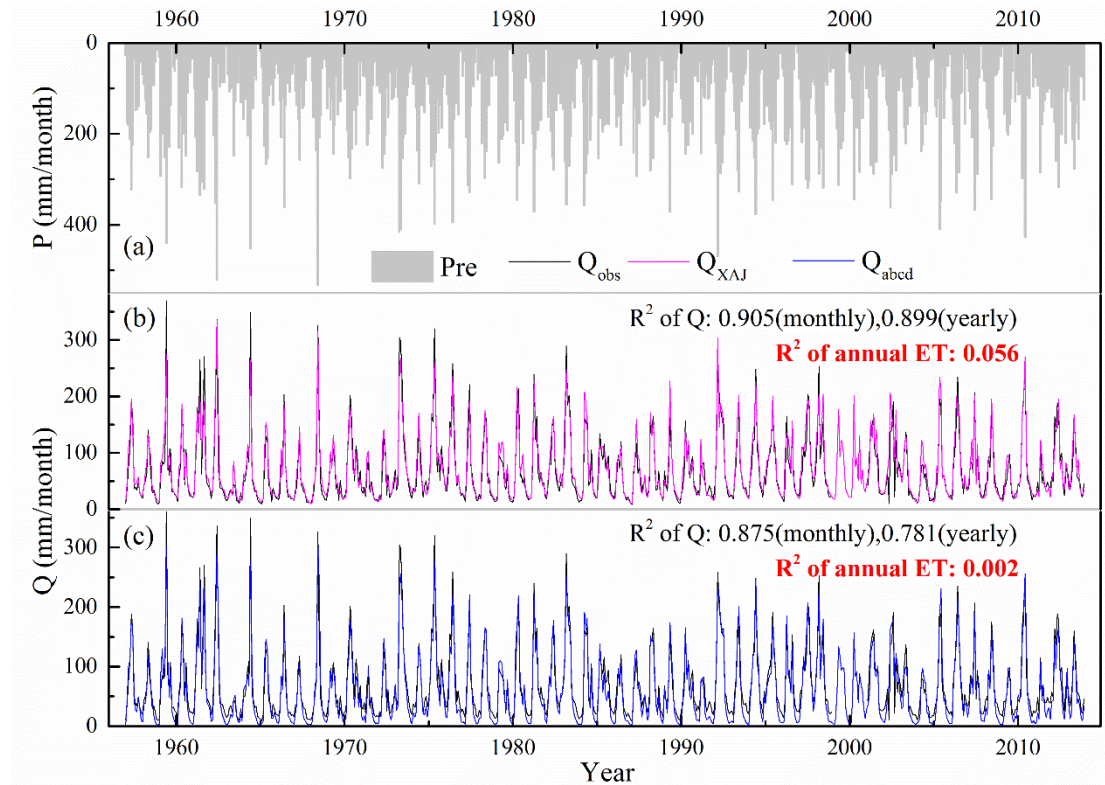


Figure 4 The monthly time series of  $P$  over 1957-2013 for the selected typical catchment in (a), and (b) the corresponding observed runoff ( $Q_{obs}$ ) and simulated one based on the Xin'anjiang model ( $Q_{XAJ}$ ), along with output from the abcd model ( $Q_{abcd}$ ) in (c).



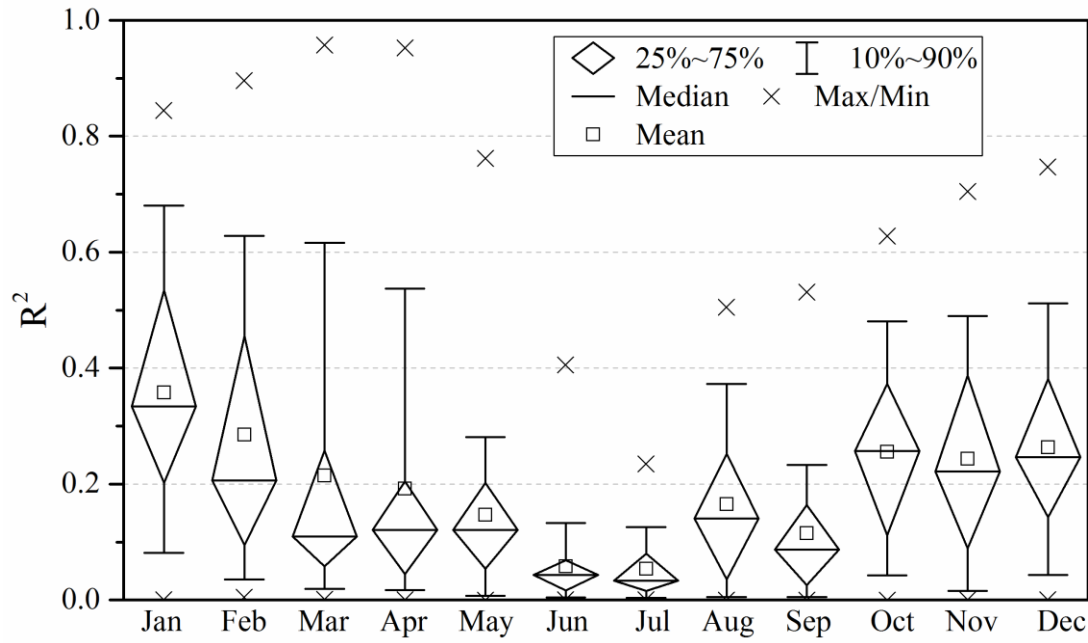


Figure 5 The box plot of  $R^2$  between monthly  $ET_{wb}$  and  $ET_{budyko}$  using the extended Budyko equation, i.e.,  $P-\Delta S$  as equivalent  $P$ , and  $\Delta S$  is obtained from abcd model.

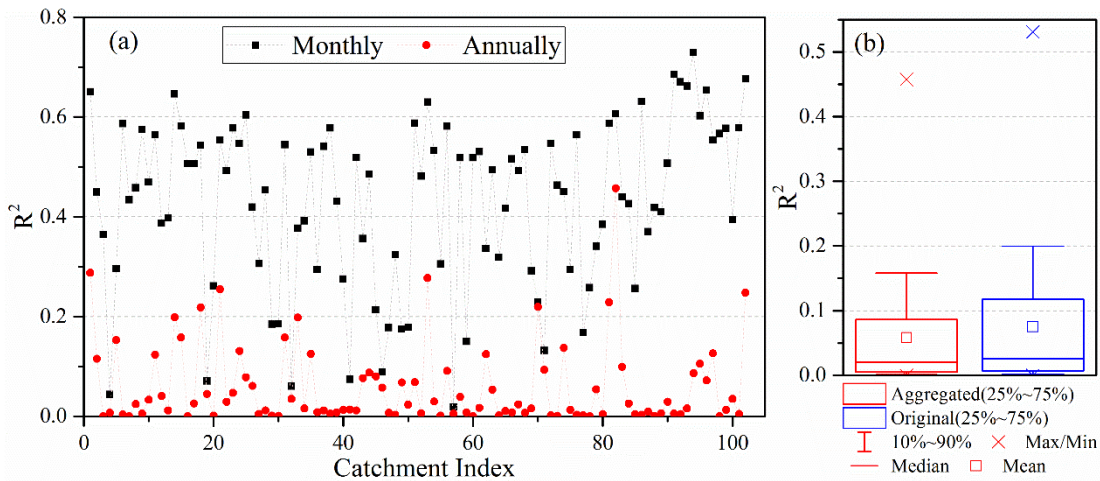


Figure 6 The  $R^2$  between  $ET_{wb}$  and  $ET_{Budyko}$  at monthly timescale and that aggregated to annual timescale in (a), and (b) the boxplot of  $R^2$  of this aggregated annual  $ET_{budyko}$  and the original  $R^2$  of annual  $ET_{budyko}$  and  $ET_{wb}$  (same as Figure 3a).

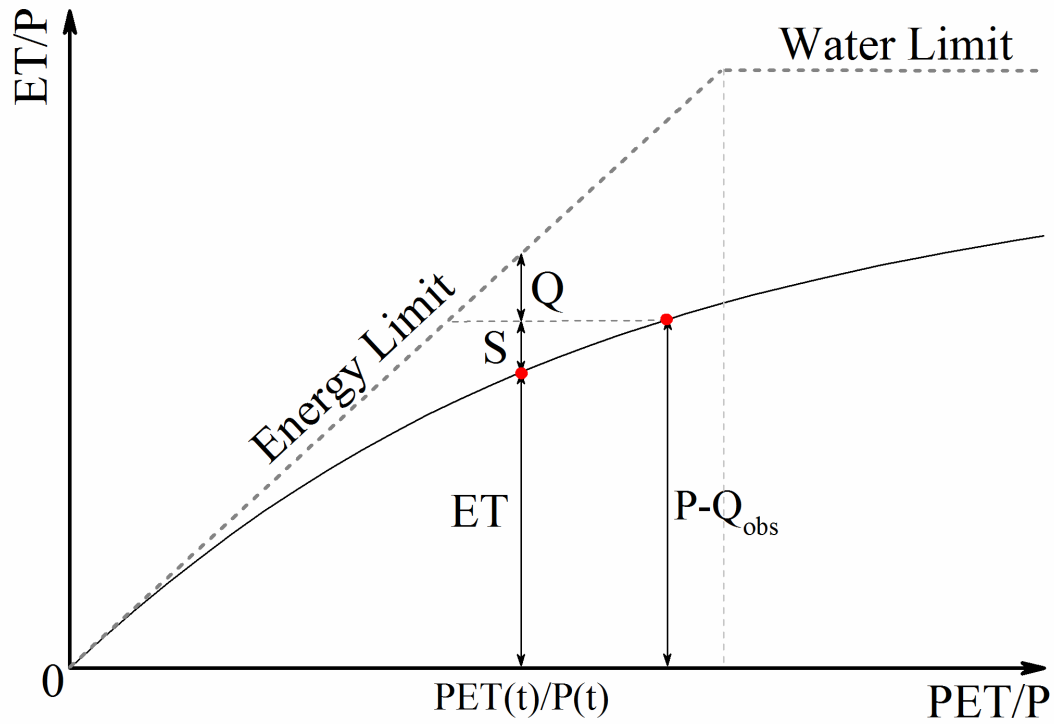
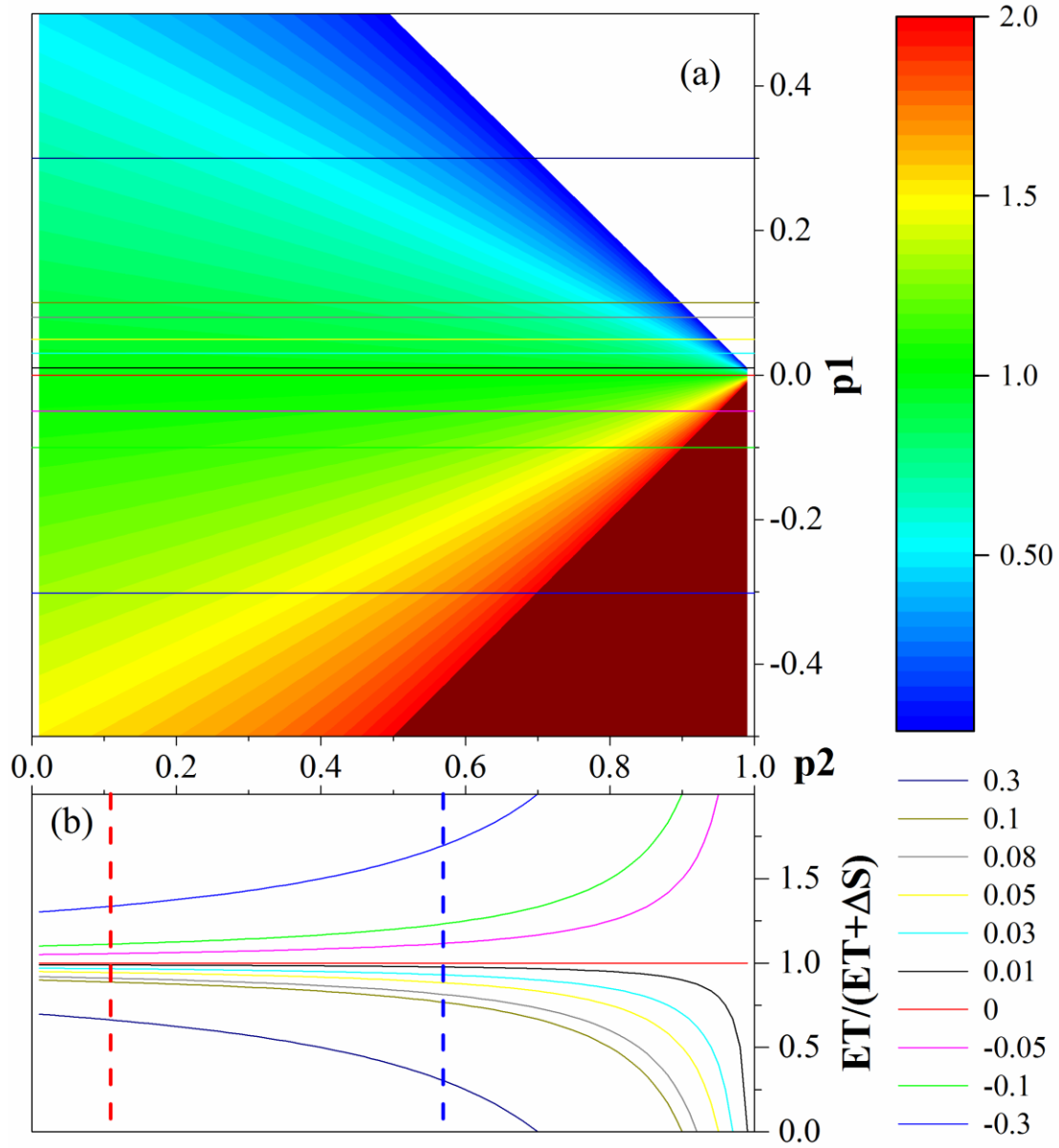


Figure 7 The schematic of  $\Delta S$  in Budyko hypothesis in humid catchments (energy limited).  $ET_{budyko}$  is estimated based on given  $P$  and  $PET$ , and validated against  $ET_{wb}$ , i.e.,  $P - Q_{obs} - \Delta S$  where  $\Delta S \sim 0$ .



803

804 Figure 8 The effect of  $\Delta S$  to  $ET_{wb}$  on various proportion of  $Q$  and  $\Delta S$ . (a) The changes  
805 of ratio  $(ET/(ET+\Delta S))$  with the change of parameter  $p1$  in range of  $(-0.5, 0.5)$  in vertical  
806 axis, and parameter  $p2$  of  $(0, 1)$  in horizontal axis (parameters  $p1$  and  $p2$  are in equations  
807 10 and 11, respectively). The value of ratio  $(ET/(ET+\Delta S))$  in range of  $(0, 2)$  are colored  
808 as color bar, and value greater than 2 in right-bottom triangle area is set as wine red. (b)  
809 The changes of ratio with the change of runoff coefficient (i.e., parameter  $p2$ ) in several  
810 selected typical proportion of  $\Delta S$  (i.e., parameter  $p1$ ), the red dash is the chosen runoff

coefficient representing the effect of  $\Delta S$  to ET in non-humid ( $PET/P > 1$ ) region, and  
blue dash for humid ( $PET/P < 1$ ) region.

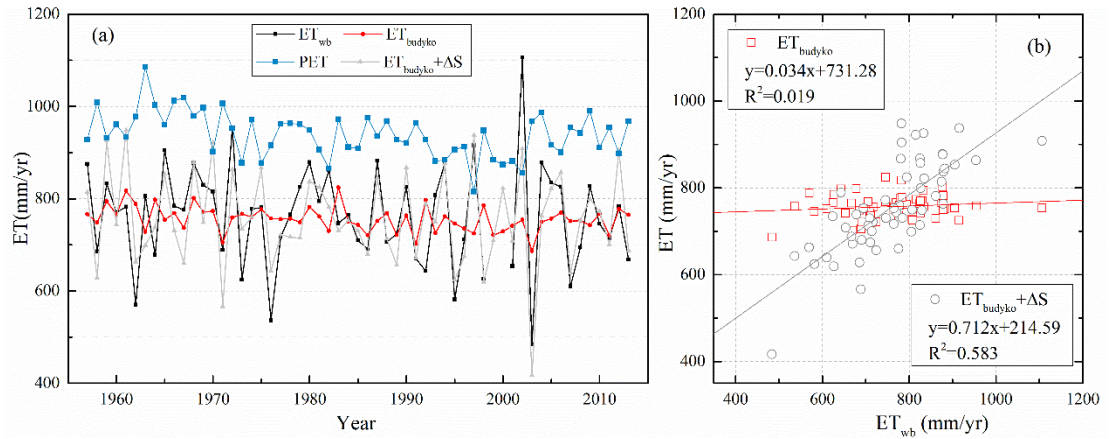


Figure 9 The annual time series of  $PET$ ,  $ET_{wb}$ ,  $ET_{budyko}$  and  $ET_{budyko} + \Delta S$  over 1957-2013 for the selected typical catchment (a), and (b) the comparison between  $ET_{budyko}$ ,  $ET_{budyko} + \Delta S$  against  $ET_{wb}$  in this catchment.

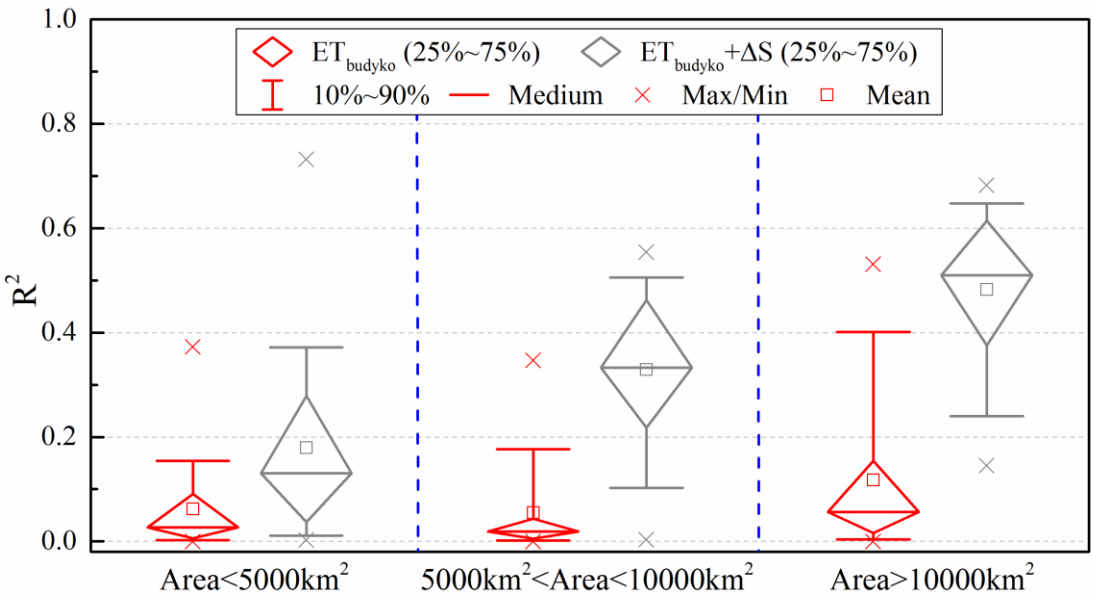
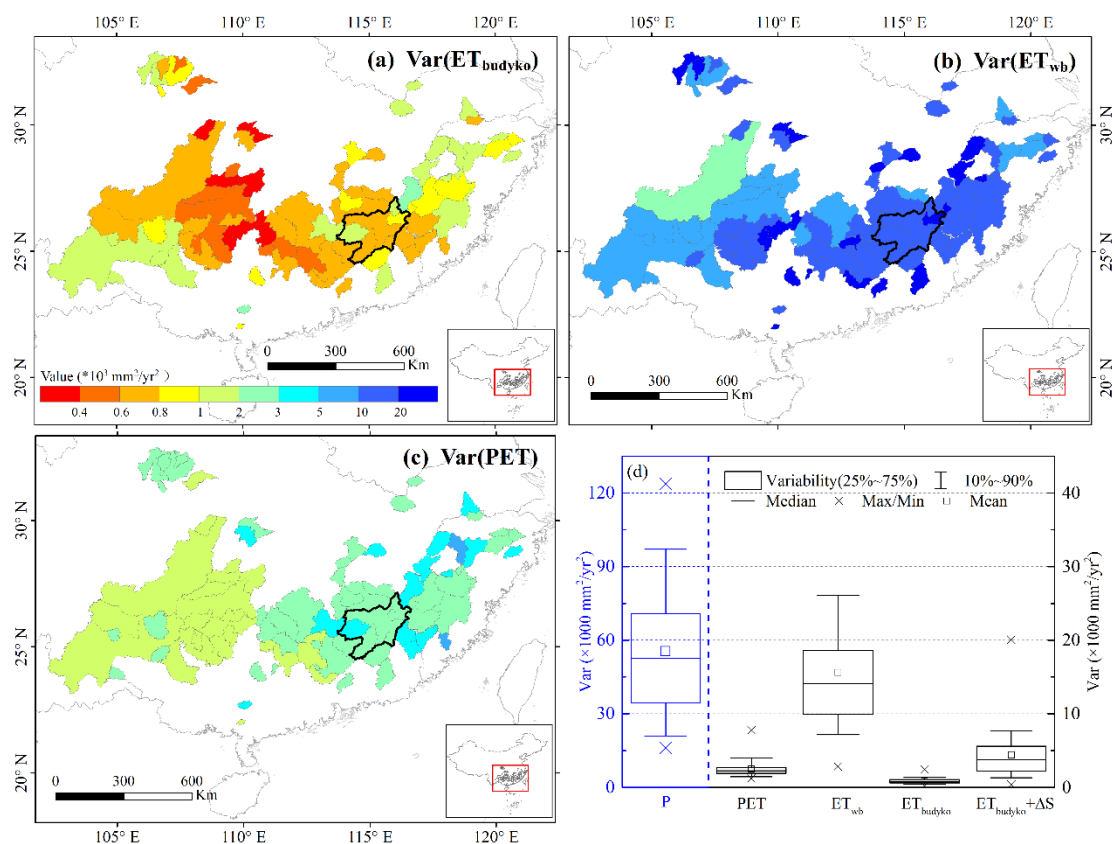


Figure 10 The box plot of  $R^2$  between  $ET_{budyko}$ ,  $ET_{budyko} + \Delta S$  against  $ET_{wb}$  for 102 humid catchments, which are categorized by catchment area.

822



823

824 Figure 11 The spatial distribution of variabilities of  $ET_{Budyko}$ ,  $ET_{wb}$  and  $PET$  in humid  
825 catchments over China in (a), (b) and (c), respectively, and their statistics information  
826 accompanied by the variabilities of annual  $P$  and  $ET_{Budyko}+\Delta S$  for 102 humid  
827 catchments in (d), the left blue y-axis is for variability of  $P$ , and the right black y-axis  
828 is for the variabilities of  $PET$ ,  $ET_{wb}$ ,  $ET_{Budyko}$ , and  $ET_{Budyko}+\Delta S$ .

829

830

831 **List of notations**

Variable name	Variable description	Units
water balance components		
$P$	Precipitation	mm
$PET$	Potential evaporation	mm
$ET$	Evapotranspiration	mm
$Q$	Streamflow	mm
$\Delta S$	Water storage change	mm
$\alpha$	Runoff coefficient	
$\beta$	Proportional of $\Delta S$ to $P$	
$w$	parameter in Fu's equation	
abcd model		
$a$	Propensity for runoff to occur before the soil is saturated to capacity	
$b$	Upper bound of $Y_t$	
$c$	Base flow index	
$d$	Proportional to the base flow recession constant	
$Sm_t$	Soil moisture storage at the end of period t	mm
$G_t$	Groundwater storage at the end of period t	mm
$Y_t$	Evapotranspiration opportunity at the end of period t	mm
$W_t$	Available water at the end of period t	mm
FAO-Penman model		
$R_n$	Net radiation	MJ/(m <sup>2</sup> day)
$G_s$	Soil heat flux	MJ/(m <sup>2</sup> day)
$\Delta$	Slope of the vapor pressure curve	kPa/°C

$u_2$	Wind speed at 2 m height	m/s
$\gamma$	Psychometric constant	kPa/°C
$e_s$	Saturation vapor pressure	kPa
$Rh$	Relative humidity	

---

832

833