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Estimation of Evaporation Trends in Six Major River Basins of China Using a New Nonlinear Formula of the Complementary Principle of Bouchet

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ABSTRACT

Evaporation (*Ea*) is a key component of the hydrological cycle. Under the impact of global change, *Ea* has changed significantly, both globally and regionally. A number of methods have been developed to estimate *Ea* and its trends. Among them, methods based on the complementary principle of Bouchet estimate *Ea* using only routine meteorological data as inputs and greatly simplify the *Ea* estimation. In this study, a new nonlinear formulation of this principle was tested for estimating *Ea* trends in 6 major river basins of China. The results indicate that the estimated annual *Ea* trends were in good agreement with that obtained from the water balance approach with the relative errors ranging from -12.0 to 11.2%. In addition, in two humid basins of this study, decreasing *Ea* trends were estimated from decreasing potential evaporation, although the nonlinear formulation is based on the complementary principle between *Ea* and potential evaporation. One advantage of the method is that only routine meteorological data are required as inputs and that it can be used to estimate *Ea* trends, wherever such data are available.

INTRODUCTION

Evaporation (*Ea*) is the crucial link between surface water and energy balances. In the context of global warming, *Ea* has changed significantly both globally and regionally (Zhang et al. 2007, Zhang et al. 2016, Jung et al. 2010, Brutsaert 2015, Yang et al. 2017). Accurate estimation of *Ea* trends is a fundamental task for hydrologic research. A number of methods such as land surface models, global climate models and hydrologic models have been developed to estimate regional and global *Ea* trends (Mueller et al. 2011, Wang & Dickinson 2012, Liu et al. 2016). These models need land, soil and vegetation information as inputs, and using these methods in practice sometimes remains a challenge due to lack of input data. Over the years among various methods for estimating *Ea*, methods based on the complementary principle (Bouchet 1963) estimate *Ea* using only routine meteorological data as inputs and greatly simplify the *Ea* estimation (Hobbins et al. 2001, Han et al. 2014, Ma et al. 2015).

The original complementary principle involved only one boundary condition and resulted in a series of linear formulations (Brutsaert & Sticker 1979, Morton 1983, Granger 1989, Brutsaert 2005). Using a linear formulation, Brutsaert (2006) obtained the increasing trend of land surface *Ea* as 0.44 mm a-2 during the second half of the 20th century, which is close to the value (i.e., 0.42 mm a-2) estimated based on the global FLUXNET network in Jung et al. (2010). Using the same linear formulation, Brutsaert (2013) estimated that the *Ea* trend on the Tibetan Plateau was 0.69 mm a-2 during 1966 to 2000, which is in agreement with the value (0.70 mm a-2) estimated based on the water balance approach in Zhang et al. (2017).

By imposing three additional but necessary boundary conditions based on strictly physical considerations, a nonlinear formulation of the complementary principle was proposed in Brutsaert et al. (2017). The nonlinear formulation has a better physical meaning than former linear formulations and has been evaluated in flux stations of China and Australia (Brutsaert 2015, Zhang et al. 2017). While the nonlinear formulation had good performance for estimating *Ea* in flux stations, its capability of simulating basin *Ea* trends has not yet been evaluated. It is the objective of the present study to test the nonlinear formulation for estimating *Ea* trends in 6 major river basins of China. The result will advance the application of the nonlinear formulation to estimate *Ea* trends under global warming.

METHODS, STUDY AREA AND DATA USED

The nonlinear formulation of the complementary principle is written as follows:

$$E_a = \left(\frac{E_{po}}{E_{pa}}\right)^2 \left(2E_{pa} - E_{po}\right) \qquad \ldots(1)$$

Here, *Epa* is the evaporation that would take place from a small saturated surface inside the large (normally) drier surface, from which *Ea* is taking place. It can be obtained from measurements by different types of pans. The variable *Epo* is the true potential evaporation, i.e., the evaporation that would take place from the same large surface as *Ea*, when it is well supplied with water. *Epo* can be calculated by Priestley and Taylor equation (Priestley & Taylor 1972):

$$E_{po} = \alpha_e \frac{\Delta}{\Delta + \gamma}\left(R_n - G\right) \qquad \ldots(2)$$

Where, R_n - G is the available energy flux, in which R_n is the net radiation and G the heat flux into the ground. When the variables were daily means, the ground heat flux G could be neglected. Δ is the slope of saturated vapour pressure at the given air temperature (Ta), $\Delta = 4098(0.6108\exp(17.27T_a/(T_a + 237.3))/(T_a + 237.3)^2$; γ is the psychrometric constant. Combining (1) and (2), the nonlinear formulation is written as follows:

$$E_a = f\left(R_n, E_{pa}, T_a\right) = \left(\frac{\alpha_e \frac{\Delta}{\Delta+\gamma} R_n}{E_{pa}}\right)^2 \left(2E_{pa} - \alpha_e \frac{\Delta}{\Delta + \gamma} R_n\right) \qquad \ldots(3)$$

Where, α_e is the only adjustable parameter. We note that α_e is not quite the Priestley-Taylor parameter, but merely a weak analog of it. When R_n, E_{pa} and T_a are time-dependent, one obtains for the E_a trend as follows:

$$\frac{dE_a}{dt} = \frac{\partial E_a}{\partial E_{pa}}\frac{dE_{pa}}{dt} + \frac{\partial E_a}{\partial T_a}\frac{dT_a}{dt} + \frac{\partial E_a}{\partial R_n}\frac{dR_n}{dt} \qquad \ldots(4)$$

Based on (3), $\frac{\partial E_a}{\partial E_{pa}}$, $\frac{\partial E_a}{\partial T_a}$ and $\frac{\partial E_a}{\partial R_n}$ can be calculated as follows:

$$\begin{cases} \dfrac{\partial E_a}{\partial E_{pa}} = \dfrac{2E_{po}{}^2(E_{po} - E_{pa})}{E_{pa}{}^3} \\ \dfrac{\partial E_a}{\partial T_a} = \alpha_e R_n \left[4\dfrac{E_{po}}{E_{pa}} - 3\left(\dfrac{E_{po}}{E_{pa}}\right)^2\right]\dfrac{\gamma}{(\Delta + \gamma)^2} \\ \qquad \dfrac{\left(3623.571 - 2T_a\right)\Delta}{\left(T_a + 237.3\right)^2} \\ \dfrac{\partial E_a}{\partial R_n} = 4\alpha_e \dfrac{\Delta}{\Delta + \gamma}\dfrac{E_{po}}{E_{pa}} - 3\alpha_e \dfrac{\Delta}{\Delta + \gamma}\left(\dfrac{E_{po}}{E_{pa}}\right)^2 \end{cases} \qquad \ldots(5)$$

The water balance approach is typically used to estimate the reference value of E_a for a basin:

$$E_a = P - R - \Delta S/\Delta t \qquad \ldots(6)$$

Where, P is the total precipitation (mm a^{-1}), R is the river discharge (mm a^{-1}), and $\Delta S/\Delta T$ is the change in

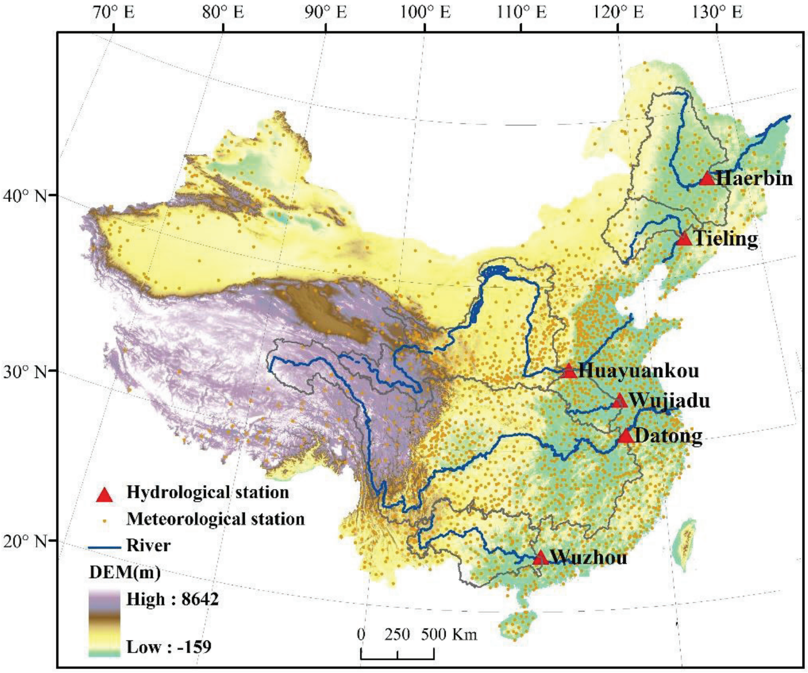

Fig. 1: The location of the 6 major river basins and corresponding hydrological stations.

Table 1: The hydro-meteorological information of the 6 basins.

Basin	Control Station	Control Area (km^2)	Ta (°C)	P (mm)
Songhua	Haerbin	389, 769	2.4	492.9
Liao	Tieling	120, 764	6.1	410.4
Yellow	Huayuankou	730, 036	6. 6	430.0
Huai	Wujiadu	121, 330	14.9	906.3
Yangtze	Datong	1,705, 383	12.5	1020.3
Pearl	Wuzhou	327, 006	18.8	1352.9

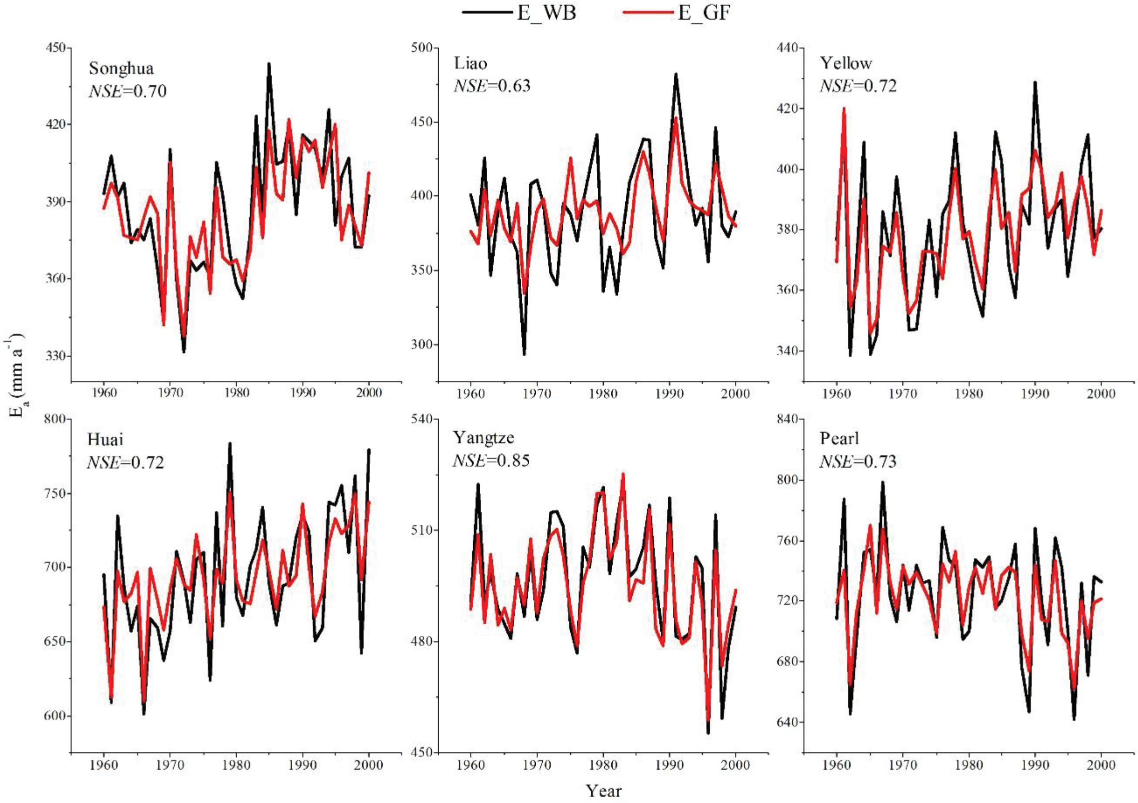

Fig. 2: Comparisons of estimated annual evaporation values using the nonlinear formulation (E_GF) against water budget approach (E_WB) for the 6 basins.

terrestrial water storage (mm a^{-1}).

Six major river basins in China, namely the Songhua River, Liao River, Yellow River, Huai River, Yangtze River and Pearl River basin, were chosen to estimate *Ea* trends in this study (Fig. 1). The 6 basins are located from northern China to southern China, with areas ranging from 120,764 to 1,705,383 km^2 (Table 1). Mean annual air temperatures of the 6 basins range from 2.4 to 18.8°C, and mean annual precipitations range from 410.4 to 1352.9 mm. The monthly streamflow data for the 6 basins from 1960 to 2000 were provided by the China Hydrological Bureau (http://www.hydroinfo.gov.cn/).

Monthly meteorological data from 1960 to 2000 at 2407 national meteorological stations, which include precipitation (*P*), air temperature (*Ta*), China D20 pan evaporation (*Epa*) and sunshine hours, were acquired from the National Meteorological Information Center of the China Meteorological Administration (http://data.cma.cn/en). The net radiation (*Rn*) at the national meteorological stations was estimated from sunshine hours following the method recommended by Allen et al. (1998). All the meteorological data were spatially averaged across each

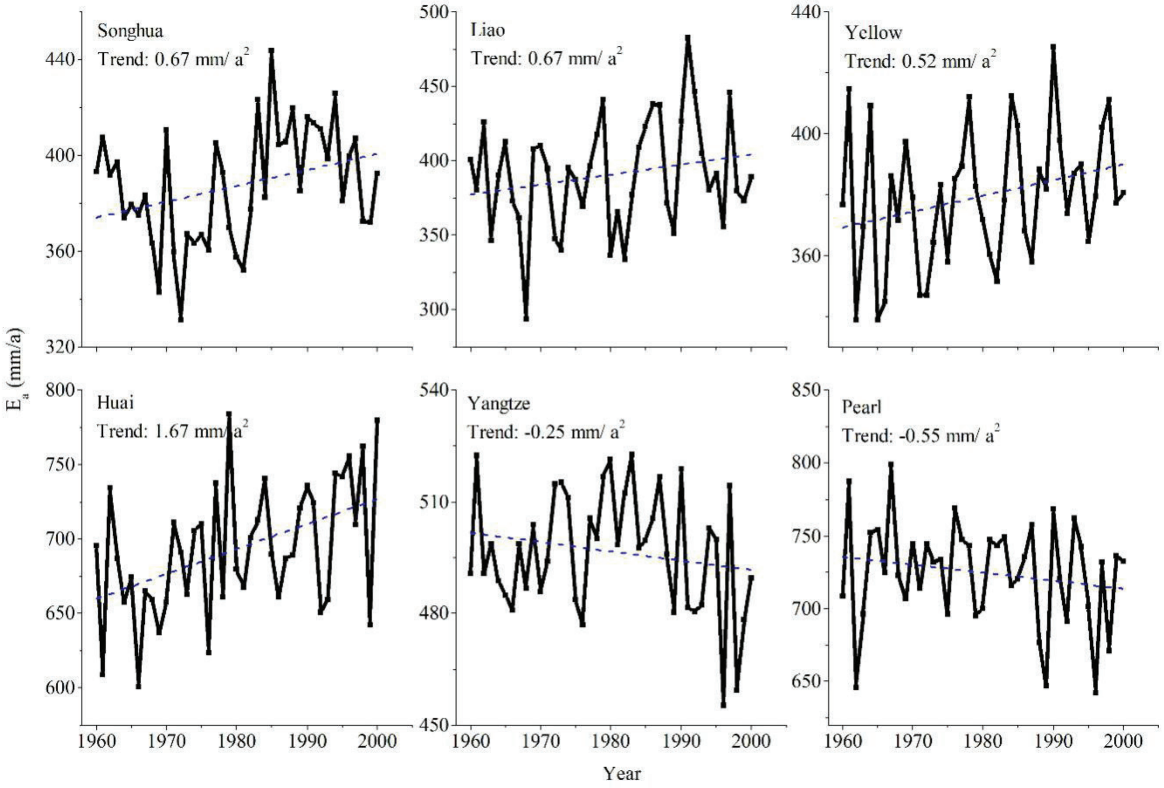

Fig. 3: Trends in annual evaporation obtained from the water balance approach for the 6 basins.

Table 2: Calculation of evaporation trends using (Eq. 4) for the 6 basins.

Basin	*Ea* trend estimation equation	$\frac{dE_{pa}}{dt}$	$\frac{dT_a}{dt}$	$\frac{dR_n}{dt}$	Sum	$\frac{dE_a}{dt}$	Error
Songhua	$-0.20dE_{pa}/dt+24.10dT_a/dt+0.70dR_n/dt$	–2.29	0.041	–1.16	0.63	0.67	–4.9
Liao	$-0.17dE_{pa}/dt+21.49dT_a/dt+0.66dR_n/dt$	–2.44	0.032	–0.61	0.69	0.67	2.6
Yellow	$-0.17dE_{pa}/dt+20.45dT_a/dt+0.56dR_n/dt$	–4.65	0.027	–1.39	0.57	0.52	10.1
Huai	$-0.27dE_{pa}/dt+24.20dT_a/dt+0.98dR_n/dt$	–9.23	0.012	–1.35	1.47	1.67	-12.0
Yangtze	$-0.24dE_{pa}/dt+20.10dT_a/dt+0.73dR_n/dt$	–3.69	0.007	–1.72	–0.23	–0.25	-9.1
Pearl	$-0.28dE_{pa}/dt+20.93dT_a/dt+0.99dR_n/dt$	–3.68	0.006	–1.78	–0.61	–0.55	11.2

of the 6 basins by the CoKriging interpolation algorithm using ArcGIS software, which takes a digital elevation model as an additional input. Annual $\Delta S/\Delta T$ were derived from the Global Land Data Assimilation System (GLDAS) Noah land surface model (Rodell et al. 2004) (http://daac.gsfc.nasa.gov/services/grads-gds/gldas). These values have a spatial resolution of 0.25° × 0.25° from 1960 to 2000.

RESULTS

The only parameter of the nonlinear formulation, namely a_e, was calibrated based on the minimal error between the average annual *Ea* calculated from the multiyear average water budget equation (6) and that from the nonlinear formulation (3) for each basin. The optimized α_e for the 6 basins is 1.08, 1.03, 1.04, 1.13, 1.18 and 1.22, respectively. Fig. 2 shows the comparisons of estimated annual E_a values using the nonlinear formulation (*E_GF*) against water budget approach (*E_WB*) for the 6 basins. The Nash-Sutcliffe efficiency coefficient (*NSE*) between *E_GF* and *E_WB* was 0.70, 0.63, 0.72, 0.72, 0.85 and 0.73 for the 6 basins, respectively. Generally, the nonlinear formulation had good performance for annual E_a estimation in the 6 basins.

Annual *Ea* trends of the 6 basins were estimated using (Eq. 4), and the detailed estimation equations for each basin are listed in Table 2. The trends of annual *Rn*, *Epa* and Ta used to estimate *Ea* trend for each basin are also listed in Table 2. With these trends together, (Eq. 4) yielded the trends of *Ea* as 0.63, 0.69, 0.57, 1.47, -0.23 and -0.61 mm a-2 for the 6 basins, respectively. Fig. 3 shows that *Ea* trends obtained from the water balance approach were 0.67, 0.67, 0.52, 1.67, -0.25 and -0.55 mm a-2 for the 6 basins, respectively. The relative errors between *Ea* trends from the nonlinear formulation and that from the water balance approach were -4.9, 2.6, 10.1, -12.0, -9.1 and 11.2%, respectively. The nonlinear formulation produced good agreement with annual *Ea* trends obtained from the water balance approach in the 6 basins.

$\frac{dE_{pa}}{dt}$, $\frac{dT_a}{dt}$ and $\frac{dR_n}{dt}$ denote annual trend in *Epa*, *Ta* and *Rn* respectively. Sum denotes the sum of the right-side hand of (Eq. 4); $\frac{dE_a}{dt}$ annual *Ea* trend obtained from the water balance approach. Error denotes the relative errors between *Ea* trends estimated from (Eq. 4) and that obtained from the water balance approach.

DISCUSSION

Table 2 shows that *Ta* has increasing trends for all the 6 basins, while *Rn* and *Epa* had decreasing trends. According to the detailed estimation equation of *Ea* trend in Table 2, the increasing *Ta* trends and decreasing *Epa* trends will lead to an increase in *Ea*, while decreasing *Rn* will result in a decrease in *Ea*. *Ea* trends for a basin were the combined effects of *Rn*, *Epa* and *Ta*. The increasing *Ea* trends in the Songhua River, Liao River, Yellow River and Huai River basin indicate that the negative *Rn* trend term was not strong enough to overcome the positive *Epa* and *Ta* trend terms. In the Yangtze River and Pearl River basin, the negative *Rn* trend term overcame the positive *Epa* and *Ta* trend terms and resulted in decreasing *Ea* trends.

The Songhua River, Liao River, Yellow River and Huai River basins are located in northern China and belong to water-limited basins, where annual precipitation is less than atmospheric evaporative demand. The Yangtze River and Pearl River basins are located in southern China and belong to energy-limited basins, where annual precipitation is larger than atmospheric evaporative demand (Mcvicar et al. 2012). In this study, decreasing *Epa* was accompanied by increasing *Ea* in the 4 water-limited basins, while decreasing *Epa* was accompanied by decreasing *Ea* in the 2 energy-limited basins. This result is consistent with the findings that *Ea* and *Epa* could be generally complementary in water-limited basins and proportional in energy-limited basins (Yang et al. 2006, Yang et al. 2007, Cong et al. 2010, Zhang et al. 2017). Interestingly, although the nonlinear formulation is based on the complementary principle between *Ea* and *Epa*, decreasing trends in *Ea* were still estimated from decreasing *Epa* in the two energy-limited basins. This provides additional support for the plausibility of the nonlinear formulation for estimating *Ea* trends.

While the agreement is excellent, admittedly *Ea* trends here and also the equation (4) used to estimate *Ea* trends are subject to some uncertainty. Firstly, the reference *Ea* trends were obtained from the water balance approach with $\Delta S/\Delta T$ simulated by the GLDAS Noah land surface model. Errors existed between the simulated and the true values of $\Delta S/\Delta T$ (Long et al. 2017). Such errors can then lead in turn to inconsistencies between Ea trends from the water balance approach and that from the nonlinear formulation. We note that these errors had limited effect on the calibration of a_e for each basin, because a_e was calibrated by the multiyear average water balance equation during 1960 to 2000, and D $\Delta S/\Delta T$ can be assumed to equal zero (Miao et al. 2015, Sun et al. 2018). Secondly, on the right-side hand of (Eq. 4), *Rn*, *Epa* and *Ta* could impact each other, and were not totally independent (Liu et al. 2011). However, the differential equations assumed that they were independent. This could lead to errors of *Ea* trends estimated from (Eq. 4). This issue will require further research.

Different methods have been developed to estimate *Ea* trends. One of the difficulties is that *Ea* trends could be significantly impacted by human activities, such as irrigation (Kong et al. 2015, Miao et al. 2016, Yang et al. 2017) and reservoir construction (Yang et al. 2017). Mao et al. (2016) indicates that with or without considering the water storage change due to reservoir construction can even obtain opposite *Ea* trends in the major river basins of China. However, the human influences on hydrologic cycle are typically difficult to quantify due to lack of data. The nonlinear formulation of the complementary principle can avoid directly estimating human influences on *Ea*, while it can indirectly reflect human influences on *Ea* (Liu et al. 2017). Theoretically, the observed trends in *Rn*, *Epa* and *Ta* were already influenced by human influences such as irrigation and reservoir construction, and thus the corresponding *Ea* trends estimated using the nonlinear formulation reflected these human influences.

CONCLUSIONS

A nonlinear formulation of complementary principle was tested for estimating *Ea* trends in 6 major river basins of China. The resulting method is shown to be fairly accurate in estimating annual *Ea* trends from routine meteorological data. In the two energy-limited basins, namely the Yangtze River Basin and Pearl River Basin, both *Ea* and *Epo* had decreasing trends during 1960 to 2000. Although the nonlinear formulation is based on the complementary principle between *Ea* and *Epo*, it accurately simulated the decreasing *Ea* trends in the two basins. In the context of global warming, accurate prediction of *Ea* trends is of great importance for estimating the changes in hydrologic cycle. The results from this study are promising as they indicate the potential of this method for predicting *Ea* trends from projections of changes in routine meteorological variables.

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