------------------------------------ Responses to RC1 --------------------------------------

Review for "Hydrological effects of climate variability and vegetation dynamics on annual fluvial water balance at global large river basins"

This paper proposed an index of climate seasonality and asynchrony to measure the mismatch of annual precipitation and evapotranspiration. The authors then assessed the impact of climate seasonality and asynchrony on the inter-annual variations of the controlling parameter within the budyko framework, and the evapotranspiration and runoff as well. This paper is well written, well-organized and easy to understand. I have several suggestions listed below to help improve the paper. I think this paper can be published if these issues are well addressed.

Re: Thank you so much for your positive comments and valuable suggestions to improve the quality of our manuscript. According to your excellent suggestion, we have made some extensive revisions to our previous draft. All of these comments have been carefully considered and all of them have been adopted and incorporated to the revised version. In the following sections, we provide point-to-point response to the comments. We believe that the concerns from you have been fully addressed. Thanks again for your time, suggestions and comments.

Specific comments:

Line 41: was proposed. Please carefully gone through the manuscript to reduce grammatical and punctuation errors.

Re: Thank you for your kind comments. It has been revised. Besides, we have checked the grammar and punctuation for the revised manuscript.

Line 114: delete therefore Line 124: were obtained

Re: It has been done.

Lines 145-149: You should introduce more background of the budyko framework and the budyko equations, and explain why you use the choudhury equation. For example, Zhou et al. (2015) has summarized existing budyko equations and suggests the choudhury equation is better than other equations, which can help readers better understand the budyko framework.

Zhou, S., Yu, B., Huang, Y., & Wang, G. (2015). The complementary relationship and generation of the Budyko functions. Geophysical Research Letters, 42(6), 1781-1790.

Re: Thank you for your kind suggestion. We have added more details about the choudhury equation. The text states as follows: "The Budyko framework has been widely used in assessment of impacts of climate and vegetation variations on hydrological cycle. There are several analytical equations proposed under the Budyko framework, among which the function deduced by Choudhury (1999) and Yang et al. (2008) has been identified to perform better than other equations (Zhou et al., 2015). The function can be expressed as…"

Line 160: by minimizing the MAE of what? Evapotranspiration or runoff? You should point out this.

Re: It has been done. The Parameter *n* is calibrated by minimizing the MAE of runoff.

Equation (8): Could you explain more of the physical meanings of a and b, and why you define SAI in this way.

Re: The a and b come from an auxiliary Angle formula, which can be expressed as:

“$asinx + bcosx = (a^2 + b^2)^{1/2}\sin(x + \varphi)$. In the function, sinx and cosx are unit vectors, a and b are the change range of unit vectors. The $(a^2 + b^2)^{1/2}$ is the modulus of the sum of the two vectors. The φ is the angle between the vector and horizontal axis.

In equation (7):

$$\frac{P(t) - E_0(t)}{\bar{P}} = (1 - DI) + \left(\delta_P \sin\left(\frac{2\pi}{\tau}\frac{t - S_P}{12}\right) - DI\,\delta_{E_0}\sin\left(\frac{2\pi}{\tau}\frac{t - S_{E_0}}{12}\right)\right)$$

$$= (1 - DI) + \left(\delta_P cos\frac{2\pi}{\tau}\frac{S_P}{12} - DI\delta_{E_0}cos\frac{2\pi}{\tau}\frac{S_{E_0}}{12}\right) sin\frac{2\pi}{\tau}\frac{t}{12} + (-\delta_P sin\frac{2\pi}{\tau}\frac{S_P}{12} + DI\delta_{E_0}sin\frac{2\pi}{\tau}\frac{S_{E_0}}{12})cos\frac{2\pi}{\tau}\frac{t}{12}$$

This equation is similar to the auxiliary Angle formula. Therefore, we defined $a = \left(\delta_P cos\frac{2\pi}{\tau}\frac{S_P}{12} - DI\delta_{E_0}cos\frac{2\pi}{\tau}\frac{S_{E_0}}{12}\right)$, $b = (-\delta_P sin\frac{2\pi}{\tau}\frac{S_P}{12} + DI\delta_{E_0}sin\frac{2\pi}{\tau}\frac{S_{E_0}}{12})$.

Then,

$$\frac{P(t) - E_0(t)}{\bar{P}} = (1 - DI) + asin\frac{2\pi}{\tau}\frac{t}{12} + bcos\frac{2\pi}{\tau}\frac{t}{12} = (a^2 + b^2)^{1/2}\sin\left(\frac{2\pi}{\tau}\frac{t}{12} + \varphi\right)$$

Where, $\varphi = \arctan(b/a)$.

Line 234: If the difference operator refers to the changes in the variables, the left and right-hand sides of equations (9a) and (9b) are not equivalent, see Yang et al. (2014) and Zhou et al. (2016). You should point out this.

Yang, H. B., D. W. Yang, and Q. F. Hu (2014), An error analysis of the Budyko hypothesis for assessing the contribution of climate change to runoff, Water Resources Research, 50, 9620–9629, doi:10.1002/2014WR015451.

Zhou, S., Yu, B., Zhang, L., Huang, Y., Pan, M., & Wang, G. (2016). A new method to partition climate and catchment effect on the mean annual runoff based on the Budyko complementary relationship. Water Resources Research, 52(9), 7163-7177.

Re: Thank you for your kind suggestion. We have revised the equal signs to approximately equal sign. Besides, we also added more details to point out that. The text states as follow: “It is worth noting that equations (9) is derived by the first-order approximation of Taylor expansion. When the changes of dP_e, dE_0 and dn are small, the error from approximation can be ignored. However, due to ignoring the higher orders of the Taylor expansion, the error will increase as the changes increase (Yang et al., 2014; Zhou et al., 2014; Yang et al., 2016).”

Yang, Hanbo, et al. “The Regional Variation in Climate Elasticity and Climate Contribution to Runoff across China.” Journal of Hydrology, vol. 517, no. 517, 2014, pp. 607–616.

Yang, H. B., D. W. Yang, and Q. F. Hu (2014), An error analysis of the Budyko hypothesis for assessing the contribution of climate change to runoff, Water Resources Research, 50, 9620–9629, doi:10.1002/2014WR015451.

Zhou, S., Yu, B., Zhang, L., Huang, Y., Pan, M., & Wang, G. (2016). A new method to partition climate and catchment effect on the mean annual runoff based on the Budyko complementary relationship. Water Resources Research, 52(9), 7163-7177.

Equation (10): If you calculate the contributions in this way, readers cannot tell whether the contribution is positive or negative. Please change the numerators to actual values instead of absoluate values.

Re: Thank you for your kind suggestion. We have deleted the absolute value sign in Equation (10). Besides, we added a Table in the revised manuscript (Table S4 in supplement), which summarizes the contribution to *R* and *E* changes in the form of positive or negative (Shown as below). In order to make the contribution to display more intuitively, we retained the Figures 8 and 9 in the form of absolute value of contributions.

Table S4. Contributions to the long-term mean changes of *R* and *E* from P_e, SAI, M and E_0 changes.

		Contributions to *R* changes				Contributions to *E* changes			
ID	Basins	P	E0	M	SSI	P	E0	M	SSI
1	Amazon	63.7	-10.1	25.5	-0.7	19.8	22.3	55.4	-2.5
2	Amur	-59.9	-11.2	4.2	24.6	-51.7	13.5	13.6	21.2
3	Aral	-13.2	-9.3	-21.4	56.1	33.9	7.0	-10.1	48.9
4	Columbia	-69.3	-15.5	4.0	11.2	-44.5	28.1	11.5	15.9
5	Congo	26.2	-8.1	-30.8	34.9	-7.8	10.1	-37.7	44.4
6	Danube	17.3	-19.0	59.4	-4.4	17.8	18.9	51.1	12.2
7	Indigirka	-54.3	-6.5	30.2	-9.0	-21.4	11.2	58.0	9.4
8	Indus	-82.8	-3.8	-4.2	9.1	-74.7	5.6	15.1	-4.6
9	Kolyma	-67.0	-3.7	-13.3	16.0	-45.6	6.1	31.2	-17.0
10	Lena	94.7	3.8	0.7	0.8	85.3	-10.6	-0.7	3.5
11	Mackenzie	-54.1	-6.2	16.5	23.3	-20.1	10.7	64.3	-4.8
12	Mississippi	-36.8	-0.2	-20.4	42.7	-17.4	0.2	51.5	-30.9
13	Niger	79.1	-1.6	15.9	3.5	81.4	1.4	15.6	1.6
14	Nile	61.8	-8.1	-13.4	16.7	68.1	6.8	-11.2	13.9
15	Northern Dvina	-29.0	-11.7	-19.8	39.6	-6.1	15.4	39.3	-39.2
16	Ob	83.5	-9.5	-1.9	5.2	70.1	17.1	7.1	-5.7
17	Olenek	82.5	2.9	6.2	8.4	54.2	-7.5	34.0	-4.3
18	Parana	-25.0	-29.2	24.7	21.1	2.2	38.1	27.0	32.7
19	Pearl	96.4	2.2	0.3	1.1	83.5	-9.8	1.8	5.0
20	Pechora	76.6	-0.9	8.4	14.1	30.7	2.7	52.3	-14.3
21	Senegal	86.4	-2.2	7.9	3.5	94.6	0.9	4.5	0.0
22	Volga	-41.3	-13.5	39.6	-5.6	-12.0	20.2	49.6	18.1
23	Yangtze	-26.2	-19.1	-11.6	43.1	-4.6	24.6	-19.8	51.0
24	Yellow	-10.9	-22.1	-18.6	48.4	-6.4	23.2	-20.8	49.6
25	Yenisei	60.7	-10.0	-8.7	20.6	42.2	14.7	-11.4	31.7
26	Yukon	-63.8	-1.3	19.6	15.3	-25.7	2.6	-20.8	50.9

Please also clearly state how to calculate the partial derivatives. Because these partial derivatives and the changes in the variables. Noting that the partial derivatives may change greatly (also see Zhou et al. (2016)), and will have large impacts on the results. The same issues also exist for the equations (11).

Re: Yes, the partial derivatives are calculated by using the total differential method. We have added this before equation (10) and (11).

Equation (11): use ≈ instead of = because SAI and M cannot fully explain the variation of the parameter n.

Re: Yes, it has been done.

Line 282: have a significant impact

Re: Yes, we have revised it.

Line 297: b is negative while c is positive

Re: Yes, we have revised it. Thank you!

Equation (14): please calibrate the parameter a, b, c in each catchment (add a table or figure for this), and show whether the parameters are robust across different regions.

Re: Thank you for your kind suggestion. We have added a table to summary these parameters and its robustness for each catchment (Table S1 in Supplement). In addition, we also added more analysis for this Table. The text states as follow:

"In addition, the Eq. (13) has also been verified in each catchment among the 26 basins (Table S1). The RMSE and MAE for each catchment is relatively small with mean values of 12.0 and 14.8 mm, respectively. Except for basins 3, 5 and 26, the R^2 values for simulation of *R* in each catchment are larger than 0.5. These results indicated that the M and SAI as well as the semi-empirical formula can well explain the variability of the controlling parameter *n*."

Table S1. The validated parameter of eq. (14) and simulation accuracy of *R* based on the estimated *n* with the validated parameters for each basin

ID	Validated basin	Model coefficients			*R* simulation accuracy		
		a	*b*	*c*	R^2	RMSE	MAE
1	Amur	5.05	-0.36	-0.05	0.90	32.7	26.4
2	Aral	0.39*	0.77*	0.04	0.80	7.9	6.1
3	Columbia	0.58***	0.47	-0.06	0.27	12.2	9.9
4	Congo	0.92	0.10	-0.36***	0.94	12.8	10.7
5	Danube	0.42	0.81	-0.21	0.22	39.4	35.4
6	Indigirka	0.02	2.37***	-0.02	0.85	16.1	13.1
7	Indus	0.26*	0.57	0.59*	0.82	11.6	9.3
8	Kolyma	0.34*	0.98**	-0.20	0.60	19.2	16.5
9	Lena	0.39***	0.71**	0.19	0.84	9.0	7.1
10	Mackenzie	0.28*	0.91**	-0.04	0.95	6.3	5.2
11	Mississippi	1.06*	-0.03	0.00	0.81	8.9	6.9
12	Niger	0.03	2.22*	0.03	0.63	24.3	18.3
13	Nile	0.99***	-0.17	0.06	0.80	14.1	10.4
14	Northern Dvina	1.53*	-0.33	-0.01	0.64	10.8	8.9
15	Ob	0.34	0.61	0.30**	0.85	14.3	11.5
16	Olenek	0.33	0.76*	0.10	0.82	10.3	8.4
17	Parana	0.35***	0.60*	0.39	0.76	11.4	8.3
18	Pearl	2.90	-0.10	-0.16**	0.80	15.7	12.9
19	Pechora	0.09	1.40*	-0.01	0.97	21.8	17.2
20	Senegal	0.44	0.44	0.06	0.87	16.5	13.1
21	Volga	1.48***	-0.04	-0.41*	0.82	4.0	3.3
22	Yangtze	0.29	0.87	-0.02	0.76	13.4	10.3
23	Yellow	0.45	0.30	-0.06	0.92	19.3	15.6
24	Yenisei	0.86	0.28	-0.01	0.58	11.0	9.1
25	Yukon	0.32	0.79*	0.02	0.80	6.0	4.7
26	Amur	0.13	1.06	0.12	0.43	16.4	14.4
	All basins	0.29***	0.86***	-3.3***	0.92	68.2	45.8

'*', '**' and '***' represent the validated parameter are significant at the level of $p = 0.1$, $p = 0.05$ and $p = 0.01$, respectively.

Line 303: You should check the relationship between SAI and M before the calibration. If SAI and M are correlated, you should not use multiple linear regression because of multicollinearity problems. Please use partial least square regression to calibrate the parameters.

Re: Thank you for your kind comments. We have used the partial least square regression (PLSR) to replace the multiple linear regression (MLR). It is worth mentioning that MLR (or PLSR) in this study is used as a comparison to analysis the performance of the semi-empirical formula (SEF). And the results show that the SEF performance much better than the MLR and PLSR. Therefore, the replacement of MLR has no effect on the later calculations and final results.

Line 303 and other sentences: change formulae to formula

Re: Yes, it has been done.

Lines 301-304: please show the calibrated parameters for the cross-validation, at least in the supporting information.

Re: Thank you for your kind comments. The calibrated parameters for cross validation has been added in the revised manuscript (Table 2 in supplement).

Table S2. The validated parameter for the cross-variation of *n*.

ID	Validated basin	*a*	*b*	*c*	ID	Validated basin	*a*	*b*	*c*
1	Amur	0.28^{***}	0.88^{***}	-0.32^{***}	14	Northern Dvina	0.29^{***}	0.86^{***}	-0.33^{***}
2	Aral	0.28^{***}	0.87^{***}	-0.33^{***}	15	Ob	0.28^{***}	0.90^{***}	-0.29^{***}
3	Columbia	0.27^{***}	0.90^{***}	-0.31^{***}	16	Olenek	0.29^{***}	0.86^{***}	-0.33^{***}
4	Congo	0.29^{***}	0.86^{***}	-0.32^{***}	17	Parana	0.28^{***}	0.87^{***}	-0.33^{***}
5	Danube	0.29^{***}	0.88^{***}	-0.13^{***}	18	Pearl	0.32^{***}	0.77^{***}	-0.36^{***}
6	Indigirka	0.29^{***}	0.85^{***}	-0.33^{***}	19	Pechora	0.29^{***}	0.87^{***}	-0.32^{***}
7	Indus	0.29^{***}	0.86^{***}	-0.33^{***}	20	Senegal	0.30^{***}	0.83^{***}	-0.33^{***}
8	Kolyma	0.27^{***}	0.88^{***}	-0.32^{***}	21	Volga	0.26^{***}	0.91^{***}	-0.33^{***}
9	Lena	0.28^{***}	0.88^{***}	-0.32^{***}	22	Yangtze	0.29^{***}	0.85^{***}	-0.34^{***}
10	Mackenzie	0.29^{***}	0.86^{***}	-0.33^{***}	23	Yellow	0.34^{***}	0.76^{***}	-0.39^{***}
11	Mississippi	0.29^{***}	0.86^{***}	-0.33^{***}	24	Yenisei	0.26^{***}	0.90^{***}	-0.32^{***}
12	Niger	0.29^{***}	0.86^{***}	-0.33^{***}	25	Yukon	0.29^{***}	0.85^{***}	-0.33^{***}
13	Nile	0.28^{***}	0.87^{***}	-0.33^{***}	26	Amur	0.30^{***}	0.83^{***}	-0.32^{***}

'***' represent the validated parameter are significant at the level of $p = 0.01$

Lines 315-320: also plot the relationships between the simulated R and E using the equation (14) and the observed values.

Re: Thank you for your kind comments. The subgraphs for simulated *R* and *E* using the equation (14) has been added in Figure 7. More analyses have been added in the revised manuscript. The text states as follow.

"As shown in Fig. 7a-b, the simulated annual *R* and *E* that estimated by Budyko model with cross-validation parameter *n* showed a remarkable agreement with the observed ones with *NSE* larger than 0.89 and MAE smaller than 50.52 mm, which is close to the simulation accuracy of these estimated by Budyko model with simulated parameter *n* by using the semi-empirical formula (i.e., eq. (14) (Fig. 7c-d)."

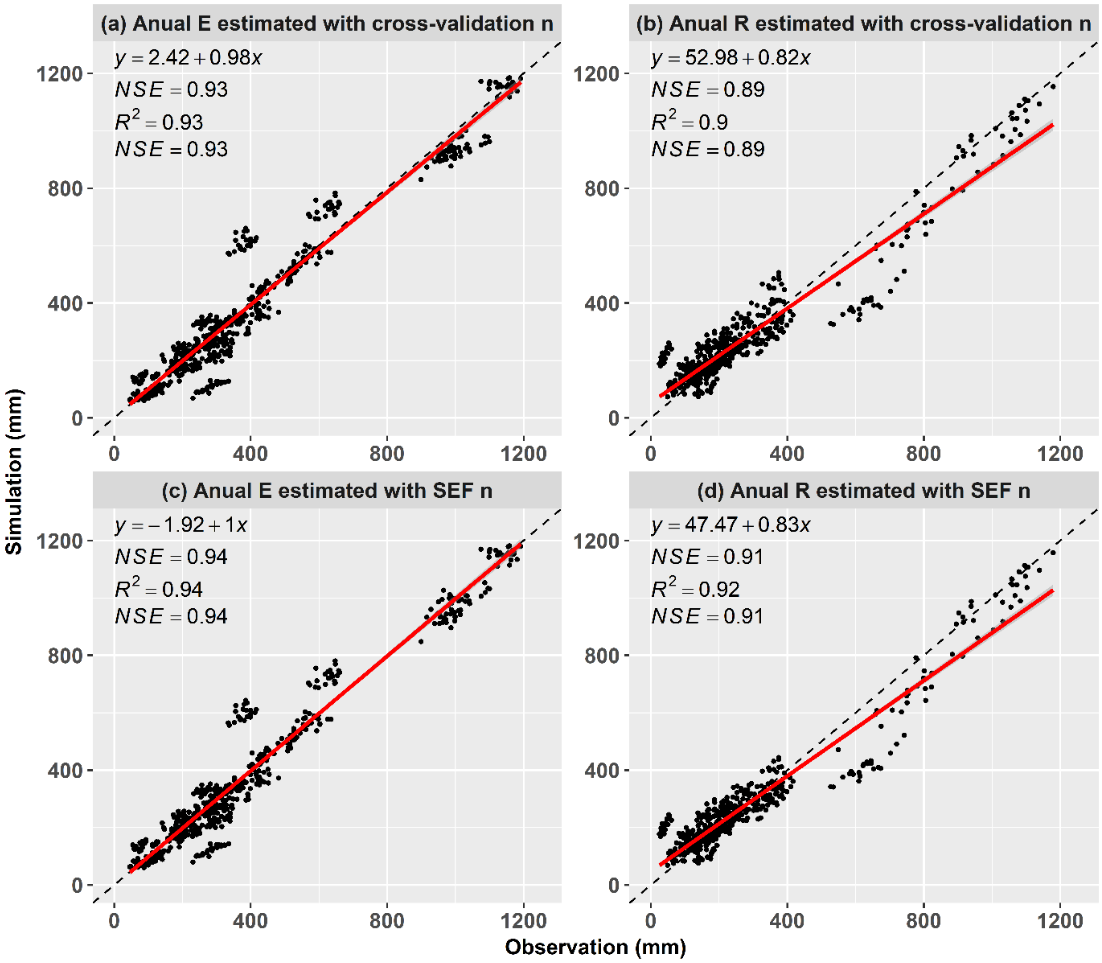

Figure 7. The observed *E* and *R* versus the simulated *E* and *R* estimated by Budyko model with simulated parameter *n* by (a-b) eq. (13) with cross-validation method and (c-d) eq. (14)

Lines 342-343: because of the monsoon variability, see Cook et al. (2010).

Cook, E. R., Anchukaitis, K. J., Buckley, B. M., D'Arrigo, R. D., Jacoby, G. C., & Wright, W. E. (2010). Asian monsoon failure and megadrought during the last millennium. Science, 328(5977), 486-489.

Re: Thank you for your kind suggestion. It has been added.

Lines 376-384: **(a)** The equations (13) and (14) are used to mainly explain temporal variations of the parameter n, and may not be useful to explain the spatial variations, especailly when large variations in land surface characteristics exist. **(b)** Are the remaining scatters in figure 4 related to different land surface characteristics? **(c)** I am wondering whether the explanatory power of the equation (13) is larger when it is applied to each one basin, than for all basins.

Re: Thanks so much for your kind comments. To test the performance of the semi-empirical formula in the modelling of spatial variations of parameter *n*, we also recalibrated the equation (13) at the long-term time scale. Then we obtained a semi-empirical formula for spatial variations of parameter *n*: $n = 0.33\mathrm{SAI}^{-0.39}\mathrm{M}^{0.77}$, the regression coefficient of which is closed to the equations (14). As shown in below Figure S1, the spatial variation of *n* simulated by this formula match well with the optimized *n* with *NSE* of 0.8 and *MAE* of 0.2. In addition, the simulated long-term *R* and *E* that estimated by Budyko model with simulated long-term *n* showed a remarkable agreement with the observed ones with R^2 larger than 0.91 and MAE smaller than 40 mm (Figure S2), which

is also similar to the simulation accuracy of these estimated by Budyko model with simulated parameter *n* by eq. (14) at annual time scale (Figure 7b-c). These results suggest that the semi-empirical formula is also useful to explain the spatial variations of parameter *n*.

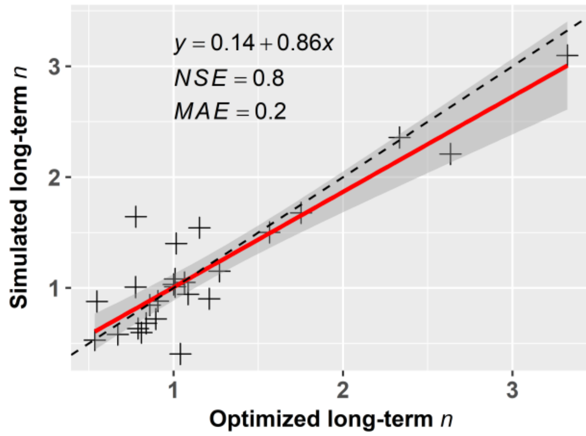

Figure S1. The Optimized long-term *n* versus the versus simulated long-term *n* estimated by eq. (13).

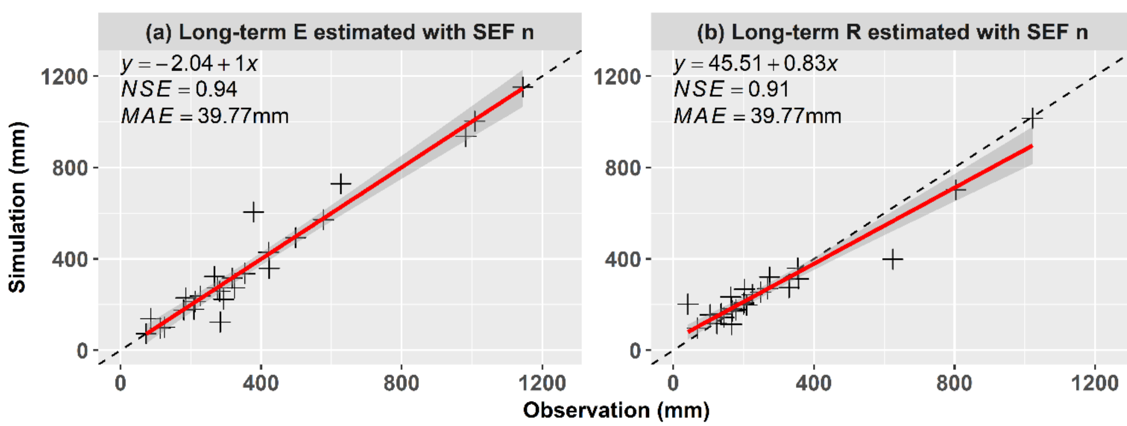

Figure S2. The observed long-term *E* and *R* versus the versus simulated long-term *E* and *R* estimated by Budyko model with simulated parameter *n* by eq. (13).

(b) Yes, you are right. The remaining scatters all belongs to the Congo river basin, which located at tropical areas. Besides, the Congo river is the deepest river across the world with steep gradients and large flow velocity. Therefore, The Congo river basin represented by the remaining scatters has different land surface characteristics compared with other basins. If we deleted the scatter of Congo, the remaining scatters in figure 4 disappear (Shown as below figure).

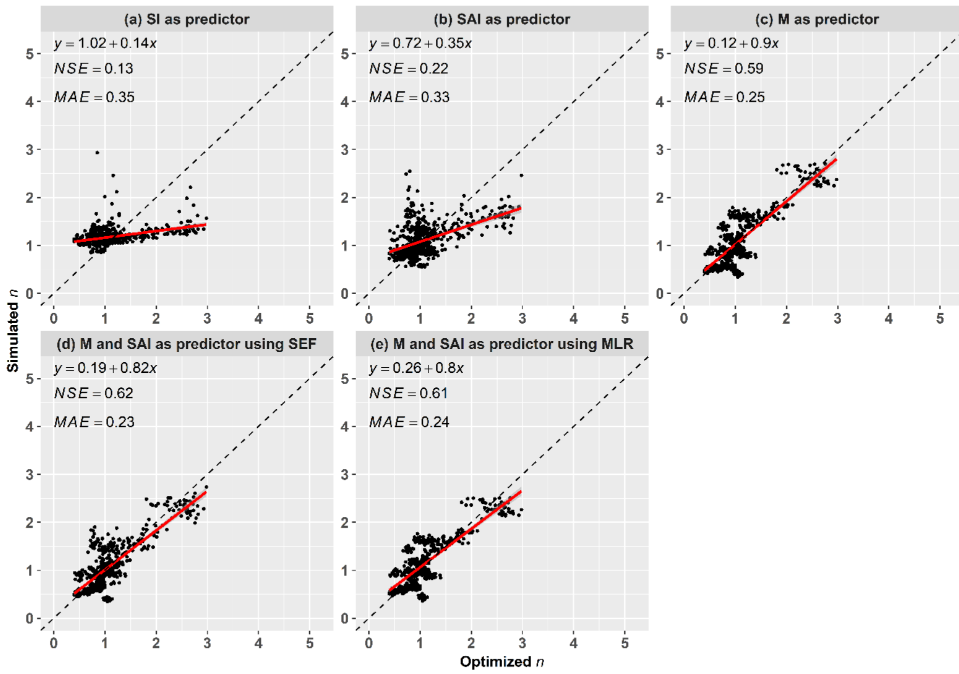

Figure S3. Same to Figure 4 but excluded the Congo river basin.

(c) Yes, the explanatory power of the equation (13) is larger when it is applied to each one basin, than for all basins. As shown in the Table S1 in Supplement, the RMSE and MAE of simulated runoff based on the *n* estimated by each one basin is obvious smaller than these for all basins, with the mean value of 16.8, 13.3mm; However, the R^2 of simulated runoff calculated by equation (14) for all basins is large than simulated runoff combined by each basin and calculated by equation (13).

Lines 396-400: why other factors such as precipitation contribute a small proporation to R and E in the Danube river basin. Please change river to river basin here and other places.

Re: We have added a table to show the detailed the change of P, R, E as well as other factors (Table S3 in Supplement). As shown in Table S3, the absolute rate of change in precipitation is much smaller than *R* and *E*, with 5.2% for the former but 12.9% and 16.3% for the later. What's more, the change direction of *R* is different to the *P*. These indicate that the *R* and *E* changes in Danube river basin is dominant by other factors, rather than precipitation. By the way, the river has been revised to river basin in the full-text. Thank you.

Table S3. The change points of runoff and the change rates of meteorological and vegetative factors after change points

ID	Basin	Changepoint of *R*	*R*	*E*	*Pe*	*PET*	*n*	*NDVI*	*SI*
1	Amazon	1998	8.5	-1.0	3.4	1.1	-9.4	3.4	0.3
2	Amur	1998	-16.4	-0.3	-5.8	3.0	4.5	-1.3	24.9
3	Aral	1994	-14.8	12.8	5.2	3.8	12.4	-0.8	-6.1
4	Columbia	1999	-10.7	1.2	-4.4	4.2	2.1	-1.7	15.7
5	Congo	1997	4.1	-2.5	-0.8	0.7	-15.5	1.0	3.5
6	Danube	1988	-12.5	16.4	5.2	5.5	27.3	6.4	1.4
7	Indigirka	1990	-7.0	4.4	-3.4	2.4	5.0	5.5	5.1

8	Indus	1998	-16.7	-4.5	-9.0	1.7	2.3	3.4	24.6
9	Kolyma	1990	-9.6	0.4	-5.0	0.9	3.7	4.2	16.9
10	Lena	1995	14.3	4.7	9.2	-1.3	0.3	1.1	-3.8
11	Mackenzie	1989	-13.3	6.2	-3.5	2.3	10.5	-2.7	13.1
12	Mississippi	1998	-20.1	5.0	-2.0	0.0	15.1	1.3	8.7
13	Niger	1990	27.9	7.7	13.7	0.6	-2.6	6.5	-4.1
14	Nile	1995	14.7	3.2	5.7	1.9	-2.9	3.1	12.5
15	Northern Dvina	2000	-7.1	6.7	-1.1	2.2	9.4	1.3	8.5
16	Ob	1998	7.5	4.7	5.9	1.8	0.9	-0.8	-7.0
17	Olenek	1988	13.9	10.7	12.6	-1.9	4.5	6.2	-20.5
18	Parana	1998	-6.6	2.0	0.1	1.6	4.6	-1.1	2.9
19	Pearl	1991	16.3	2.9	10.1	-0.7	-0.5	-1.6	19.0
20	Pechora	1990	20.4	-3.9	11.1	0.7	-10.2	2.7	-12.4
21	Senegal	1993	28.3	15.3	16.9	0.9	1.7	7.6	-9.3
22	Volga	1994	-8.9	4.1	-1.2	2.3	6.8	3.8	1.6
23	Yangtze	2000	-4.5	5.9	-0.6	3.0	5.2	-0.3	-3.2
24	Yellow	1990	-10.1	3.2	-0.3	2.9	5.1	2.6	24.2
25	Yenisei	1996	2.1	3.9	3.1	1.1	2.3	1.6	12.1
26	Yukon	1994	-8.0	-28.4	-15.6	2.2	-18.9	-3.4	8.9

Lines 401-402: n is only a parameter without specific physical meanings.

Re: Yes, it has been modified as "the impact of **other factors represented by parameter** *n* on the water balance not only includes SAI and M**…"**