We greatly appreciate the constructive suggestions and have carefully revised the manuscript accordingly. Please check the following responses for our detailed modification. The supplementary document contains our specific responses to the comments.

I. Point-to-point responses:

Anonymous Referee #1

General comments:

1. *Usually, the Budyko framework is used in long-term scale so that the water storage change can be ignored. It is a big challenge to apply this framework in interannual catchment water balance. The hydrological year is better than the calendar year, but it is not enough. In present researches, the parameter, such as oumiga, was determined for each catchments then the relation between this parameter and other factors, such vegetation, landscape and climate characteristics were discussed. For example, Li et al. published in WRR in 2013. Therefore, my advice is to set up the relation between oumiga and M and S based on the long-term water balance for the 13 catchments then to discuss the contribution of different part to the runoff change.*

Response: Thanks for your good comments. We agree your opinion that the Budyko framework is mostly used in long-term scale. The reason why we use a period of hydrologic year to develop the semi-empirical formula is to exclude the cross correlation between *M* and *S*. We checked the relationship of *M* and *S* on the 5-year, 10-year and 30-year scales, and found that they are cross correlated. Particularly, the correlation coefficients increase with the lengths of time scale, and the determining coefficient (R^2) is 0.8 for the 30-year scale. If *M* and *S* is not independent of each other, they cannot be used together to express different functions. After substantial tests, we found that the relationship between *M* and *S* is not significant in a period of hydrologic year. Thus, they can be used to express the controlling parameter. Furthermore，there are several researches have figured out that although the parameter in the Budyko relationship has been used to represent the catchment characteristics, this parameter is also affected by climate seasonality (Milly, 1994;Donohue et al., 2011;Williams et al., 2012;Berghuijs and Woods, 2016;Zhou et al., 2016). In our study, we also found that parameter ω has a negative correction with climate seasonality. Thus, the climate seasonality should be incorporating into the parameter.

Your concern about the changes in water storage is really very important in water balance equation. To exclude the potential impacts, we checked the interannual variation of catchment-scale water storage in some studies, and presented some discussion about this part. Specifically, we found that the water storage change in the Loess Plateau is relative small compared with the other regions of China. In such cases, assessing catchment-scale water balance by ignoring water storage change should be reasonable on a time scale of hydrologic year.

2. *For the contribution analysis, it is better to divide the whole period into two periods, for example, before 1980 and after 1980. A, B and C in Equation 5 can be estimated by the P, ET0*

and oumiga of the whole period. Then deltaP=P2-P1, deltaET0=ET02-ET01, delta oumiga = oumiga 2- oumiga 1. After that, the contribution of P, ET0 and oumiga can be estimated.

Response: Thanks for reviewer's good suggestion. We recalculated the contribution according to your suggestion by dividing the whole study period into two subperiods. Further, we replaced the previous method with a new method developed by Zhou et al. (2016). The previous method ignored the higher orders of the Taylor expansion and resulted in errors; however, the new method proposed by Zhou et al. (2016) decompose the runoff/ET changes into two components precisely without any residuals. And the detailed revisions are showed in the section 2.3 and 4.3.

3. It is better to analyze the trend of runoff and climate factors with MK test.

Response: The trend analysis of each variable has been shown in table 3.

Special comments:

1. *Please give more detail about the climate seasonality index (S).*

Response: Thanks for reviewer's good suggestion, and the more detailed description has been added in the section 2.2.

2. *L225, "out of phase", "out phase", which one is right?*

Response: "out of phase" should be more suitable. The same expression was also used by Potter et al. in WRR in 2005.

3. *L237, just from 0.45 to 0.51, it is not a significant improvement.*

Response: Thanks for reviewer's comment. The more important meaning of incorporating the climate seasonality into the controlling parameter oumiga is to further explore the factors that controlling the interannual catchment water balance, rather than only considering its function of improving the estimation of parameter oumiga. And the results of attribution analysis showed that the contribution of vegetation coverage changes to ET variation will be estimated with a large error if the effects of climate seasonality were ignored. Thus, we will no longer address the improvement of the estimation of parameter oumiga after considering climate seasonality, and remove Table 2 as well as related comparison.

4. *L242, crossing-validation is not a good choice here because each catchments has its own characteristics, so it can not be validated by other catchments.*

Response: We agree. Each catchment has its own characteristics, mainly including the underlying physical conditions (such as soil properties and topography), vegetation and climate characteristics. Ignoring the spatial heterogeneity of underlying physical conditions for studied basins may influence the performance of the empirical equation we built. However, we think that the crossing-validation approach can be used to calibrate and test the semi-empirical formula for parameter oumiga, because the rotated calibrations using 12 basins instead of all 13 basins only produce slight variations in the slopes and intercepts from regressions (Table 3), which suggests that the formula we built are robust and it can be used to assess catchment actual evapotranspiration in the Loess

Plateau. And the subsequent validations further prove the good performance of our formula. This method was also widely used by previous studies (e.g. Li et al., 2013;Chen et al., 2014;Schnier and Cai, 2014;Kim et al., 2015;Nerini et al., 2015;Lv and Zhou, 2016;Rakovec et al., 2016;Toth, 2016). Among them, the study of Li et al. (2013) is similar with ours, who also used the crossing-validation approach to test their formula for each catchment.

5. *Keep all the panels (including the label, range and scale of x/yaxis) within a figure be consistent. Have a close look at the Fig 2-4.*

Response: Thanks for reviewer's suggestion, and we have unified the format of Fig 2-4 & S1.

6. *It may be better to replace Fig 3 and 4 by a table show R^2 with a certain category. The original figures could be provided as supplementary documents.*

Response: We have moved the Fig3 &4 into the supplementary documents. Since these two figures have contained "R^2" and "p", we think it is not necessary to make new tables.

7. *Table 4, "Relative contributions of vegetation change and climate seasonality to ET trends for each basin", which miss out the contributors from "ET0 and P".*

Response: We have corrected this title as "Attribution analysis for *ET* changes for each basin"

8. *For reading convenience, better to insert the ordering number according to the ordering system given in Fig1 and Table1 in the text when mentioning a particular basin in Results.*

Response: We have inserted the ordering number of each basin in the revised text, for example, "Huangfu" was revised as "basin #1".

Anonymous Referee #2:

1. *The major concern is that the inter-annual water storage change is assumed to be negligible even though hydrologic year is used. The estimated value of w could be affected by this assumption of storage change. Since the purpose of this study is to evaluate the contribution of vegetation and seasonal climate variability to inter-annual variability of water balance, this assumption is important and needs to be further invsetigated and discussed.*

Response: Thanks for reviewer's good suggestion. And the other anonymous referees also figured out this problem and suggested us build the relationship between ω and M as well as S on the long-term scale. However, after checking the relationship of M and S on the 5-year, 10-year and 30-year scales, we found that they are cross correlated. Particularly, the correlation coefficients increase with the lengths of time scale, and the determining coefficient (R^2) is 0.8 for the 30-year scale. If M and S is not independent of each other, they cannot be used together to express different functions. After substantial tests, we found that the relationship between M and S is not significant in a period of hydrologic year. Thus, they can be used to express the controlling parameter. Furthermore，there are several researches have figured out that although the parameter in the Budyko relationship has been used to represent the catchment characteristics, this parameter is also affected by climate seasonality (Milly, 1994;Donohue et al., 2011;Williams et al., 2012;Berghuijs and Woods, 2016;Zhou et al., 2016). In our study, we also found that parameter ω has a negative correction with climate seasonality. Thus, the climate seasonality should be incorporating into the parameter.

Your concern about the changes in water storage is really very important in water balance equation. To exclude the potential impacts, we checked the interannual variation of catchment-scale water storage in some studies, and presented some discussion about this part. Specifically, we found that the water storage change in the Loess Plateau is relative small compared with the other regions of China. In such cases, assessing catchment-scale water balance by ignoring water storage change should be reasonable on a time scale of hydrologic year.

2. *To develop the semi-empirical formula of parameter w, the limiting conditions of M and S were considered in this paper, which is significant for understanding the variability of water balance under the extremely hydrometeorological conditions. However, I think the limiting condition of S is not exactly right: when* $\emptyset \rightarrow \infty$ *and* $\delta_{ET_0} \neq 0$ *in the equation (3), i.e. P*$\rightarrow 0$*, and monthly ET0 is not uniform distributed within a year, w can also close to unity.*

<u>*Response*</u>: Yes, the limiting condition of S is indeed not right and we have corrected it according to your suggestion in the revised manuscript, thanks for your carefulness.

3. *It has been reported that the first-order approximation (ignoring the higher orders of the Taylor expansion) in the Equations (4-6) will bring errors (Yang et al. 2014, WRR); furthermore, the function of P and ET0, and their interaction may play some roles in the attribution analysis. Thus, it is better to consider these errors in the paper.*

<u>*Response*</u>: Thanks for reviewer's good suggestion and we agreed with your opinion. Thus, we applied the new method proposed by Zhou et al. (2016) to conduct attribution analysis. The algebraic identities in their work can ensure that the change in runoff/*ET* can be decomposed into two components precisely without any residuals and reduced the errors of ignoring the higher orders of the Taylor expansion in the traditional attribution method. Furthermore, the errors and uncertainties induced by the attribution analysis have been added and presented in the discussion section.

4. *In previous attribution analyses of variation in runoff or ET based on the climate elasticity method, the study period was first divided into two periods, and then the contribution of a variable on the change in runoff or ET from the first period to second period was defined as the product of the elasticity coefficient and the variation of this variable. While in this study, the climate elasticity method was used to explain the change trend of ET for the whole study period. Even the comparisons of these two methods was conducted in the discussion section, there still need more data to support this estimation.*

Response: Thanks for reviewer's good suggestion. We have to admit that the attribution method we used will produce some uncertainties. And other two anonymous referees also figured out this problem. Therefore, considering the suggestions of three referees, "the complementary method" proposed by Zhou et al. (2016) was adopted in our revised manuscript. And the corresponding revision was shown in the section 2.3 and 4.3.

5. *Line 64. Also cite Donohue et al. 2012 JOH.*

Response: This reference has been cited.

Response to the short comment:

1. *In the attribution equation (6), the impact factors are precipitation, ET0 and w. In equation (7), the authors further present that w is the function of M and S. S is a function of precipitation and ET0. Thus, in equation (6), precipitation, ET0 and w are not independent. This independence could have impacts on partial derivatives. This uncertainties could be added and presented in the paper.*

Response: Thanks for your comments. However, it must be noted that the concepts of "P" and "ET_0" in the equation (6) and (3) are different: in the equation (6), they refer to the total precipitation and potential evapotranspiration in a year, i.e. annual P and ET_0; while in the equation (3), they represent the intra-annual distribution characteristics of precipitation and potential evapotranspiration, respectively, and thus the information of annual total amounts does not been contained in this equation. Therefore, P, ET_0 and ω are independent. The uncertainties in the contribution quantification are mainly from ω interpretation. The residuals in this study suggest that ω cannot be fully explained by M and S, and more factors should be incorporated.

2. *The impacts of interannual changes of water storage could also be discussed in the paper. The traditional Budyko frame, i.e., equation (1), is conducted on average annual timescale. Therefore, delt_s can be ignored. In this study, the timescale is interannual and delts_s could be discussed in the uncertainty section. It would be better to add some reference to show that delts_s can be ignored on interannual timescale in the LP. The LP is a sub-arid and sub-humid area and delts_s may be relative small on interannual timescale.*

Response: We very agree with your opinion. In the section of discussion, we have added some reference according to your suggestion to show that the water storage change in the Loess Plateau is relative small compared with other regions of China.

II. All major relevant changes made in the manuscript:

1. **For the general comment 1 of Referee #1, #2 and short comment 2 of Dr. Liu:**

   The following paragraph was added in the discussion section:

Despite that catchment-scale water storage changes are usually assumed to be zero on long-term scale, the interannual variability of storage change can be an important component in annual water budget during dry or wet years (Wang and Alimohammadi, 2012), and cannot be ignored. However, the Loess Plateau has a subhumid to semiarid climate, the water storage and its annual variation are relatively small compared with humid regions (see Figure 5 from Mo et al., 2016). For example, using GRACE (Gravity Recovery and Climate Experiment), the water storage variations in the Yangtze, Yellow and Zhujiang from 2003 to 2008 were analyzed by Zhao et al. (2011), and the values for the Yangtze and Zhujiang basins were 37.8 mm and 65.2 mm, while no clear annual variations are observed in the Yellow River basin (3.0 mm). Furthermore, Mo et al. (2016) found that the water storage in Yellow River kept decreasing from 2004 to 2011, whereas it was changing slowly with a rate of 1.3 mm yr^{-1}. Therefore, considering the small water storage change in study area, ignoring water storage change in a period of hydrologic year is reasonable.

2. **For the general comment 2 of Referee #1 and comment 4 of Referee #2:**

   The following revisions are showed in the section 2.3 and 4.3:

2.3. Evaluating the contributions of climate change and surface condition alterations

Based on the climate elasticity method, which was introduced by (Schaake and Waggoner, 1990) and improved by (Sankarasubramanian et al., 2001), the contribution of change for each climate factor to runoff was defined as the product of the sensitivity coefficient and the variation of the climate factor (Roderick and Farquhar, 2011):

$$dR = \frac{\partial R}{\partial P} dP + \frac{\partial R}{\partial ET_0} + \frac{\partial R}{\partial \omega} d\omega \qquad (5)$$

However, due to ignoring the higher orders of the Taylor expansion in equation (5), this method will result in high errors (Yang et al., 2014). Recently, Zhou et al. (2016) proposed a new method to partition climate and catchment effect on the mean annual runoff based on the Budyko complementary relationship, called “the complementary method”. The algebraic identities in their work can ensure that the change in runoff can be decomposed into two components precisely without any residuals. Here, we extend “the complementary method” to conduct attribution analysis of ET changes for each basin by further incorporating the effects of vegetation coverage and climate seasonality:

$$\Delta ET = \alpha\left[\left(\frac{\partial ET}{\partial P}\right)_1 \Delta P + \left(\frac{\partial ET}{\partial ET_0}\right)_1 \Delta ET_0 + P_2\Delta\left(\frac{\partial ET}{\partial P}\right) + ET_{0,2}\Delta\left(\frac{\partial ET}{\partial ET_0}\right)\right]$$
$$+(1-\alpha)\left[\left(\frac{\partial ET}{\partial P}\right)_2 \Delta P + \left(\frac{\partial ET}{\partial ET_0}\right)_2 \Delta ET_0 + P_1\Delta\left(\frac{\partial ET}{\partial P}\right) + ET_{0,1}\Delta\left(\frac{\partial ET}{\partial ET_0}\right)\right] \quad (6)$$

where α is a weighting factor that varies from 0 to 1, which can determine the upper and lower bounds of the climate and the controlling parameter effect. In this study, we defined α=0.5 according to the recommendation of Zhou et al. (2016).The difference operator (Δ) refers to the difference of a variable from period 1 (1981 to the changing point detected by Pettitt's test (Pettitt, 1979)) to period 2 (period-1 end to 2012) ,e.g., $\Delta ET_0 = ET_{0,2} - ET_{0,1}$. Then the contributions of P, ET_0, and ω changes to the ET changes can be expressed as follows:

$$C\_(P) = \alpha\left[\left(\frac{\partial ET}{\partial P}\right)_1 \Delta P\right] + (1-\alpha)\left[\left(\frac{\partial ET}{\partial P}\right)_2 \Delta P\right] \quad (7a)$$

$$C\_(ET_0) = \alpha\left[\left(\frac{\partial ET}{\partial ET_0}\right)_1 \Delta ET_0\right] + (1-\alpha)\left[\left(\frac{\partial ET}{\partial ET_0}\right)_2 \Delta ET_0\right] \quad (7b)$$

$$C\_(\omega) = \alpha\left[P_2\Delta\left(\frac{\partial ET}{\partial P}\right) + ET_{0,2}\Delta\left(\frac{\partial ET}{\partial ET_0}\right)\right] + (1-\alpha)\left[P_1\Delta\left(\frac{\partial ET}{\partial P}\right) + ET_{0,1}\Delta\left(\frac{\partial ET}{\partial ET_0}\right)\right] \quad (7c)$$

After obtaining the contribution of parameter ω to the ET change, the contributions of vegetation coverage (M) and climate seasonality (S) to ET change can be further decomposed as follows.

First, the contributions of M and S to parameter ω are calculated by using the sensitivity method similar to Eq. (5) based the relationship between ω and M as well as S we built:

$$\Delta\omega = \frac{\partial\omega}{\partial M}\Delta M + \frac{\partial\omega}{\partial S}\Delta S \quad (8)$$

Furthermore, the individual relative contributions (RC) of M and S to ω can be calculated. Then, the contributions of M (C_(M)) and S (C_(S)) to ET changes can be obtained as follows:

$$C\_(M) = C\_(\omega) \times RC\_(M) \quad (9a)$$

$$C\_(S) = C\_(\omega) \times RC\_(S) \quad (9b)$$

4.3. Quantitative attribution of the variation in *ET*

The impacts of vegetation changes on ET have been widely studied with the Budyko framework by assuming surface conditions can be represented by the controlling parameter. However, according to the developed relationships in our study, the controlling parameter is not only related to surface condition change, but also to climate seasonality. The contributions of changes in climate (P, ET_0, and S) and vegetation (M) to the ET change were thus estimated by using the semi-empirical formula for parameter ω in the context of Fu’s framework.

Trend in hydrometeorological variables and vegetation coverage were first analyzed for each basin (Table 4). ET_0 and S in all basins exhibited an upward trend, though with different significances. Similarly, M in most basins increased during past several decades. Based on the sensitivity coefficients of ET (Table S1) and the changes in mean annual P, ET_0, ω, M and S from period I to period II (Table 5), the changes in ET due to those in P, ET_0, M and S were estimated using the method described in Section 2.3. The contributions of four variables to ET change for each basin were presented in Table 5. In basin #1, 3-4 and #6, the ET changes were controlled by vegetation improvement; however, in the other basins, the dominant factor was precipitation. Except for basin #6, #9 and #12, elevated vegetation in most basins positively contributed to ET changes, which is consistent with Feng et al. (2016). ET in several basins showed a downward trend even though M positively contributed to ET changes; which is due to the offsetting effect of the other factors.

Table 3. Trend analysis for the hydrometeorological variables and vegetation coverage^{b}.

ID	**Basin**	**ET,mm yr^{-2}**	**ET_0,mm yr^{-2}**	**P,mm yr^{-2}**	**M**	**S**
1	Huangfu	1.89	1.16	0.61	0.002*	0.001
2	Gushan	0.76	3.85**	-0.01	0.004**	0.012
3	Kuye	2.34*	2.04*	0.53	0.004**	0.006
4	Tuwei	1.87	2.33**	0.53	0.005**	0.006
5	Wuding	0.88	1.17	0.31	0.006**	0.004
6	Qingjian	-0.45	1.78*	-0.94	0.007**	0.006
7	Yan	-1.62	2.03*	-1.99	0.005**	0.006
8	Beiluo	-5.4*	4.6*	-6.2*	0.0001	0.017
9	Jing	-0.97	1.47*	-1.79	0.002**	0.001
10	Fen	-0.72	1.93*	-1.16	0.002*	0.003
11	Xinshui	0.33	1.80	-0.12	0.003**	0.005
12	Sanchuan	1.49	1.84	0.09	-0.0004	0.004
13	Qiushui	-0.50	1.79	-0.83	0.002	0.008

^{b*} and ** indicate the trend is significant at the level of p = 0.05 and p = 0.01 by the Mann–Kendall test, respectively.

It should be noted that the climate seasonality (represented by S) played an important role in the catchment ET variation. The contributions of S to ET changes ranged from 0.1% to 65.5% (absolute values). Besides basin #6, #9 and #12, the climate seasonality had a negative effect on ET variation in most of the basins, which means that larger seasonality differences between seasonal water and heat will lead to smaller amounts of evapotranspiration. Accordingly, if ω is supposed to only represent the landscape condition, the effects of landscape condition change on ET variation will be underestimated in basin #1, #3, #6-7, #9 and #11. Except for basin #9, the area of these basins is relative smaller; while its effects will be overestimated in the other basins, and the error would be equal to the contributions of S to ET changes.

Table 4. Attribution analysis for ET changes for each basin [c]

ID	Basin	Break point of ET	Change from Period 1 to Period 2					ET_0/ P/M/S induced ET change (mm)					Contribution to ET change (%)			
			ΔET	ΔET_0	ΔP	ΔM	ΔS	C_ (ET_0)	C_ (P)	C_ (ω)	C_ (M)	C_ (S)	φ_ (ET_0)	φ_ (P)	φ_ (M)	φ_ (S)
1	Huangfu	2001(ns)	41.7	7.0	22.2	0.03	0.01	0.28	18.67	22.70	22.73	-0.04	0.7	44.8	54.6	-0.1
2	Gushan	2000(ns)	33.6	64.9	20.6	0.07	-0.10	2.81	17.01	13.77	8.87	4.90	8.4	50.6	26.4	14.6
3	Kuye	2000(**)	51.4	32.0	17.3	0.06	0.05	1.54	13.34	36.48	55.95	-19.47	3.0	26.0	108.9	-37.9
4	Tuwei	2000(**)	43.2	39.6	24.0	0.07	-0.03	2.57	15.28	25.35	21.85	3.49	5.9	35.4	50.6	8.1
5	Wuding	2000(*)	35.2	17.6	26.9	0.09	-0.12	0.77	21.82	12.64	8.24	4.40	2.2	61.9	23.4	12.5
6	Qingjian	1988(**)	-50.1	32.0	-48.0	0.08	0.19	2.06	-37.80	-14.31	-47.09	32.78	-4.1	75.5	94.08	-65.5
7	Yan	1985(**)	-82.3	44.6	-86.9	0.05	0.30	3.19	-69.52	-15.96	22.19	-38.14	-3.9	84.5	-27.0	46.4
8	Beiluo	1985(**)	-65.1	49.4	-79.8	0.01	0.19	4.33	-62.9	-6.75	3.69	-10.43	-6.6	96.3	-5.7	16.0
9	Jing	1990(**)	-33.7	43.0	-47.8	0.03	0.11	4.1	-37.2	-0.61	-8.23	7.61	-12.2	110.3	24.4	-22.6
10	Fen	2005(ns)	23.1	8.5	21.2	0.07	-0.20	0.33	19.00	3.81	2.13	1.68	1.4	82.1	9.2	7.3
11	Xinshui	1990(**)	-19.1	39.7	-24.7	0.02	0.09	2.06	-21.08	-0.14	0.41	-0.55	-10.8	110.1	-2.1	2.9
12	Sanchuan	1996(ns)	-27.0	45.4	-43.4	-0.01	0.22	3.01	-32.52	2.56	0.20	2.36	-11.2	120.6	-0.7	-8.8
13	Qiushui	1996(ns)	-80.3	77.5	-103.5	-0.01	0.68	3.76	-83.68	-0.40	-0.02	-0.37	-4.7	104.2	0.1	0.5

[c] The relative contribution of a certain variable to the ET change ($\varphi(x)$) was calculated as follows: $\varphi(x) = (\mathrm{C}\_(x)/\Delta ET) \times 100\%$, where C_($x$) represents the contribution of each variable.

3. **For the general comment 3 of Referee #1:**

Table 3. Trend analysis for the hydrometeorological variables and vegetation coverage[b].

ID	Basin	ET,mm yr^{-2}	ET_0,mm yr^{-2}	P,mm yr^{-2}	M	S
1	Huangfu	1.89	1.16	0.61	0.002*	0.001
2	Gushan	0.76	3.85**	-0.01	0.004**	0.012
3	Kuye	2.34*	2.04*	0.53	0.004**	0.006
4	Tuwei	1.87	2.33**	0.53	0.005**	0.006
5	Wuding	0.88	1.17	0.31	0.006**	0.004
6	Qingjian	-0.45	1.78*	-0.94	0.007**	0.006
7	Yan	-1.62	2.03*	-1.99	0.005**	0.006
8	Beiluo	-5.4*	4.6*	-6.2*	0.0001	0.017
9	Jing	-0.97	1.47*	-1.79	0.002**	0.001
10	Fen	-0.72	1.93*	-1.16	0.002*	0.003
11	Xinshui	0.33	1.80	-0.12	0.003**	0.005
12	Sanchuan	1.49	1.84	0.09	-0.0004	0.004
13	Qiushui	-0.50	1.79	-0.83	0.002	0.008

[b] * and ** indicate the trend is significant at the level of p = 0.05 and p = 0.01 by the Mann–Kendall test, respectively.

4. **For the special comment 1 of Referee #1:**

The following revisions are showed in the section 2.2:

Solar radiation was considered as the dominant factor that controls the climate seasonality and thus the seasonality of P and ET_0 can be can be expressed by sine functions (Milly, 1994;Woods, 2003):

$$P(t) = \bar{P}(1 + \delta_P sin\omega t) \qquad (3a)$$

$$ET_0(t) = \overline{ET_0}(1 + \delta_{ET_0} sin\omega t) \qquad (3b)$$

where $\bar{P}$ and $\overline{ET_0}$ are the mean monthly P and ET_0; δ_P and δ_{ET_0} are the seasonal amplitude of precipitation and potential evapotranspiration, respectively. The values of δ_P and δ_{ET_0} might both range from -1 to 1 because P and ET_0 always have positive value on physical grounds. Larger absolute values of δ_P and δ_{ET_0} mean larger variability of climate seasonality. φ is the duration of the seasonal cycle, $2\pi\varphi$ equal to 1 year. Woods (2003) summarized the modelled climate of Eqs.(3a) and (3b) in dimensionless form and defined the climate seasonality index (S) and here it was used to reflect the non-uniformity in the annual distribution of water and heat in our study:

$$S = \left|\delta_P - \delta_{ET_0}\emptyset\right| \qquad (4)$$

where $\emptyset$ is the dryness index, $\emptyset = \overline{ET_0}/\bar{P}$. If S=0, there is no seasonal fluctuation of the difference between P and ET_0. Larger values of S indicate that the larger changes in the balance between P and ET_0 during the seasonal cycle.

5. For the comment 2 of Referee #2:

If $S \to \infty$, i.e. $\emptyset \to \infty$ and $\delta_{ET_0} \neq 0$ in the equation (3), which means monthly ET_0 is not uniform distributed within a year and $P \to 0$, thus $ET \to 0$, and $\omega \to 1$.

6. For the comment 3 of Referee #2 and short comment 1 of Dr. Liu:

The following paragraph was added in the discussion section:

Errors still exhibited in the attribution analysis of ET changes. As the changes in evapotranspiration has been decomposed without residual by the complementary method (Equation 6-7), the errors were induced from the developed empirical formula for w (Equation 11). It suggested that ω cannot be completely explained by M and S, and it might include some other factors. Therefore, discussing more factors influencing ω remains future work.

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III. The marked-up manuscript

Vegetation dynamics and climate seasonality jointly control the interannual catchment water balance in the Loess Plateau under the Budyko framework

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Abstract. Within the Budyko framework, the controlling parameter (ω in the Fu equation) is widely considered to represent landscape conditions in terms of vegetation coverage (M); however, some qualitative studies have concluded that climate seasonality (S) should be incorporated in ω. Here, we discuss the relationship between ω, M, and S, and further develop an empirical equation so that the contributions from M to actual evapotranspiration (ET) can be determined more accurately. Taking 13 catchments in the Loess Plateau as examples, ω was found to be well correlated with M and S. The developed empirical formula for ω calculations at the annual scale performed well for estimating ET by the cross-validation approach. By combining the Budyko framework with the semi-empirical formula, the contributions of changes in ω to ET variations were further decomposed as those of M and S. Results showed that the contributions of S to ET changes ranged from 0.1% to 65.5 % (absolute values); therefore, the impacts of climate seasonality on ET cannot be ignored. Otherwise, the contribution of M to ET changes will be estimated with a large error. The developed empirical formula between ω, M, and S provides an effective method to separate the contributions of M and S to ET changes.

KEYWORDS: Budyko framework; Controlling parameter; Vegetation dynamics; Climate seasonality; Loess Plateau

1. Introduction

The water cycle has been influenced greatly by human activities and climate change since the 1960s, and considerable variability in hydrological processes has been observed in many basins around the world; this has led to a series of problems concerning essential water resources (Stocker et al., 2014). Analyses of the mechanisms of the interactions among the water balance, climate, and catchment surface conditions are important for understanding these complex processes at different spatio-temporal scales (Zhang et al., 2008), and such work has practical significance in regard to the improvement of water resources and land management (Rodriguez-Iturbe, 2000; Xu et al., 2014).

Budyko (1948, 1974) postulated that precipitation (P, represents the water supply from the atmosphere) and potential evapotranspiration (ET_0, represents the demand by the atmosphere) are the two dominant variables that control the long-term average water balance. The Budyko framework is considered one of the most abiding frameworks linking climatic conditions to the runoff (R) and actual evapotranspiration (ET) of a catchment (Donohue et al., 2007), and it has been used successfully to investigate interactions between hydrological processes, climate variability, and landscape characteristics (e.g. (Milly, 1994; Woods, 2003; Yokoo et al., 2008; Yang et al., 2009)). A series of empirical formulas have been developed for the Budyko curve based on theoretical research and case studies of regional water balance over the past 50 years. Among them, the Fu (Fu, 1981; Zhang et al., 2004) and Choudhury–Yang equations (Choudhury, 1999; Yang et al., 2008) have been used widely; furthermore, the controlling parameters ω (in the Fu equation) and n (in the Choudhury–Yang equation) are related linearly (Yang et al., 2008).

Deviations from the Budyko curve have been detected in previous studies, which indicates that in addition to climate conditions, other variables can also influence the variability of regional water balances (Yang et al., 2007; Wang and Alimohammadi, 2012). Two kinds of factors have been identified to be responsible for the deviations. The first type of factors are related to land surface conditions, and these include vegetation dynamics (Donohue et al., 2007; Yang et al., 2009; Donohue et al., 2010; Li et al., 2013; Zhang et al., 2016), soil properties, and topography (Yang et al., 2007; Peel et al., 2010). The second type of factors include seasonal climate variability (in addition to P and ET_0), such as storm depth (Donohue et al., 2012; Shao et al., 2012; Li et al., 2014), frequency of daily rainfall (Milly, 1994), and differences in the timing of P and ET_0 (Budyko, 1961; Potter et al., 2005). All of these factors can be encoded into the controlling parameter of the Budyko equations (e.g. ω in the Fu equation and n in the Choudhury–Yang equation). So far, a great deal of attention has been paid to the relationships between land surface conditions and the controlling parameter. Based on satellite products of vegetation such as the Normalized Difference Vegetation Index (NDVI), vegetation has been found to correlate well with the controlling parameter, and some empirical relationships have been successfully developed (Yang et al., 2009; Li et al., 2013). In particular, the controlling parameter can be better represented by vegetation when higher spatiotemporal resolution products are used. Therefore, the impacts of dynamic changes in vegetation on hydrology can be effectively quantified.

Many current studies attribute any effects of the controlling parameter to landscape characteristics (Roderick and Farquhar, 2011; Zhou et al., 2015; Zhang et al., 2016). However, both empirical evidence and modelling tests have demonstrated the important function of climate seasonality on catchment water yield, and thereby, evidence exists that climate seasonality also strongly affects the controlling parameter in the Budyko equations (Berghuijs and Woods, 2016). Some indices and models have thus been developed to address this issue, and several potential solutions have been discussed (Milly, 1993, 1994; Potter et al., 2005; Yokoo et al., 2008; Feng et al., 2012; Li, 2014). Yang et al. (2012) introduced the climate seasonality index into the Budyko framework and proposed an empirical equation to include its effect in the estimation of the long-term controlling parameters; however, by focusing on the mean annual scale, the effects of vegetation dynamics were not considered. Therefore, how the vegetation dynamics and climate seasonality jointly control the interannual variability in the controlling parameters needs further interpretation.

Therefore, the primary motivation behind this study was to detect the potential linkages between the controlling parameter and surface condition change, as well as climate seasonality at an annual scale. The specific objectives were to derive an appropriate analytic formula between parameter ω in the Fu equation and the above two factors for typical catchments in the Loess Plateau, and then, quantify the impacts of vegetation change and climate seasonality variability on the catchment water balance.

2. Methods

2.1. Annual water balance definition

The Budyko framework assumes that the long-term average water balance is in a steady state (Wang and Alimohammadi, 2012), and the water storage change in a catchment can be negligible. The interannual variability of the water balance in individual basins can also be studied by overlooking the interannual variation of the catchment water storage (Sankarasubramanian and Vogel, 2002; Yang et al., 2007; Potter and Zhang, 2009). However, water storage change can be great when analysing the interannual variability of the water balance (Wang, 2012). To minimize the potential errors introduced by neglecting water storage variation, the hydrological year (Sivapalan et al., 2011; Carmona et al., 2014) and moving windows (Jiang et al., 2015) were introduced to the time series of annual hydrological variables. Similar to Sivapalan et al. (2011) and Carmona et al. (2014), the hydrological year rather than the calendar year is introduced to calculate the annual *ET*, and this is called the ‘‘measured’’ *ET* in the subsequent discussion. Specifically, as the study area has a semiarid climate with most rainfall occurring in summer and autumn (July–September), a hydrological year is defined as July to June of the following year. In this way, the water input occurs mainly at the beginning of the year and the water is consumed within that year.

2.2. Identification of factors determining parameter ω in Fu's equation

The Fu equation is used in this study with the following expressions:

$$\frac{ET}{P} = 1 + \frac{ET_0}{P} - \left[1 + \left(\frac{ET_0}{P}\right)^{\omega}\right]^{1/\omega} \text{or}$$

$$\frac{ET}{ET_0} = 1 + \frac{P}{ET_0} - \left[1 + \left(\frac{P}{ET_0}\right)^{\omega}\right]^{1/\omega} \qquad (1)$$

where ω is the controlling parameter of the Budyko curve. ET_0 is calculated by using the equation of Priestley and Taylor (1972).

The important issue regarding the parameterization of ω in Fu's equation is to choose factors with physical meanings. According to the results from related studies, land surface conditions can be mainly represented by vegetation, which was also true in this study. With an arid to semiarid climate, water availability is the key factor that controls vegetation dynamics. Although soil properties and topography also influence vegetation growth, their impacts can be ignored on an annual scale because they would be expected to be almost constant over a year. Therefore, vegetation dynamics (i.e. vegetation coverage) were chosen to represent the variations in surface conditions. The vegetation coverage (M) was estimated by the following equation (Yang et al. (2009)):

$$M = \frac{NDVI - NDVI_{\min}}{NDVI_{max} - NDVI_{min}} \qquad (2)$$

where $NDVI_{max}$ and $NDVI_{min}$ are the NDVI values of dense forest (0.80) and bare soil (0.05), respectively.

Two limiting conditions were used to illustrate the effects of seasonal variations in coupled water and energy on the regional water balance. If P and ET_0 are in phase, the intra-annual distribution of precipitation is very symmetrical, and thus, $R \rightarrow 0$ in non-humid regions and $ET \rightarrow P$. However, if P

and ET_0 are out phase, the total precipitation of one year is concentrated at a certain moment, and thus, $R \rightarrow P$ and $ET \rightarrow 0$. Therefore, the impacts of seasonal variations in coupled water and energy on the regional water balance cannot be neglected, and they can only be reflected by the controlling parameter. Solar radiation was considered as the dominant factor that controls the climate seasonality and thus the seasonality of P and ET_0 can be can be expressed by sine functions (Milly, 1994;Woods, 2003):

$$P(t) = \bar{P}(1 + \delta_P sin\omega t) \tag{3a}$$

$$ET_0(t) = \overline{ET_0}(1 + \delta_{ET_0} sin\omega t) \tag{3b}$$

where δ_P and δ_{ET_0} are the seasonal amplitude of precipitation and potential evapotranspiration, respectively. The values of δ_P and δ_{ET_0} might both range from -1 to 1 because P and ET_0 always have positive value on physical grounds. Larger absolute values of δ_P and δ_{ET_0} mean larger variability of climate seasonality. φ is the duration of the seasonal cycle, $2\pi\varphi$ equal to 1 year. Woods (2003) summarized the modelled climate of Eqs.(3a) and (3b) in dimensionless form and defined the climate seasonality index (S) and here it was used to reflect the non-uniformity in the annual distribution of water and heat in our study:

$$S = \left|\delta_P - \delta_{ET_0}\emptyset\right| \tag{4}$$

where $\emptyset$ is the dryness index, $\emptyset = \overline{ET_0}/\bar{P}$. If S=0, there is no seasonal fluctuation of the difference between P and ET_0. Larger values of S indicate that the larger changes in the balance between P and ET_0 during the seasonal cycle.

2.3. Evaluating the contributions of climate change and surface condition alterations to *ET* changes

Based on the climate elasticity method, which was introduced by (Schaake and Waggoner, 1990) and improved by (Sankarasubramanian et al., 2001), the contribution of change for each climate factor to runoff was defined as the product of the sensitivity coefficient and the variation of the climate factor (Roderick and Farquhar, 2011):

$$dR = \frac{\partial R}{\partial P}dP + \frac{\partial R}{\partial ET_0} + \frac{\partial R}{\partial \omega}d\omega \qquad (5)$$

However, due to ignoring the higher orders of the Taylor expansion in equation (5), this method will result in high errors (Yang et al., 2014b). Recently, Zhou et al. (2016) proposed a new method to partition climate and catchment effect on the mean annual runoff based on the Budyko complementary relationship, called “the complementary method”. The algebraic identities in their work can ensure that the change in runoff can be decomposed into two components precisely without any residuals. Here, we extend “the complementary method” to conduct attribution analysis of *ET* changes for each basin by further incorporating the effects of vegetation coverage and climate seasonality:

$$\Delta ET = \alpha\left[\left(\frac{\partial ET}{\partial P}\right)_1 \Delta P + \left(\frac{\partial ET}{\partial ET_0}\right)_1 \Delta ET_0 + P_2\Delta\left(\frac{\partial ET}{\partial P}\right) + ET_{0,2}\Delta\left(\frac{\partial ET}{\partial ET_0}\right)\right]$$

$$+(1-\alpha)\left[\left(\frac{\partial ET}{\partial P}\right)_2 \Delta P + \left(\frac{\partial ET}{\partial ET_0}\right)_2 \Delta ET_0 + P_1\Delta\left(\frac{\partial ET}{\partial P}\right) + ET_{0,1}\Delta\left(\frac{\partial ET}{\partial ET_0}\right)\right] \qquad (6)$$

where α is a weighting factor that varies from 0 to 1, which can determine the upper and lower bounds of the climate and the controlling parameter effect. In this study, we defined α=0.5 according to the recommendation of Zhou et al. (2016).The difference operator (Δ) refers to the difference of a variable from period 1 (1981 to the changing point detected by Pettitt’s test (Pettitt, 1979)) to period 2 (period-1 end to 2012) ,e.g., $\Delta ET_0 = ET_{0,2} - ET_{0,1}$. Then the contributions of *P*, *ET₀*, and ω changes to the *ET* changes can be expressed as follows:

$$\mathrm{C\_}(P) = \alpha\left[\left(\frac{\partial ET}{\partial P}\right)_1 \Delta P\right] + (1-\alpha)\left[\left(\frac{\partial ET}{\partial P}\right)_2 \Delta P\right] \qquad (7a)$$

$$\mathrm{C\_}(ET_0) = \alpha\left[\left(\frac{\partial ET}{\partial ET_0}\right)_1 \Delta ET_0\right] + (1-\alpha)\left[\left(\frac{\partial ET}{\partial ET_0}\right)_2 \Delta ET_0\right] \qquad (7b)$$

$$\mathrm{C\_}(\omega) = \alpha\left[P_2\Delta\left(\frac{\partial ET}{\partial P}\right) + ET_{0,2}\Delta\left(\frac{\partial ET}{\partial ET_0}\right)\right] + (1-\alpha)\left[P_1\Delta\left(\frac{\partial ET}{\partial P}\right) + ET_{0,1}\Delta\left(\frac{\partial ET}{\partial ET_0}\right)\right] \qquad (7c)$$

After obtaining the contribution of parameter ω to the *ET* change, the contributions of vegetation coverage (*M*) and climate seasonality (*S*) to *ET* change can be further decomposed as follows.

First, the contributions of *M* and *S* to parameter ω are calculated by using the sensitivity method similar to Eq. (5) based the relationship between ω and *M* as well as *S* we built:

$$\Delta\omega = \frac{\partial\omega}{\partial M}\Delta M + \frac{\partial\omega}{\partial S}\Delta S \qquad (8)$$

Furthermore, the individual relative contributions (RC) of *M* and *S* to ω can be calculated. Then, the contributions of M (C_(M)) and S (C_(S)) to ET changes can be obtained as follows:

$$\mathrm{C\_}(M) = \mathrm{C\_}(\omega) \times \mathrm{RC\_}(M) \quad (9a)$$

$$\mathrm{C\_}(S) = \mathrm{C\_}(\omega) \times \mathrm{RC\_}(S) \quad (9b)$$

3. Study area and data

The Loess Plateau, which is located in the middle reaches of the Yellow River in China, experiences a sub-humid and semiarid continental monsoon climate (Ning et al., 2016). Frequent heavy summer storms, sparse vegetation coverage, easily erodible wind-deposited loess soil, and a long agricultural history have all contributed to severe drought and soil erosion problems in this region (Li et al., 2012). To recover and preserve the ecosystem, the Chinese government has launched numerous soil and conservation measures since the 1950s, and these include biologic measures ("Grain to Green" Project) and engineering measures (building terraces and sediment trapping dams) (Mu et al., 2007). As a result, the hydrological processes of this area have undergone significant changes (Huang and Zhang, 2004; Zhang et al., 2008). Thirteen catchments on the Loess Plateau were selected as our study area (Figure 1).

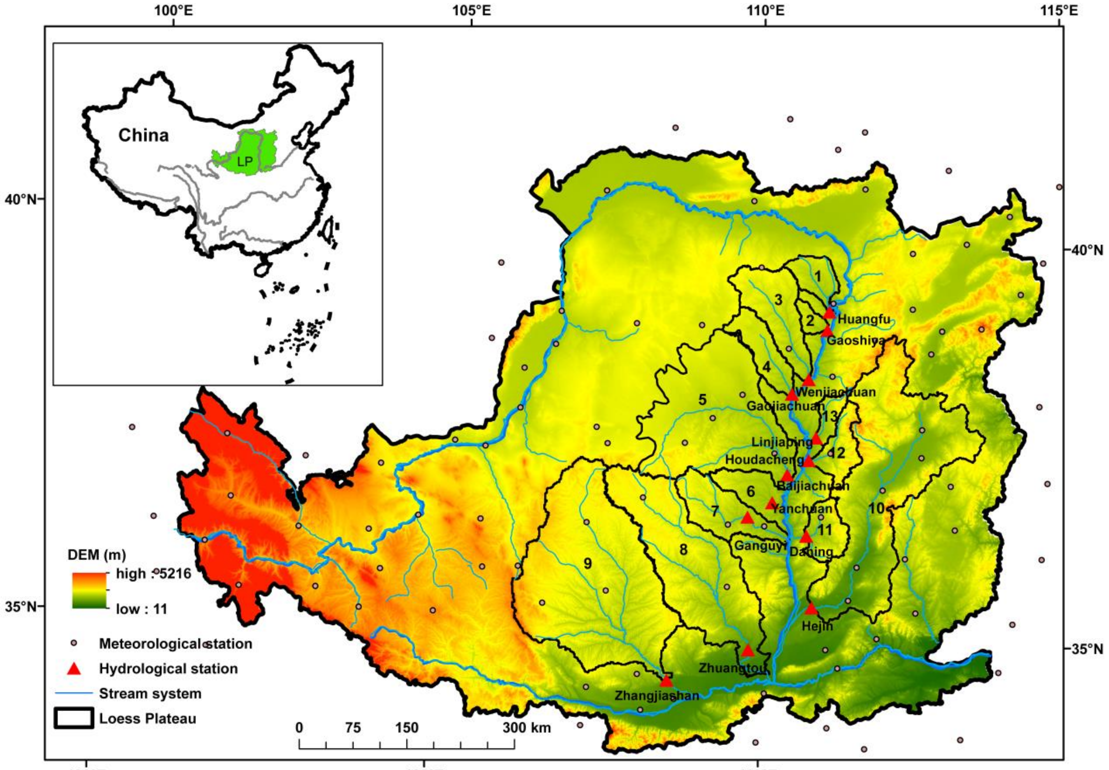

Figure 1. Locations of the study area and hydrometeorological stations.

Monthly runoff data for the 13 catchments were supplied by the Yellow River Conservancy Commission. Detailed information about the catchment characteristics and data durations are shown in Table 1. Daily meteorological data (1960–2012) comprised of precipitation, daily maximum and minimum temperatures, atmospheric pressures, wind speeds, mean relative humidity values, and sunshine durations, which were recorded at 96 stations, were provided by the China Meteorological Administration. The new NDVI third generation (NDVI3g) dataset was used to represent the vegetation characteristics of the study area, and detailed information about this dataset was presented earlier by Fensholt and Proud (2012). The maximum value compositing (MVC) procedure (Holben, 1986) was applied to produce the annual NDVI values.

Table 1. Long-term hydrometeorological characteristics and vegetation coverage (1981-2012).

ID	Basin	Data length, year	P, mm/yr	ET_0, mm/yr	ET, mm/yr	ω	M	S
1	Huangfu	32	372	972	347	3.15	0.42	0.94
2	Gushan	32	424	1078	394	2.74	0.47	0.90
3	Kuye	32	375	1018	333	2.45	0.43	0.99
4	Tuwei	32	383	1031	308	1.99	0.41	0.95
5	Wuding	32	385	1045	356	2.68	0.46	0.95
6	Qingjian	32	451	1009	417	3.00	0.60	0.60
7	Yan	32	462	984	433	3.21	0.70	0.51
8	Beiluo	28	502	960	475	3.76	0.88	0.34
9	Jing	32	529	936	497	3.74	0.59	0.51
10	Fen	29	465	982	452	4.21	0.87	0.43
11	Xinshui	32	478	992	458	3.77	0.87	0.45
12	Sanchuan	24	444	998	397	2.70	0.57	0.58
13	Qiushui	23	442	1006	418	3.33	0.67	0.60

[a] Because a few runoff data points were missing for several basins, the data length in these basins was less than 32. Each item represents the mean annual value.

4. Results

4.1. The variability of parameter ω

The Budyko framework is usually used for analyses of long-term average data on catchment-scale water balances; however, in this study, it was employed for the interpretation of the interannual variability of the water balances by using the hydrological year approach described earlier. To validate the feasibility of using Fu's equation for interannual variability, the evapotranspiration ratio (ET/P) and dryness index (ET_0/P) on an annual scale for 13 basins are presented in the supporting information (Figure S1), and it can be seen that almost all points are focused on Fu's curves in each basin. Therefore, Fu's equation was considered adequate for the analysis of the interannual variability of the water balance.

If the controlling parameter ω on an annual scale can reflect the combined impacts of vegetation change and climate seasonality, it should also exhibit interannual variability with the seasonal variation in vegetation and climate, especially in those basins affected significantly by climate change and human activities. Obviously, this is true for basins in Loess Plateau (Figure 2). During 1961–2012, ω values in all 13 basins had an upward trend. Along with such a changing trend in ω, ET should increased for the same levels of P and ET_0. Before the 1980s, the variation in ω for each basin was relatively gentle; however, since that time, it has increased dramatically.

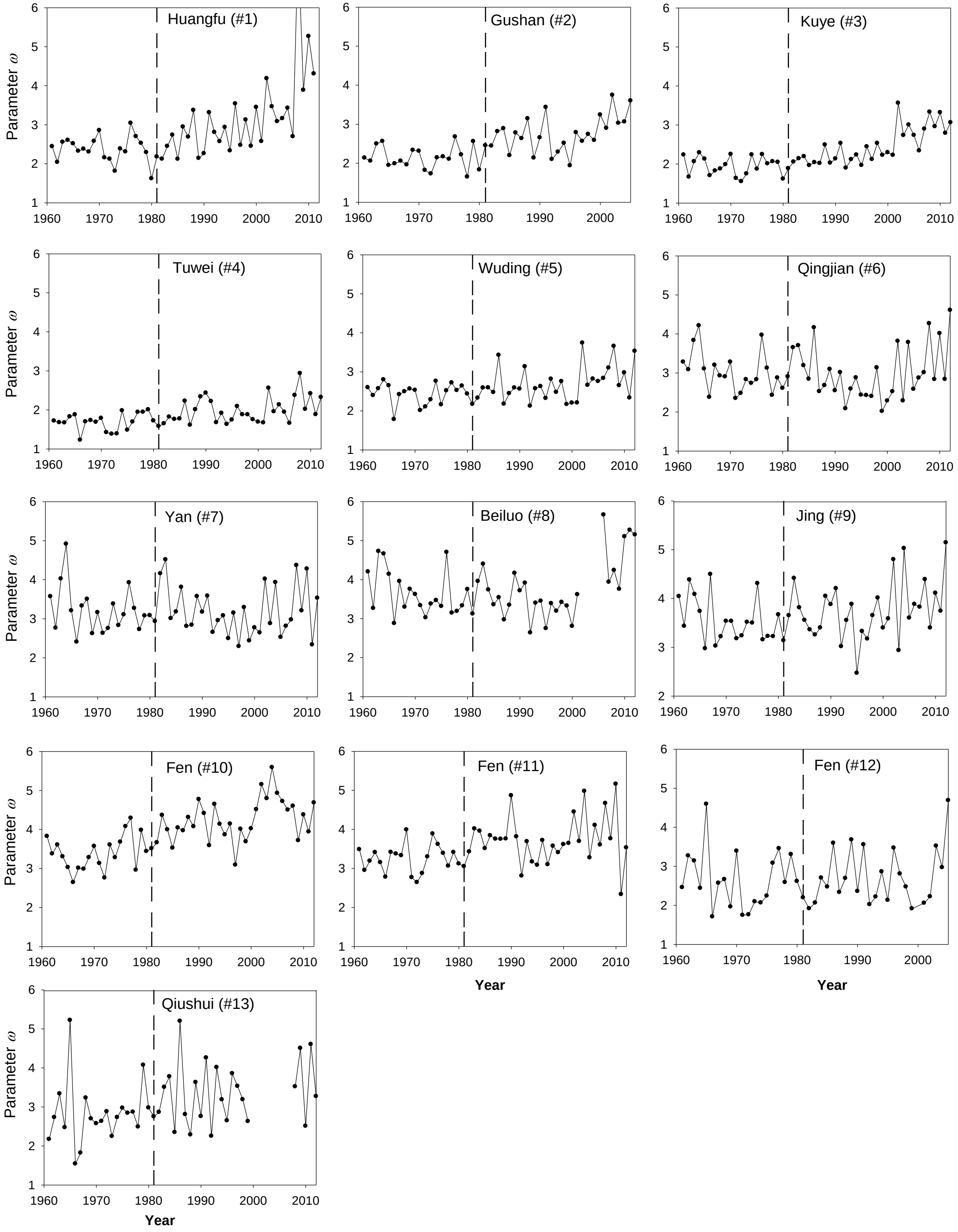
Huangfu (#1)
Gushan (#2)
Kuye (#3)
Tuwei (#4)
Wuding (#5)
Qingjian (#6)
Yan (#7)
Beiluo (#8)
Jing (#9)
Fen (#10)
Fen (#11)
Fen (#12)
Qiushui (#13)
Parameter ω
Year
1960
1970
1980
1990
2000
2010
1
2
3
4
5
6

Figure 2. The variability of parameter ω for 13 basins during 1961 to 2012.

4.2. Development of the semi-empirical formula for parameter ω

The relationships between the annual parameter ω and vegetation coverage M as well as the climate seasonality index S were first explored in each study basin during the period 1981–2012, and the results are shown in Figures S2 and S3. We can see that the parameter ω generally had a positive correlation with M, which implies that evapotranspiration increased with improvements in the vegetation conditions. However, ω was correlated negatively with S, which means that larger seasonal variations of coupled water and energy resulted in less evapotranspiration in this area. The relationships between ω and M as well as S imply that the annual variation in parameter ω can be estimated by the changes in vegetation dynamics and climate seasonality.

To expand the sample size and span a wider range of climate conditions, as well as to make the derived semi-empirical formula of parameter ω more representative, relationships were then developed based on the combined dataset from the 13 basins (Figure 3). These results also indicate a good relationship between ω and M ($R^2 = 0.40$, $p < 0.01$) as well as S ($R^2 = 0.28$, $p < 0.01$).

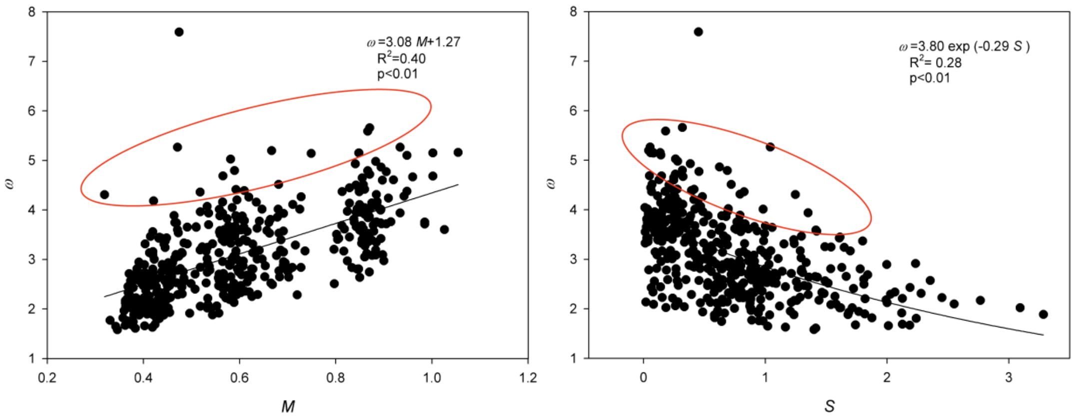

Figure 3. Relationships between the (a) annual ω and vegetation coverage (M) and (b) ω and climate seasonality index (S) based on the combined dataset from 13 basins.

To develop the semi-empirical formula of parameter ω, the limiting conditions of the two variables were considered as follows:

(1) If $M \to 0$, i.e. the land surface was bare, which indicates that the climate was extremely dry, $P \to 0$, $ET \to 0$, and thus, $\omega \to 1$;

(2) If $S \to \infty$, i.e. $\emptyset \to \infty$ and $\delta_{ET_0} \neq 0$ in the equation (3), which means monthly ET_0 is not uniform distributed within a year and $P \to 0$, thus $ET \to 0$, and $\omega \to 1$.

Considering the relationships shown in Figure 3 and given the above limiting conditions, the general form of parameter ω can be expressed as follows:

$$\omega = 1 + a \times M^b \times \exp(cS) \tag{10}$$

where a, b, and c are constants. Using the least linear square regression method, the semi-empirical formula of parameter ω is derived as follows:

$$\omega = 1 + 3.525 \times M^{0.783} \times \exp(-0.218\, S) \tag{11}$$

The coefficient of determination R^2 and the statistics for the F test of the modelled ω were 0.51 and 218.94, respectively.

A cross-validation approach was chosen to calibrate and test the above semi-empirical formula for parameter ω. Specifically, the dataset for the 13 basins in our study was separated into two groups. One was applied to build the semi-empirical formula, and it consisted of 12 basins for each time; the other was used for testing the performance of the semi-empirical formula, and it consisted of the remaining 1 basin. In total, the cross-validation process was conducted 13 times. After building the semi-empirical formula by using the vegetation coverage data and climate seasonality index data for the 12 basins, the parameter ω for the validated basin was modelled by using this fitted formula, and the annual ET for the validated basin was evaluated with the modelled ω, which is referred to as the “modelled” ET. Then, the “modelled” *ET* was compared with the ‘‘measured’’ *ET*.

Table 2 shows the cross-validation results for each basin. The model coefficients of each calibration formula for parameter ω were very close with the coefficients of Eq. (11), which means the relationship between ω and *M* as well as *S* we built is stable. Except for the basin #4 and #12, the MAE (mean absolute error) and RMSE (square root of the mean square error) values for each cross-validation process were relative low, with mean values of 13.5 mm and 16.8mm, respectively. The NSE coefficient (Nash–Sutcliffe coefficient of efficiency) for each process was greater than 0.8, thus suggesting that vegetation changes and climate seasonality can well explain the variation in the controlling parameter of the catchment water balance on the shorter time scale.

Table 2. Cross-validation results for each basin.

		Model coefficients			**ET estimation accuracy**		
ID	**Validated basin**	a	b	c	MAE	RMS	NSE
1	Huangfu	3.597	0.868	-0.228	22.3	23.8	0.88
2	Gushan	3.525	0.787	-0.231	16.3	21.3	0.90
3	Kuye	3.490	0.743	-0.233	17.4	22.7	0.88
4	Tuwei	3.350	0.627	-0.224	33.4	37.5	0.84
5	Wuding	3.525	0.803	-0.211	8.3	12.5	0.97
6	Qingjian	3.525	0.794	-0.206	13.9	18.1	0.96
7	Yan	3.560	0.803	-0.210	11.3	14.0	0.98
8	Beiluo	3.633	0.826	-0.213	10.2	11.9	0.97
9	Jing	3.456	0.814	-0.188	23.1	25.8	0.87
10	Fen	3.421	0.738	-0.223	6.3	8.9	0.98
11	Xinshui	3.560	0.803	-0.216	6.6	9.0	0.99
12	Sanchuan	3.561	0.782	-0.215	25.6	31.0	0.88
13	Qiushui	3.525	0.800	-0.204	12.5	16.4	0.96

4.3. Quantitative attribution of the variation in *ET*

The impacts of vegetation changes on *ET* have been widely studied with the Budyko framework by assuming surface conditions can be represented by the controlling parameter. However, according to the developed relationships in our study, the controlling parameter is not only related to surface condition change, but also to climate seasonality. The contributions of changes in climate (P, ET_0, and S) and vegetation (M) to the ET change were thus estimated by using the semi-empirical formula for parameter ω in the context of Fu's framework.

Trend in hydrometeorological variables and vegetation coverage were first analyzed for each basin (Table 3). ET_0 and S in all basins exhibited an upward trend, though with different significances. Similarly, M in most basins increased during past several decades. Based on the sensitivity coefficients of ET (Table S1) and the changes in mean annual P, ET_0, ω, M and S from period I to period II (Table 4), the changes in ET due to those in P, ET_0, M and S were estimated using the method described in Section 2.3. The contributions of four variables to ET change for each basin were presented in Table 4. In basin #1, 3-4 and #6, the ET changes were controlled by vegetation improvement; however, in the other basins, the dominant factor was precipitation. Except for basin #6, #9 and #12, elevated vegetation in most basins positively contributed to ET changes, which is consistent with Feng et al. (2016). ET in several basins showed a downward trend even though M positively contributed to ET changes; which is due to the offsetting effect of the other factors.

Table 3. Trend analysis for the hydrometeorological variables and vegetation coverage^{b}.

ID	**Basin**	ET,**mm yr**$^{-2}$	ET_0,**mm yr**$^{-2}$	P,**mm yr**$^{-2}$	M	S
1	Huangfu	1.89	1.16	0.61	0.002*	0.001
2	Gushan	0.76	3.85**	-0.01	0.004**	0.012
3	Kuye	2.34*	2.04*	0.53	0.004**	0.006
4	Tuwei	1.87	2.33**	0.53	0.005**	0.006
5	Wuding	0.88	1.17	0.31	0.006**	0.004
6	Qingjian	-0.45	1.78*	-0.94	0.007**	0.006
7	Yan	-1.62	2.03*	-1.99	0.005**	0.006
8	Beiluo	-5.4*	4.6*	-6.2*	0.0001	0.017
9	Jing	-0.97	1.47*	-1.79	0.002**	0.001
10	Fen	-0.72	1.93*	-1.16	0.002*	0.003
11	Xinshui	0.33	1.80	-0.12	0.003**	0.005
12	Sanchuan	1.49	1.84	0.09	-0.0004	0.004

13	Qiushui	-0.50	1.79	-0.83	0.002	0.008

^{b*} and ** indicate the trend is significant at the level of p = 0.05 and p = 0.01 by the Mann–Kendall test, respectively.

It should be noted that the climate seasonality (represented by *S*) played an important role in the catchment *ET* variation. The contributions of *S* to *ET* changes ranged from 0.1% to 65.5% (absolute values). Besides basin #6, #9 and #12, the climate seasonality had a negative effect on *ET* variation in most of the basins, which means that larger seasonality differences between seasonal water and heat will lead to smaller amounts of evapotranspiration. Accordingly, if ω is supposed to only represent the landscape condition, the effects of landscape condition change on *ET* variation will be underestimated in basin #1, #3, #6-7, #9 and #11. Except for basin #9, the area of these basins is relative smaller; while its effects will be overestimated in the other basins, and the error would be equal to the contributions of *S* to *ET* changes.

Table 4. Attribution analysis for *ET* changes for each basin [c]

ID	Basin	Break point of ET	Change from Period 1 to Period 2					ET_0/ *P*/*M*/*S* induced ET change (mm)					Contribution to ET change (%)			
			ΔET	ΔET_0	ΔP	ΔM	ΔS	C_ (ET_0)	C_ (*P*)	C_ (ω)	C_ (*M*)	C_ (*S*)	φ_ (ET_0)	φ_ (*P*)	φ_ (*M*)	φ_ (*S*)
1	Huangfu	2001(ns)	41.7	7.0	22.2	0.03	0.01	0.28	18.67	22.70	22.73	-0.04	0.7	44.8	54.6	-0.1
2	Gushan	2000(ns)	33.6	64.9	20.6	0.07	-0.10	2.81	17.01	13.77	8.87	4.90	8.4	50.6	26.4	14.6
3	Kuye	2000(**)	51.4	32.0	17.3	0.06	0.05	1.54	13.34	36.48	55.95	-19.47	3.0	26.0	108.9	-37.9
4	Tuwei	2000(**)	43.2	39.6	24.0	0.07	-0.03	2.57	15.28	25.35	21.85	3.49	5.9	35.4	50.6	8.1
5	Wuding	2000(*)	35.2	17.6	26.9	0.09	-0.12	0.77	21.82	12.64	8.24	4.40	2.2	61.9	23.4	12.5
6	Qingjian	1988(**)	-50.1	32.0	-48.0	0.08	0.19	2.06	-37.80	-14.31	-47.09	32.78	-4.1	75.5	94.08	-65.5
7	Yan	1985(**)	-82.3	44.6	-86.9	0.05	0.30	3.19	-69.52	-15.96	22.19	-38.14	-3.9	84.5	-27.0	46.4
8	Beiluo	1985(**)	-65.1	49.4	-79.8	0.01	0.19	4.33	-62.9	-6.75	3.69	-10.43	-6.6	96.3	-5.7	16.0
9	Jing	1990(**)	-33.7	43.0	-47.8	0.03	0.11	4.1	-37.2	-0.61	-8.23	7.61	-12.2	110.3	24.4	-22.6
10	Fen	2005(ns)	23.1	8.5	21.2	0.07	-0.20	0.33	19.00	3.81	2.13	1.68	1.4	82.1	9.2	7.3
11	Xinshui	1990(**)	-19.1	39.7	-24.7	0.02	0.09	2.06	-21.08	-0.14	0.41	-0.55	-10.8	110.1	-2.1	2.9
12	Sanchuan	1996(ns)	-27.0	45.4	-43.4	-0.01	0.22	3.01	-32.52	2.56	0.20	2.36	-11.2	120.6	-0.7	-8.8
13	Qiushui	1996(ns)	-80.3	77.5	-103.5	-0.01	0.68	3.76	-83.68	-0.40	-0.02	-0.37	-4.7	104.2	0.1	0.5

[c] The relative contribution of a certain variable to the *ET* change ($\varphi(x)$) was calculated as follows: $\varphi(x) = (\mathrm{C}\_(x)/\Delta ET) \times 100\%$, where C_(*x*) represents the contribution of each variable.

5. Discussion

Although the controlling parameter ω showed a good relationship with the vegetation change and climate seasonality index, two groups of deviations around the regressed curves were detected (Figure 3). The deviation points for the relationship between ω and M were mainly located at the top of the curve, i.e. corresponding to the same M values, where ω values were greater. We checked those points and found that precipitation and vegetation coverage in those years were normal, but runoff was very low compared to normal years. Excluding abrupt climate change, possible reasons for the extremely low runoff in those years include dam and reservoir operations, as well as irrigation diversions. A study conducted by Liang et al. (2015) on the same basins that we investigated in the Loess Plateau showed that check-dams increased continuously starting from the 1960s. By the year 2006, the numbers of dams along the basin #10 and #5 reached up to 482 and 181, respectively. Dams can intercept stormwater runoff for a short period during flood seasons and allow more time for infiltration (Polyakov et al., 2014). A total of 21 large and 136 medium-sized reservoirs were installed along the Yellow River by 2001. Such infrastructure can also influence the runoff change by controlling the flooding, regulating the water discharge, and diverting the water to other regions (Chen et al., 2005). Agricultural production is heavily dependent on irrigation throughout the entire Yellow River basin, and it has been reported that water consumption by agricultural irrigation accounted for nearly 80.0% of the entire water consumed from 1998 to 2011 (Wang et al., 2014). Thereby, water withdrawn for irrigation also plays an important role in the changing trends in runoff. In this study, the deviation points around the relationship curve between the annual ω and S fell in the upper left, and they were likely influenced by the low runoff. However, separation of the impacts on runoff from vegetation change, climate seasonality, and engineering works will have to await future work.

The relationships of parameter ω with vegetation dynamics and climate seasonality in some single basins were not significant in this study. Similarly, Yang et al. (2014a) also found a weak relationship between parameter n and vegetation coverage in 201 basins in China. This implies that the parameter ω might represent the combined effects of some other factors. For example, strong interactions among vegetation, climate, and soil conditions will lead to specific hydrologic partitioning at the catchment scale. In dry years, with low soil water contents, plants are trying to adapt by making use of hydrological processes, e.g. ground water dynamics and plant water storage mechanisms, etc. (Renger and Wessolek, 2010). Therefore, the relationship between the parameter ω and vegetation dynamics can be influenced by climate and soil conditions. However, it is difficult to separate the climatic and soil components from the vegetation change. Moreover, Zhang et al. (2001) reported that the impact of different vegetation types on catchment water balance can be vastly different, and the plant-available water coefficient in their function, which is similar to parameter ω in Fu's equation, is related to vegetation type. Therefore, the vegetation type may also be an important variable that influences the parameter ω.

Despite that catchment-scale water storage changes are usually assumed to be zero on long-term scale, the interannual variability of storage change can be an important component in annual water budget during dry or wet years (Wang and Alimohammadi, 2012), and cannot be ignored. However, the Loess Plateau has a subhumid to semiarid climate, the water storage and its annual variation are relatively small compared with humid regions (see Figure 5 from Mo et al., 2016). For example, using GRACE (Gravity Recovery and Climate Experiment), the water storage variations in the Yangtze, Yellow and Zhujiang from 2003 to 2008 were analyzed by Zhao et al. (2011), and the values for the Yangtze and Zhujiang basins were 37.8 mm and 65.2 mm, while no clear annual variations are observed in the Yellow River basin (3.0 mm). Furthermore, Mo et al. (2016) found that the water storage in Yellow River kept decreasing from 2004 to 2011, whereas it was changing slowly with a rate of 1.3 mm yr^{-1}. Therefore, considering the small water storage change in study area, ignoring water storage change in a period of hydrologic year is reasonable.

Errors still exhibited in the attribution analysis of ET changes. As the changes in evapotranspiration has been decomposed without residual by the complementary method (Equation 6-7), the errors were induced from the developed empirical formula for w (Equation 11). It suggested that ω cannot be completely explained by M and S, and it might include some other factors. Therefore, discussing more factors influencing ω remains future work.

6. Conclusions

This study explored the concomitant effects of vegetation dynamics and climate seasonality on the variation in interannual controlling parameter ω from Fu's equation within the Loess Plateau. First, to reduce the impact of ignoring the water storage change on annual catchment water balance, the hydrological year approach was introduced to examine the interannual variability of the controlling parameter ω for the 13 basins in the Loess Plateau from 1961 to 2012. The findings showed that parameter ω in all these basins presented an increasing trend, especially after the 1980s. Furthermore, we checked the relationship between ω and vegetation dynamics (represented by the annual vegetation coverage, M) as well as climate seasonality (represented by the climate seasonality index, S). The interannual changes of parameter ω were found to be related strongly to M and S. As such, a semi-empirical formula for the annual value of ω was developed based on these two parameters, and it was proven superior for estimating the actual evapotranspiration (ET) by a cross-validation approach. Finally, based on the proposed semi-empirical formula for parameter ω, the contributions of changes in climate (P, ET_0, and S) and vegetation (M) to ET variations were estimated. The results showed that the improved vegetation conditions in all basins made a positive contribution to the ET change, but these effects were largely offset by other variables in some basins. The contribution of landscape condition changes to ET variation will be estimated with a large error if the effects of climate seasonality were ignored.

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