Dear Dr. Roger Moussa,

We would like to express our sincere thanks to the three reviewers for their thoughtful comments and constructive suggestions. Based on the suggestions and comments, the manuscript is revised significantly, especially in sections 3, 4 and 5.

The major revisions are summarized as below:

(1) Presentation of the study area is allocated to Section 2, prior to the presentation of the models. A preliminary analysis using the (P-Q)/P data is presented in Section 2.3 according to the reviewers' comments and shows the requirement of hydrological models. It enhances the logic outline of the article.

(2) The misleading sentences, such as "this hypothesis is robust for long-term mean annual water balance but is dubious for the inter-annual variations in catchment with varying dryness", are deleted in the revised manuscript according to comments from all of the reviewers. Our study did not try to invalid the Budyko hypothesis but just to reveal the effects of groundwater dependent evapotranspiration on the shift of annual water balance in the F-ϕ space (the standard Budyko space). Shallow groundwater is an extra water supply source for evapotranspiration. The relevant analysis and discussions in the whole article are modified to correctly show the scope.

(3) Following the comments from reviewer #1, we checked the efficiency of the modified Budyko space with the effective precipitation incorporating the change in storage that proposed by Wang (2012) in Section 5.2. We pointed out that this modified Budyko space has the difficulty in dealing with the feedback between the water supply and evapotranspiration as well as the existence of inaccessible storage for evapotranspiration. Instead, the empirical formula proposed in this study for the standard Budyko space provides a straightforward method to predict the trend of annual water balance with the varying dryness.

(4) The effects of human activities are discussed in Section 5.3 according to the comments from reviewer #2.

(5) Most of the figures are modified to giveclear presentation.

Below we provide the detailed accounts to the questions and comments from the reviewers. The original comments are in bold face and our replies are in regular font.
Thank you for your consideration of this paper. If you have any further questions on the replies and the revised manuscript, please let us know!

Dr. Xu-Sheng Wang
Dr. Yangxiao Zhou

Reply to Reviewer #1: Dr. Donohue

We appreciate Dr. Donohue's critical comments on the significance of the manuscript. Dr. Donohue presented two response documents in the open discussions. In the following paragraphs, we organized the comments and discussions into key points and provided our responses and revisions accordingly.

1. **One of the basic points in the Budyko framework is that evaporation can't exceed the supply of water or of energy because mass and energy must be conserved. For long-term average water balance, rainfall could be reasonably assumed as the single water supply. However, when P isn't the only significant source of water available for evaporation, the original Budyko framework needs to be modified to reflect this. If ground water is being accessed by vegetation and transpired, the total water supply is P + plant-available-ground water. When the supply of water is greater than P, but only P is used to formulate Budyko, then evaporation can indeed be higher than P, and F can be greater than 1. This occurrence is not a failure or inadequacy of the Budyko framework but a misapplication of it.**

Reply: Accepted. We are aware of the misunderstanding of the original Budyko hypothesis. The meaning of the Budyko's theory is that the evapotranspiration (ET) will be less than the total water supply in a catchment. The hypothesis of P=(Water supply) only refers to long-term steady state water balance. The F>1 cases did not mean the failure of the Budyko framework. In the revised manuscript, groundwater dependent evapotranspiration is regarded as an additional source of water supply for ET in the studied catchment.

2. **At non-steady state (with inter-annual or intra-annual changes), the change in storage and the contribution of stored water to the water supply both need to be accounted for. Failure to do so can result in dubious estimates of evaporation and in high (>1) estimates of the evaporative index. Wang (2012) and Chen et al (2013) both discuss and demonstrate the importance of the concept of effective precipitation (including storage change) when working at small time scales.**

Reply: Accepted. We added the references of Wang (2012) and Chen et al. (2013) and used their definition of "effective rainfall" to modify the Budyko space with the modified aridity index and ET ratio. In the revised manuscript, this concept of "effective precipitation" is applied in Section 5.2 to analyze the shift of annual water balance in the modified Budyko space.

3. **In previous work (Potter et al., 2005; Zhang et al., 2008; Wang, 2012; Chen et al., 2013), the effect on Budyko of the interaction between intra-annual or seasonal application and stored water has been revealed. In particular, the effective rainfall approach (P-dS) has been found to work quite well in reproducing the limits and scatter of the standard Budyko framework. Thus, it is questionable what are news in your study?**

Reply: We appreciate this comment for re-thinking the contribution of our study. It is clear that the highlighted problem (the role of groundwater dependent ET in annual water balance) in our manuscript was not soundly analyzed in Wang et al. (WRR, 2012), Chen, Alimohammadi and Wang (WRR, 2013), Potter et al. (WRR , 2005) and Zhang et al.(jHyd, 2008). In these previous studies, inter-annual variation in storage was highlighted but only Wang et al. (2012) mentioned the groundwater contribution for ET in a few of sentences in the discussion part. Wang et al. (2012) did not analyze how groundwater dependent ET in a natural state will create F>1 cases. Our paper provides detailed account of groundwater dependent evapotranspiration in the Budyko framework.

Reply to Reviewer #2: Dr. Jaramillo

Major comments：

1. **Why the authors have not just used the annual Q data from observations and simply used it to calculate the Evaporative index simply as ET/P=(P-Q)/P and plot the annual data in Budyko's space to understand the behavior of the basin from REAL data. This should be done in order to strengthen and further compare the results of their modified ABCD model and the "natural" and "irrigated" model. It is possible that the "linear" behavior seen in Budyko's space among years maybe an artifact of the model or the modifications done to it.**

Reply: In the revised manuscript, a preliminary analysis using (P-Q)/P is presented in the Section 2.3. It shows the negative trend of (P-Q)/P with the aridity index, which is similar to the phenomenon found in Wang et al. (2009) and Istanbulluoglu et al. (2012) and has been demonstrated to be a wrong replica of the actual E/P in a catchment with significant inter-annual change in storage (Istanbulluoglu et al., 2012). Consequently, the (P-Q)/P approach is not appropriate to analyze the change in annual E/P values in this study. It compels us to use an appropriate hydrological model to estimate the actual ET.

1(a). It is not that the "Budyko hypothesis is not valid for the inter-annual variability of catchment water balance with groundwater dependent evapotranspiration"(conclusions), it is more that the annual time scale might not be enough to accomplish steady state conditions, especially if how the authors state, the changes in groundwater in the basin are considerable within the annual time scale. Another possibility is just that the size of the basin is too small, 2645 km^2, so changes at the catchment scale of groundwater flux cannot be assumed as negligible. By the way, all this is carefully explained in the article from the other reviewer and colleagues (Donohueet al., 2007): "On the importance of including vegetation dynamics in Budyko's hydrological model".

Reply: Accepted. We delete the misleading sentences in the revised manuscript. We noted that Donohue et al. (2007) highlighted the inter-annual variations of landscapes, especially the vegetation dynamics, in application of the Budyko framework on analyzing catchment water balance. In the revised paper, we discussed the landscape-driven shift in the Section 5.3. However, on the whole, this study is focused on the role of groundwater dependent evapotranspiration in the varying annual water balance, which is not widely investigated in the literature.

1(b). Impoundment of reservoirs and irrigation may substantially increase evapotranspiration from the entire basin, regardless of the size of the area covered by these activities in the basin. These activities definitely move a basin upwards in Budyko space, probably beyond the water limit. Is the water from irrigation from groundwater resources? Please see (Jaramillo and Destouni, 2014) and the Supplementary Materials on water storage change in basins due to these activities (Jaramillo and Destouni, 2015), for just a possible approach to this issue. Again, plotting the annual data based on Q observations could shed some light on the influence of these activities on the water cycle of the HRC basin. I know that the authors are not using the Q observations to do their Budyko's space analysis, but they are indeed using these observations to calibrate the model!

Reply: Accepted. In the Section 5.3 of the revised paper, the landscape-drivenshift of annual water balance in different periods are analyzed, using the method proposed by Jaramillo and Destouni (2014). The impacts of human activities (reservoirs and dams) were also discussed using the coefficient of variation (CV) values of runoff and precipitation, following Jaramillo and Destouni (2015). Results are shown in Figure 10 and discussed in the text. In the studied catchment, the relative impacts of landscape-driven shift and human-controlled change in the evaporation ratio is not significant (limited in ±5%).

1(c). How can you separate Zone 1 and Zone 2 and plot them in Budyko space (Figure 8). The water system is not closed when doing this. Please explain further what this means, and what assumptions need to be done to do this separation.

Reply: It is true that the Zone-1 and Zone-2 are not closed individually, but, they can have their own evapotranspiration rate and the annual *E* of them, E1 and E2, can be respectively estimated from the model without any external assumptions. This is the reason why we can plot E1/P and E2/P in the original Figure 8 (now is Figure 7 in the revised version). The objective of the plot is to compare the different responses of the evapotranspiration ratio on the varying aridity index in the Zone-1 and Zone-2.

2. I understand the term "groundwater evapotranspiration", however, it sounds a little bit strange to the general reader and me. How can groundwater (especially deep groundwater) evaporate (and/or transpirate) on a desert that has only sparse vegetation? Maybe some important information on the type of soils, a land cover map, location of shallow or deep groundwater could be useful to understand this process, and some process description that goes beyond the equations of the model.

Reply: We do not use the term "groundwater evapotranspiration" but just use "groundwater dependent evapotranspiration". This is only available for the zone with shallow groundwater (Zone-2) where the root zone is connected with water table and so that the vegetation can uptake groundwater for transpiration. In the zone with deep groundwater (Zone-1), it is assumed that no contribution of groundwater for evapotranspiration. The original Figure 2 has been modified to show the landscape characteristics in Figure 1(c) in the revised version. The type of soils and the distribution of groundwater depth are presented in the text of the site background. Details of the Hailiutu River Basin was also presented in Lv et al. (2013).

Minor comments:

(1)What do the authors mean by "soil water" and "groundwater", what are the boundaries differentiating them?

Reply: The boundaries of the Zone-1 and Zone-2 as well as the soil water zone, transition vadose zone and groundwater zone, in particular, are presented for the studied catchment in the revised version, as can be seen in the Section 3.2. However, we should be aware of that it is not necessary to find distinct and exact boundaries for the zones, since the ABCD-GE model is a conceptual hydrological model.

(2)If groundwater is "within" the boundaries of the basin, changes in it should not represent a flux but rather a change in storage.

Reply: Yes, groundwater is included in the storage. But groundwater discharge in the rivers is a flux included in the total runoff. The transition vadose zone (Figure 4 in the revised version) is a special zone between the soil water reservoir and the groundwater reservoir. In the Zone-1, groundwater recharge is the downward flux of this transition zone.

(3)The diagram of the model (Figure 1) is never called in the text.

Reply: Figure 1 becomes Figure 4 in the revised version and is called in the text of the hydrological model.

(4)A map of land cover of the basin could be useful. It is not clear how much vegetation and where it is located, and its location in terms of the location of the shallow groundwater.

Reply: Accepted. The landscape characteristics are shown in Figure 1(c) in the revised version.

(5)What is the purpose of Figure 4, it is also hard to see anything there.

Reply: It becomes Figure 2 in the revised version. This figure is important because it show that how the observed data vary during the study period; in particular, the intra-annual patterns indicate the necessary of using a monthly hydrological model. The figure is organized in a very high-resolution map and can be clearly seen in a zoom up mode.

(6)What do you mean by "regime shifts detected in Q".

Reply: The sentence of "regime shifts were detected in Q" is modified to "regime shifts were found that exist in the streamflow" in the last paragraph in Section 2.2.

(7)"The runoff ratio was decreased inactual due to irrigation water use, which weakened the linear relationship but remained the increase trend of Q/P vs. aridity index" Page 11629. What does this mean? I think that the role of irrigation has not been properly accounted for

in this analysis.

Reply: This sentence has been deleted. The role of irrigation water use is discussed in Section 5.3.

Reply to Reviewer #3: Anonymous

Major comments:

1. **Why In your conclusions you write about the Budyko hypothesis: "This hypothesis is robust for long-term mean annual water balance but is dubious for the inter-annual variations in catchment with varying dryness." (P. 11633, l. 19-20). I'm not happy with the word "dubious" in this context. It is important to note (again) that the original Budyko hypothesis is defined at climatological, catchment scales with no changes in storage. Hence, under conditions of additional water supply from groundwater the Budyko framework is not "dubious", it is simply not valid.**

Reply: Accepted. This misleading sentence is deleted.

2. **You discussed several limitations of your approach in section 4.4. However, since groundwater provides just one additional source of water (among soil moisture, snow storage, etc.), I think the limitations are rather strong. I would love to see a comment on the use and applicability of the modified approach.**

Reply: Accepted. More limitations of the model are presented in the discussion part.

3. **I do miss a convincing line of argument on why you don't directly use and show the observations. Of course, you need the model to make the difference between deep groundwater and shallow groundwater. But this is not so clear from the manuscript. I would also like to see the data cloud of the observations within the Budyko space (Fig. 7a) to have a better comparison and feel for the "natural" model in the context of Budyko.**

Reply: We did not have the observation data of the actual ET rate but just estimated it from the model. A possible approach of obtaining the "real" E/P is using (P−Q)/P as a substitute. In the revised version, Section 2.3, a preliminary analysis using (P−Q)/P is presented with a plot of the data cloud. It clearly show the negative trend of (P-Q)/P with the aridity index, which is similar to the phenomenon found in Wang et al. (2009) and Istanbulluoglu et al. (2012) and has been demonstrated to be a wrong replica of the actual E in a catchment with significant inter-annual change in storage (Istanbulluoglu et al., 2012). Consequently, the (P-Q)/P approach is not available to analyze the change in annual E/P values in this study. It compels us to use an appropriate hydrological model to estimate the actual ET.

4. **How does the modified Budyko formulation provided by Eq. 23 and shown in Figure 8 actually look like for the HRC. It would be beneficial to see the modified curve in Fig.7a to have a direct comparison to the data points of the "natural model". What value of would you get if you estimate it directly from the observations and Eq. 23? How would you explain differences in the estimates are different?**

Reply: In the revised version the original Figures 7 and 8 are modified and combined into Figure 7. The results of the "actual" ET and "natural" model are both plotted in the space for comparison. In the new Figure 8, the data points of the HRC are also plotted in comparison with the curves determined with the *F* equation proposed in this study, Eq. (22) in the revision.

Minor comments：

(1)The Budyko hypothesis as formulated in Eq. 1, E/P=F(ϕ), does only assume that the Budyko curve is determined by ϕ and not an additional catchment specific parameter.

Reply: Accepted. The parameter independent property of Eq. (1) is presented after the equation.

(2)You can't really see the crosses and dots in Fig. 5a. Is the R-square value for the runoff or the groundwater discharge.

Reply: Figure 5 is revised with clear cross line and data dots.

(3)Fig. 7: Why is it "Including irrigation" in a) and "Observations" in b) ?.

Reply: The figures including Fig. 7 are modified to clearly show the data.

(4)Fig. 8: Could you please explain in more detail how you separate between zone-1and zone-2 evapotranspiration. Is this based on equation 17 and simply the particular fraction of E?

Reply: Accepted. It is expressed as E1 and E2 with Eq. (19) in the revised version.

(5)Fig. 8-9: Some lines are very wriggly.

Reply: The lines were redrawn in revised version.

Shift of annual water balance in the Budyko space for a catchment with groundwater dependent evapotranspiration

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Abstract

The Budyko framework ~~reveals~~ represents ~~Empirical equations have been formulated for~~ the general relationship between the evapotranspiration ratio (*F*) and the aridity index (ϕ) ~~in~~ for the mean annual water balance at catchment scale~~the Budyko framework~~. ~~Though it is normally applied for mean annual behaviors,~~ It is ~~attractive~~ interesting to investigate if this standard *F*-ϕ space can be also applied to capture the shift of annual water balance in a catchment with the varying dryness. ~~the Budyko hypothesis has been directly adopted to analyze the interannual change in water balance. However,~~ ~~there~~ There are reported cases where the original Budyko framework can't be directly applied ~~to where the annual evapotranspiration ratio is larger than 1.0 (*F*>1).~~ for annual ~~hydrology~~water balance due to additional sources of water supply for evapotranspiration besides precipitation. ~~.~~This study ~~reveals~~ ~~highlights~~ investigates ~~the effects role of~~ how groundwater dependent evapotranspiration causes ~~in triggering such abnormal~~ shifts of annual water balance in the ~~conventional~~standard Budyko space. A widely used monthly hydrological model, the ABCD model, is modified to incorporate ~~the~~ groundwater dependent evapotranspiration in the zone with shallow water table and delayed groundwater recharge in the zone with deep water table. This model is applied in the Hailiutu River catchment in China to estimate the actual annul evapotranspiration, where the depth to water table is less than 2 m in a zone occupying 16% of the catchment area~~,~~. Results show that the variations in the annual ~~evapotranspiration ratio~~*F* value with the aridity index do not satisfy ~~the traditional~~ the normal Budyko

~~hypothesiscurves~~formulas. The shift of the annual water balance in the ~~conventional~~standard Budyko space is a combination of the Budyko-type response in the deep groundwater zone and the quasi-enegy limited condition in the shallow groundwater zone. ~~depends on the proportion of shallow water table area, intensity of groundwater dependent evapotranspiration, and the normal Budyko-type trend of F in the deep groundwater zone.~~ Excess evapotranspiration (F>1) could occur in extreme dry years, which is contributed ~~enhanced~~ by the significan~~ce~~t supply of groundwater~~-dependent~~ for evapotranspiration. Use of groundwater for irrigation ~~may~~ can increase the frequency of ~~occurrence of~~ the F>1 cases.

1 Introduction

Estimating catchment water balance is one of the fundamental tasks in hydrology. Efforts have long been devoted to construct physical, empirical, and statistical models to explain the general relationship among precipitation (P), runoff (Q), potential evapotranspiration (E_0) and actual evapotranspiration (E) in terms of mean annual fluxes at the catchment scale (Budyko, 1948, 1958, 1974; Mezentsev, 1955; Fu, 1981; Porporato et al., 2004; Gerrits et al., 2009). A simple and highly intuitive approach widely used for estimating E at mean annual scale is the Budyko framework, in which the mean annual evapotranspiration ratio (E/P) was presumed as a function of the climatic dryness as:

$$\frac{E}{P} = F\left(\frac{E_0}{P}\right) = F(\phi), \tag{1}$$

where ϕ is the aridity index defined as E_0/P, and $F(\phi)$ is an empirical function that relates E/P to ϕ based on general water-energy balance behaviors in catchments. The proposed formula by Budyko (1958; 1974) was:

$$F(\phi) = \sqrt{\phi[1-\exp(-\phi)]\tanh(1/\phi)}, \tag{2}$$

which indicates a nonlinear relation between F and ϕ without any parameter. This F-ϕ curve has been called the Budyko curve (Zhang et al., 2004; Roderick and Farquhar, 2011) and the F-ϕ space was called Budyko space (Renner et al., 2012).

Instead of using a single curve determined by Eq. (2) in the Budyko space, researchers have introduced a specific catchment parameter in $F(\phi)$ to consider the impacts of catchment properties such as soils and vegetation (Mezentsev, 1955; Fu, 1981). ~~Mezentsev (1955) proposed:~~

$$F(\phi)=\frac{\phi}{(1+\phi^{n})^{1/n}},$$ ~~(3)~~

~~where n is a dimensionless parameter which was related to the catchment landscape characteristics. Following the idea of Mezentsev (1955), Fu (1981) derived a new semi-empirical formula for the F-ϕ relationship that was published in Chinese and later used by Zhang et al. (2004):~~

$$F(\phi)=1+\phi-(1+\phi^{\omega})^{1/\omega},$$ ~~(4)~~

~~where is a catchment parameter, which synthetically represents the negative features for runoff producing (Fu, 1981).~~ For example, ~~The~~ Fu's equation (Fu, 1981) was derived following the idea of Mezentsev (1955) and has been widely used in the last decade (Zhang et al., 2004; Yang et al., 2006; Yang et al., 2007; Zhang et al., 2008; Greve et al., 2015). In ~~addition~~particular, Zhang et al. (2001) presented an empirical equation for the Budyko framework in relation to vegetation cover at the catchment scale as:

$$F(\phi)=\frac{w\phi}{1+w\phi+\phi^{-1}}, \qquad (\cancel{5}3)$$

where w is called the plant-available water coefficient. Donohue (2007) highlited the role of vegetation dynamics in application of the Budyko framework. Recently, Wang and Tang (2014) also developed a one-parameter Budyko model based on the proportionality hypothesis and revealed a complex relationship between the catchment specfic parameter and remote sensing vegetation index. These modified formulas suggested a group of Budyko curves instead of the single ~~origional~~original Budyko curve, in which a curve represents a specific type of the catchments with similar features controling the mean annual water balance.

Budyko hypothesis has been directly used to analyze the interannual change in water balance in catchments (Arora, 2002; Zhang et al., 2008; Potter and Zhang, 2009) even through it ignoring the change in storage (ΔS) under the assumption of steady state water balance.~~is normally applied for mean annual behaviors.~~ One can plot annually the estimated E/P data in the Budyko space to check whether the normal Budyko curves are sufficient or not to represent the interannual variability of evapotranspiration with varying dryness. ~~By~~ In this way, Potter and Zhang (2009) found that the Budyko ~~model~~ framework is generally applicable for the catchments in Australia and the optimal curve of annual E/P versus ϕ is highly dependent on the seasonal variations in rainfall. However, this approach should be carefully used when the E/P values are approximated by $(P-Q)/P$ values. Wang et al. (2009) and Istanbulluoglu et al. (2012) reported that the annual data of $(P-Q)/P$ in some basins are negatively related to the aridity index, exhibiting an inverse trend in comparison with the normal Budyko curves. According to long-term groundwater observation in the North Loup River basin~~ (NLRB)~~, Nebraska, USA, Istanbulluoglu et al. (2012) demonstrated that the annual E/P values estimated by $(P-Q-\Delta G)/P$ basically follows the Budyko hypothesis, where ΔG is the change in groundwater storage. However, in some other studies, unexpected high evapotranspiration ratio (E/P>1) was observed (Cheng et al., 2011; Wang, 2012; Chen et al, 2013)~~ which could not be interpreted by the conventional Budyko curves~~. Among the 12 watersheds investigated ~~in~~ by Wang (2012), half of them exhibited such high E/P values in two or more dry years. The physical base of the phenomena is the significant contribution of storage in extremely arid situation by which the high level of evapotranspiration is maintained. Although some of the cases was due to extracting groundwater for irrigation in farmlands (Cheng et al., 2011; Wang, 2012), it could ~~happen~~ occur in natural conditions as a result of the temporal redistribution of water from seasonal patterns (Chen et al., 2013). Wang (2012) and Chen et al. (2013) proposed an approach to extend the Budyko framework for annual or even intra-annual water balance by considering the decrease in soil water storage as an potential source of water supply for evapotranspiration. They define $P-\Delta S$ for the selected time scales as the effective rainfall in building the modified Budyko space with $E/(P-\Delta S)$ and $E_0/(P-\Delta S)$, instead of E/P and ϕ, respectively.~~, in the conventionalstandard Budyko space.~~ Then, they found that the annual water balance of the catchments show the Budyko-type behaviro~~s~~ in the modified Budyko sapce.

The excess annual evapotranspiration over the annual precipitation may be originated from both soil water and groundwater. As reported by Wang (2012), during the drought year in 1988, two watersheds in Illinois, USA, showed E/P=1.1 with ~100 mm depletion in soil water and ~200 mm decrease in groundwater storage, respectively. It seemed that the contribution of groundwater is more significant (partially enhanced by pumping). Small depth to water table is an advantage to keep a high level of soil water content near ground surface for evapotranspiration (Chen and Hu, 2004). Therefore, it could be argued that the existence of shallow groundwater in a catchment would enhance the occurrence of E/P>1 in dry years.

Groundwater dependent evapotranspiration at the regional scale has been noticed in a few of the previous studies (York et al, 2002; Chen and Hu, 2004; Cohen et al, 2006; Yeh and Famiglietti, 2009). Nevertheless, little has been known on the role of groundwater in the interannual variability of the evapotranspiration ratio with the varying dryness. Chen et al. (2013) did not identify the change in groundwater storage to explain the controls of the E/P>1 cases. Wang (2012) mentioned the potential role of groundwater in occurrence of the E/P>1 cases but the individual contribution of groundwater dependent evapotranspiration was not soundly analyzed.

This study aims to ~~advance check~~investigate how groundwater dependent evapotranspiration ~~will~~ influences the ~~understanding of the interannual variability of~~annual water balance behavior~~s~~ in the standard Budyko space and develop a ~~for catchments with groundwater dependent runoff and evapotranspirationand in the so called~~ modified Budyko space to account groundwater dependent evapotranspiration. At the first, a monthly hydrological model was developed from the widely used ABCD model (Thomas, 1981) to incorporate the groundwater dependent evapotranspiration as well as the deep infiltration in the vadose zone. The value of E was partitioned into two componentes in accounting for the individual roles of the normal soil water dependent and the specific groundwater dependent evapotranspiration. Then, the modified model was applied to ~~the Hailiutu Rivr Catchment (HRC) in the Erdos Plateau of central China~~a real world catchment as an example. The calibrated model was used to produce the annual data of evapotranspiration components which are linked with variable soil water and groundwater storages. With varying climatic dryness, the shift behaviors of the interannual water balance in the Budyko space for the catchment were analyzed in detail. The impacts of human activities were also discussed. The study reveals the contribution of groundwater in the interannual variability of catchment water balance under a changing climate.

2 Study Site, Data and Preliminary Analysis

2.1 Study area

The study site is the Hailiutu River catchment (HRC), with an area of 2,645 km^2, located in the Erdos Plateau in north-central China (Fig. ~~2~~1a). The HRC lies on the southeast edge of the Mu Us Desert and is a sub-catchment of the Wuding River basin, which drains into the

Yellow River (Fig. ~~2~~1b). The climate of the Erdos Plateau is typically inland semiarid to arid. The mean annual precipitation in the HRC is ~350 mm/a. More than 60% of the annual precipitation is received in the warm season (June, July, August and September). ~~The land cover within the catchment is characterized by desert sand dunes with patches of mostly shrub-grassland.~~ The main channel of the HRC has a length of approximately 85 km and flows southwards to the Hanjiamao hydrological station, as shown in Fig. ~~2~~1c. Due to the arid climate and desert landscape, the land cover within the catchment is characterized by desert sand dunes with patches of mostly shrublands. ~~Due to the arid climate and desert landscape, vegetation cover in the HRC is sparse. *Salix psammophila* (shrubs) and *Artemisia desertorum* (grasses) are the dominant plants on the sand dunes.~~ Depression areas and terrace lands with shallow groundwater are covered by ~~grasses~~meadows and some farmlands. Wind-breaking trees (*Salix matsudana* and *Populus tomentosa*) can be found along the roads and crop areas. Farmlands are mainly located in the southern area and especially in the river valley. Crops cover only ~3% of the total catchment area. Maize is the dominant crop and is irrigated with streamflow and/or groundwater. Several diversion dams have been constructed along the Hailiutu River since the early 1970s for irrigation.

In the study area, groundwater is stored in an thick aquifer system with the sandy sediments and the underlying sandstones. Regional groundwater level distribution ~~in the study area~~ has been investigated in Lv et al. (2013) based on a hydrogeological survey carried out in 2010. According to this investigation, depth to water table (DWT) in the area varies in a large range from ~~0.5m~~zero up to 110 m. ~~Fig. 3 shows the histogram of DWT based on the 300-m-resolution gridded data of groundwater level (Lv et al., 2013).~~ In more than half of the area, DWT is less than 10 m. The shallow groundwater zone, where DWT is no more than 2 m, occupies ~~the~~ 16.0% of the whole catchment area. As investigated in Yin et al. (2015) at the site of the HRC, when DWT is less than 2 m, the transpiration rate of trees is generally higher than 90% of the potential transpiration rate and the soil surface evaporation rate is generally higher than 60% of the potential. As a whole, the evapotranspiration rate would be generally higher than 80% of the potential when DWT is less than 2 m, whereas the evapotranspiration ratio is generally less than 0.4 for the deep groundwater condition (Yin et al., 2015). This investigation confirms that groundwater dependent evapotranspiration is an essential process in the HRC.

2.2 Data

Daily streamflow data since 1957 is available from the Hanjiamao hydrological station. A rainfall gauge was also installed at the hydrological station in 1961, providing daily data of precipitation. In addition to the Hanjiamao station, rainfall is observed at the city of Uxin Qi, located in the northern half of the basin (Fig. ~~2c~~1c), where a meteorological station has been in operation since 1961.

Because of the limitations of only two rainfall gauges in a relatively large area and to better account for the variability of monthly rainfall in space and time, we used gridded monthly precipitation data. We developed gridded precipitation data with 1-km resolution between 1957 and 2010 by using rainfall data from 14 national meteorological stations ~~on~~ in the Erdos Plateau (Fig. ~~2b~~1b). Monthly rainfall data at these 14 stations were downloaded from the China Meteorological Data Sharing Service System (CMDSSS, http://cdc.nmic.cn). We constructed the gridded monthly data using the inverse distance square weighting (IDSW) method due to the moderate topography of the Erdos Plateau in the form of low-relief rolling hills. Figure ~~2b~~ 1b shows the mean annual precipitation contours of the Erdos Plateau obtained from the gridded data. Within the HRC, precipitation is relatively uniformly distributed (Yang et al., 2012) because of the flat topography of the region, but a subtle (~40 mm) increase in precipitation from north to south across the basin can be observed in Fig. ~~2b~~1b. In this study, the area-averaged monthly precipitation in the HRC for the period 1963-2010 was estimated by imposing the basin boundaries on the gridded monthly precipitation data and taking the arithmetic average of the grid cells within the HRC boundaries.

The method applied in constructing the gridded precipitation data were further applied in constructing a 1-km resolution gridded data set for monthly pan evaporation between 1957 and 2010 for the Erdos Plateau. The pan evaporation data were based on observations from 200-mm diameter pans that were installed in most stations on the Erdos Plateau and can also be downloaded from CMDSSS (http://cdc.nmic.cn). The average monthly potential evapotranspiration (E_0) in the HRC was estimated from the spatially averaged data of pan evaporation using a local pan coefficient (0.58) for the 200-mm diameter pan. This coefficient was suggested by various investigations of pan coefficients for Chinese meteorological stations (Shi et al., 1986; Fan et al., 2006).

In Fig. ~~4a~~2a, the variation patterns of the monthly rainfall and potential evapotranspiration at the catchment scale during 1957-2010 are shown. Both rainfall and evapotranspiration are high in the summer and low in the winter. However, there is a difference in the patterns which may influence the seasonal variation in runoff: the rainfall peak normally arrives in the August but the highest evaporation is exhibited in the June. With respect to these meteorological patterns, the total runoff drops in the Spring and in the early Summer until the heavy rainfall coming in the August, as shown in Fig. ~~4b~~2b. In comparison with the rainfall and the potential evapotranspiration, the mean monthly runoff (2.6 mm) and its fluctuation magnitude (0.8-11.9 mm) are quite small. This indicates that most of the precipitation in the HRC returns to the atmosphere by evapotranspiration. During 1957 to 2010, the mean annual P and Q are 350 mm and 32 mm, respectively. The runoff ratio is $Q/P \approx 0.09$. The mean annual potential evaporation in this period is E_0=1248 mm/a, indicating a mean aridity index of $\phi \approx 3.6$. The annual aridity index in this period generally ranged between 2 and 7, covering the semiarid and arid climatic conditions as classified in the scheme recommended by the United Nations Environment Programme (UNEP) (Middleton and Thomas, 1992).

In the HRC, there are interannual fluctuations in E_0, P, and Q. However, no significant trends were detected in the E_0 and P data, whereas several regime shifts were ~~detected~~found ~~that exist~~ in ~~Q~~the streamflow. Yang et al. (2012) found that the annual regime shifts in streamflow were caused largely by land use policy changes and river water diversions for irrigation. Table 1 shows the mean annual fluxes in four typical periods with different numbers of diversions in the Hailiutu River and major branches during 1957-2010. These diversions influenced the hydrological behavior in the HRC and will be discussed in the following sections. However, before 1967, the Hailiutu River was free of hydraulic engineering, and the studied area was close to natural conditions.

2.3 Preliminary analysis using $(P\text{–}Q)/P$

In many cases, it is ~~available~~possible to estimate the annual E in a catchment from the annually observed P and Q by $P-Q$ when the change in storage is sufficiently small. Then it could be treated as the "real" data of the annual E and the shift of annual water balance in the Budyko space could be investigated with the plot of $(P-Q)/P$ versus E_0/P. In this section, we check the validity of this approach in the HRC.

Both the plots of Q/P and $(P-Q)/P$ versus E_0/P for the HRC are shown in Figure 3. The annual Q/P value ranges between 0.08 and 0.18, approximately following a linear increasing trend with the aridity index (Figure 3a). If the original Budyko formula is available for annual water balance in the catchment, the annual Q/P value could be calculated as $1-F(\phi)$ and the shift path with the varying aridity index should be a descending curve. However, this trend is contrary to the observed trend of the annual Q/P. Correspondingly, the real annual $(P-Q)/P$ data show a negative trend in the standard Budyko space (Figure 3b). This trend is contrary to the positive E/P trend in the original Budyko framework. In a previous study, Istanbulluoglu et al. (2012) also highlighted this abnormal trend in the North Loup River basin, Nebraska, USA, and they demonstrated that the trend was due to ignoring the change in storage. They used long-term monitoring data of groundwater level to estimate the inter-annual change in groundwater storage (ΔG) and replaced the $(P-Q)/P$ data with the $(P-Q-\Delta G)/P$ data to reproduce a normal Budyko curve for the basin.

It is a good idea to estimate the change in groundwater storage using groundwater monitoring data. However, this kind of long-term monitoring was not available in the HRC, China. In addition, the approach of using $(P-Q-\Delta G)/P$ data still has a risk in ignoring the inter-annual change in the soil moisture storage. ~~Instead,~~ In~~in~~ this study, we used a hydrological model to estimate the actual annual E from monthly modeling steps, in which the groundwater dependent evapotranspiration is incorporated. With the model, both the storage components and the contribution of groundwater for the annual E can be obtained at the catchment scale.

3 Hydroclimatologic models

3.1 The ABCD model

The ABCD model is a conceptual hydrological model with 4 parameters (a, b, c, and d) developed by Thomas (1981) to account for the actual evapotranspiration, surface and sub-surface runoff, and storage changes. The ABCD model was originally applied at an annual time step but has been recommended as a monthly hydrological model (Alley, 1984). It was widely applied as a hydroclimatologic model to investigate the response of catchments on climate change (Vandewiele et al., 1992; Fernandez et al., 2000; Sankarasubramanian and Vogel, 2002; Li and Sankarasubramanian, 2012).

Both soil water and groundwater storages are considered in the model, as shown in Fig. ~~1a~~4a. At the monthly time step, the change in soil water storage is determined by

$$W_m - W_{m-1} = P_m - E_m - R_m, \qquad (\cancel{6}4)$$

where $\cancel{S_m}W_{m-1}$ and $\cancel{S_m}W_m$ are the effective soil water storage at the beginning and the end of the m-th month, respectively; P_m and E_m are the monthly precipitation and evapotranspiration values, respectively; and R_m is the monthly loss of soil water via direct runoff and groundwater recharge. The change in groundwater storage is determined by

$$G_m - G_{m-1} = cR_m - dG_m \,, \qquad (\cancel{7}5)$$

where G_{m-1} and G_m represent the groundwater storage at the beginning and the end of the m-th month, respectively; and c and d are two parameters that account for groundwater recharge and discharge from R_m and G_m, respectively. The monthly streamflow is the summation of the monthly direct runoff and groundwater discharge, as follows:

$$Q_m = (1-c)R_m + dG_m \,. \qquad (\cancel{8}6)$$

The change in storage in the ABCD model is the summation of the changes in soil water storage and groundwater storage, which can be expressed as $\cancel{W_m}\cancel{W_{m1}=}(\cancel{S_m}W_m - \cancel{S_m}W_{m-1}) + (G_m - G_{m-1})$.

Thomas (1981) proposed a nonlinear function to estimate $(E_m+\cancel{S_m}W_m)$ from $(P_m+\cancel{S_m}W_{m-1})$ as follows:

$$E_m + W_m = \frac{P_m + W_{m-1} + b}{2a} - \sqrt{\left(\frac{P_m + W_{m-1} + b}{2a}\right)^2 - \frac{(P_m + W_{m-1})b}{a}} \,, \qquad (\cancel{9}7)$$

where a is a dimensionless parameter, and b is the upper limit of $(E_m+\cancel{S_m}W_m)$. In addition, Thomas (1981) assumed

$$W_m = (E_m + W_m)\exp(-E_{0m}/b) \,, \qquad (\cancel{10}8)$$

where E_{0m} is the monthly potential evaporation for the m-th month. Substituting ~~equation~~ Eq. ($\cancel{10}8$) into ~~equation~~ Eq. ($\cancel{9}7$), the monthly evapotranspiration can be estimated as

$$E_m = \left[\frac{P_m + W_{m-1} + b}{2a} - \sqrt{\left(\frac{P_m + W_{m-1} + b}{2a}\right)^2 - \frac{(P_m + W_{m-1})b}{a}}\right]\left[1 - \exp\left(-\frac{E_{0m}}{b}\right)\right]. \qquad (\cancel{11}9)$$

Wang and Tang (2014) demonstrated that Eq. ($\cancel{9}7$) can be derived from the generalized proportionality principle and yield an equivalent Budyko-type model.

3.2 The ABCD-GE model

To investigate the effects of groundwater dependent runoff and evapotranspiration in basins with both shallow and deep groundwater, the original ABCD model is extended in this study as the ABCD-GE model where GE denotes groundwater dependent evapotranspiration. As shown in Fig. ~~1~~4b, a catchment is conceptually divided into two zones where the Zone-1 and Zone-2 represent different areas with deep and shallow groundwater, respectively. Surface water is also included in the Zone-2. The soil water reservoir in the Zone-1 is the same as that in the ABCD model whereas no direct runoff occurs on its surface. In addition, a transition vadose zone is specified between the soil layer and water table to represent the delayed groundwater recharge. In the Zone-2, rainfall and evapotranspiration are the components directly involved in the water balance of groundwater as well as the surface runoff. Thus, three storage components are considered as a chain in the hydrological processes.

Dividing the Zone-1 and Zone-2 in a catchment depends on how groundwater can be accessed by evapotranspiration~~?~~. It is controlled by the depth of plant roots and the rise of capillary water over groundwater level. In the case study of the HRC, it was observed that some trees have long roots penetrated 2-3 m or more into the earth (Lv et al., 2013), but in general the dominant root zone is less than 2 m below ground surface for shrubs and grasses. When DWT is larger than 2 m, the ~~efficient~~ contribution of groundwater for evapotranspiration will dramatically decreased in an ignorable level (Yin et al., 2015). Thus, it is reasonable to use the contours of 2-m-depth of groundwater as the approximate boundary of the Zone-1 and Zone-2 in the HRC. In the Zone-1, according to the data in Lv et al. (2013), the depth to water table ranges between 2 m and 110 m. The transition vadose zone is roughly defined as the zone between 2-m-depth below ground surface and 2-m-height above groundwater level. In the assumptions of the ABCD-GE model, this zone could not be influenced by both of the evapotranspiration and groundwater flow processes. Thus, the thickness of the soil layer would be less than 2 m in the model for the HRC. However, one should be aware of that it is not necessary to find the distinct and exact boundaries for the zones, since the ABCD-GE model is a conceptual hydrological model.

In the ABCD-GE model, direct runoff only occurs in the Zone-2 and is assumed to be proportional to the precipitation as $(1-c)P_m$ where c is similar to the dimensionless parameter used in the ABCD model, but now is linked with the precipitation. The total runoff in the catchment is the sum of the direct runoff and groundwater discharge as follows

$$Q_m = \alpha(1-c)P_m + dG_m \, , \qquad (~~12~~10)$$

where α is the ratio of the area Zone-2 to the area of the whole catchment. Using 2 m as the bound value of groundwater depth for the Zone-2, α=0.16 is initially determined in the HRC. In comparison with Eq. (~~8~~6), herein the direct runoff is estimated with the amount of precipitation (αP_m) in the Zone-2, rather than with R_m.

Similar to that in the ABCD model, the change in the soil water storage is determined by

$$W_m - W_{m-1} = P_m - E_{1m} - R_m \, , \qquad (~~13~~11)$$

where $E_{1\mathrm{m}}$ is the monthly evapotranspiration in the Zone-1 dependent on Eq. (~~11~~9), R_m becomes the monthly leakage of soil water, forming the recharge to the transition vadose zone in the Zone-1. The change in this vadose zone storage is described with

$$V_m - V_{m-1} = R_m - kV_m \, , \qquad (~~14~~12)$$

where V_m and V_{m-1} represent the storages in the transition vadose zone at the end and beginning of the m-th month, respectively, and k is the parameter that accounts for groundwater recharge rate as kV_m. In considering of the gain-loss processes of groundwater, the change in the effective groundwater storage is yielded by

$$G_m - G_{m-1} = (1-\alpha)kV_m + \alpha(cP_m - E_{2m}) - dG_m \, , \qquad (~~15~~13)$$

where $E_{2\mathrm{m}}$ is the monthly evapotranspiration in the Zone-2, which depends on the effective groundwater storage as follow

$$E_{2m} = gG_m E_{0m} \, , \qquad (~~16~~14)$$

where g is a parameter controlling the intensity of groundwater dependent evapotranspiration. ~~Equation~~ Eq. (~~16~~14) assumes that the evapotranspiration rate in the Zone-2 is simply proportional to both the groundwater storage (which is positively related to groundwater level) and the potential evapotranspiration rate. Thus, the evapotranspiration rate as a whole in the catchment is summarized as

$$E_m = (1-\alpha)E_{1m} + \alpha E_{2m} \, . \qquad (~~17~~15)$$

~~Equstions~~ Eqs. (~~13~~11)-(~~15~~13) are solved one by one and finally the value of G_m is substituting into Eq. (~~12~~9) to obtain the runoff. The solutions of the ABCD-GE model are controlled by 7 parameters as: a, b, c, d, g, k and α. The parameter values should be identified with the model calibration process.

4 Model ~~calibration~~ Calibration and Modelling ~~results~~Results

4.1 Model calibration

We applied the ABCD-GE model to estimate the monthly evapotranspiration and the change in storage in the HRC ~~with~~ after the ~~calibrated~~ model parameters were calibrated. The monthly evapotranspiration data were then ~~used~~ summed up to estimate the annual evapotranspiration for further analysis. The model calibration was based on the observed monthly streamflow data at the Hanjiamao station and the separated base-flow data.

Because groundwater discharge has been included in the model, a base–flow analysis was performed to obtain the expected groundwater discharge for the model calibration. Using the automated hydrograph separation method HYSEP (Sloto and Crouse, 1996) on the daily streamflow data, such 'observed' groundwater discharge data were obtained for the period 1957-2010. These data were partly reported in Zhou et al. (2013). The base-flow index ranges between 0.80 and 0.95 for annual streamflow, indicating that groundwater flow is the dominant hydrological process in the HRC. Variation patterns of the monthly groundwater discharge are shown in Fig. ~~4b~~2b.

The ordinary least squares (OLS) criterion was applied for parameter estimation. The errors of both log-streamflow and log-base-flow were included in the OLS objective function, as follows:

$$\min U = \sum_{m=1}^{N} \left(e_m^2 + q_m^2 \right), \qquad (\cancel{18}16)$$

where

$$e_m = \ln(\hat{Q}/Q)_m, \quad q_m = \ln(\hat{Q}_b/Q_b)_m, \qquad (\cancel{19}17)$$

and U is the value of the objective function; N is the number of months; $\hat{Q}$ and Q are the simulated and observed monthly streamflow, respectively; $\hat{Q}_b$ is the simulated monthly groundwater discharge through dG_m in Eq. (12); and Q_b is the 'observed' monthly groundwater discharge obtained from the base flow analysis. The log form errors given in

~~equation~~Eq. (~~19~~17) can be used to obtain homoscedastic residuals (rather than the residual errors) of the normal absolute differences between the observed data and the model outputs (Alley, 1984). The nonlinear optimization algorithm Generalized Reduced Gradient (GRG) (Lasdonet al., 1978) was used to determine the optimum values of the parameters. The Nash-Sutcliffe efficiency (NSE) (Nash and Sutcliffe, 1970) was also applied to evaluate the performance of the model. The NSE value ranges in ($-\infty$, 1) whereas a higher than zero value is required for a well-perform model.

The parameters in the model were firstly identified using the 1957-1966 data, and this calibrated model was considered to be a 'natural' model due to the minimum impact of human activities during this 10-years period. The initial storage values were also regarded as the unknown parameters to be determined in the calibration process. Changes in the initial conditions generally influenced the simulated results in the first and second years. Therefore, the residual errors in the later years were applied to estimate the parameter values with less influence from the initial conditions. A sensitivity analysis was carried out to schematically capture the ranges of the parameter values. The best fitting parameter values obtained through the model calibration are shown in Table 2. The a value approximates to 1.0. In previous studies using the ABCD model, the a value was found generally to be higher than 0.9 (Alley, 1984; Sankarasubramanian and Vogel, 2002; Li and Sankarasubramanian, 2012). The b and d values fall into the ranges suggested by Alley (1984). The c value is 0.92, indicating that there are 8% of the precipitation in the Zone-2 were transferred to direct runoff during the 1957-1966 period. The fractional area of the shallow groundwater zone, α, is 0.21, which was larger than the current area (16.0%) of the zone with the DWT less than 2 m. Such a difference is reasonable because ~~the~~ groundwater level before 1967 should be higher than that at present as indicated by the decrease trend of the baseflow began from 1967. The k value controls the rate of groundwater recharge below the transition vadose zone. The transition vadose zone is a necessary component in the HRC as demonstrated by the sensitivity analysis on the k value. When an extremely high value of k is used (k >100), the kV_m value would be almost equal to R_m so that the transition vadose zone does not make sense. However, in this situation the model could never capture the seasonal variation patterns of the runoff and groundwater discharge in the HRC. The best fitting k value is significantly less than 1.0, indicating a strong delay effect. Thus, the delayed groundwater recharge is an essential process in this study area.

4.2 Modelling results

For the 1957-1966 period, the mean standard error of the calibrated model is smaller than 15%. The NSE value of the model is 0.51, not very high but significantly larger than zero. It is usually difficult to obtain a high NSE value for a catchment with weak seasonal variation in runoff (Mathevet et al., 2006). We used this 'natural' model to estimate the monthly hydrological components during the whole 1957-2010 period. For the runoff estimation, ~~The~~ the annual ~~simulation~~ results match the observation much better than the monthly ~~simulation~~ results as indicated by the ~~correlation~~ coefficient of determination (compare Fig. 5a with Fig. 5b). ~~We used this 'natural' model to estimate~~ Variations of the monthly total runoff ~~(Fig. 6a)~~ and groundwater discharge ~~(Fig. 6b)~~ estimated by the 'natural' model are shown in Fig. 6a and Fig. 6b, respectively.~~for the whole 1957-2010 periods.~~ The model ~~output~~ estimated monthly runoff after 1966 are higher than the observed values due to ignoring the impacts of land use changes and increased utilization of water for irrigation. However, the simulated patterns of groundwater discharge are similar to the observations: falling in the summer, rising in the ~~autumn~~winter. This agreement between the simulated and observed patterns demonstrates the ability of the ABCD-GE model in simulating the hydrological behaviors in the studied catchment: significant groundwater-dependent evapotranspiration occurs in the summer, and a strong recovery of storage in the shallow-groundwater zone occurs in the ~~autumn~~ winter due to ~~persistent~~ delayed recharge from the thick vadose zone.

For the periods after 1966, the differences between the model calculated natural annual runoff and the observed values as shown in Fig. 6c could be interpreted as the excess evapotranspiration induced by increasing agricultural water use from river diversion. Enhanced evapotranspiration also occurred in the shallow groundwater zone due to groundwater pumping for irrigation. To evaluate the actual water balance, the following equation

$$E_{ACT} \approx E_{NAT} + (Q_{NAT} - Q_{OBS})\,, \qquad (\cancel{20}18)$$

is applied ~~in an~~ approximately ~~way~~ to estimate the actual annual evapotranspiration (E_{ACT}) after 1966 from the 'natural' model result (E_{NAT}) plus the difference of annual runoff between the 'natural' model (Q_{NAT}) and the observation (Q_{OBS}). Thus, the irrigation water use in the catchment is included in E_{ACT}. Results are shown in Fig. 6d. It seems that the difference between E_{NAT} and E_{ACT} is not significantly large in comparison with the mean annual evapotranspiration. The maximum $Q_{\mathrm{NAT}} - Q_{\mathrm{OBS}}$ value is less than 10% of the mean annual evapotranspiration (~315 mm). Accordingly, the irrigation water use in the HRC did not significantly influence the annual evapotranspiration at the catchment scale. However, it dramatically influenced the streamflow. As shown in Fig. 6a, almost all of the direct runoff was removed from the total runoff after 1987 and groundwater discharge was significantly decreased even though the seasonal patterns were basically remained (Fig. 6b).

4.3 Annual water balance in the standard Budyko space

In Fig. 7a, the E_0/P and E/P data for the annual water balance obtained from the 'natural' model over this 55-years period are plotted in the standard Budyko space. For comparison, both E_{NAT}/P and E_{ACT}/P data ~~the results of the actual evapotranspiration (including irrigation) obtained with Eq. (16)~~ are plotted~~ as well~~. The E/P values obtained from the 'natural' model (E_{NAT}/P) is a little bit lower than ~~that including irrigation~~the actual E/P data (E_{ACT}/P). For both data sets, with increase in the aridity index, the evapotranspiration ratio (F=E/P) increases almost linearly with the R-square as high as 0.88. When ϕ is larger than 4, the ~~evapotranspiration ratios~~E/P data fall above the line of F=1. Since F=1 is the bound of the mean annual evapotranspiration ratio predicted by the ~~traditional~~ original Budyko hypothesis, the occurrence of such high F values indicates that the ~~traditional normal~~standard Budyko formulas, ~~shown in~~such as Eqs. (2) and (3), cannot be applied in analyzing the annual water balance in the HRC. During extreme dry years when ϕ >4, the annual precipitation is generally less than 290 mm whereas the annual evapotranspiration is generally higher than 300 mm. The excess evapotranspiration is sustained by shallow groundwater.

~~For mean annual water balance, as indicated in the traditional Budyko framework, the runoff ratio (Q/P) would decrease with increase in the aridity index. It is represented by a decay curve in the Q/P versus plot. However, the annual runoff ratio in the HRC shows an opposite trend (Fig. 7b). The annual runoff ratio obtained from the 'natural' model increases almost linearly with increasing aridity index. The reason for this positive trend is also the large contribution of groundwater storage to river discharge during the extreme dry years. The runoff ratio was decreased in actual due to irrigation water use, which weakened the linear relationship but remained the increase trend of Q/P versus .~~

The effects of groundwater dependent evapotranspiration can be clearly observed when the evapotranspiration ratio is divided into two parts and plotted in the Budyko space separately with respect to the shallow and deep groundwater zones, as shown in Fig. ~~8~~7b. The annual E values in the Zone-1 and Zone-2 are estimated respectively as

$$E_1 = \sum_{m=1}^{12} E_{1m}(W_{m-1}, a, b), \text{ and } \quad E_2 = \sum_{m=1}^{12} E_{2m}(G_m, g), \tag{19}$$

for every year, where E_{1m} ~~is~~was calculated with Eq. (9) whereas E_{2m} ~~is~~was calculated with Eq. (14). The data in Figure 7b ~~are~~were estimated with the parameter values of a, b and g for the 'natural' model. It is obvious that the annual E_1/P values in the Zone-1 (deep groundwater) for the whole range of the aridity index are smaller than 1.0 and fall below the Budyko curve determined by Eq. (2). The low E_1/P value in the Zone-1 is mainly due to the ~~deep water table~~significantly water limited condition. ~~Since the water table is deep,~~A large portion of precipitation (more than 30%) converts to effective groundwater recharge in the Zone-1 when ϕ is less than 5. The land covers in the deep groundwater zone are dominated by sparse desert grasses which have much lower evapotranspiration rates. The E_1/P trend can be sufficiently fitted by the Budyko curve determined with Eq. (~~5~~3) for w=0.5. As suggested by Zhang et al. (2001), the plant-available water coefficient, w, ranges between 0.5 and 2.0 where the lower limit refers to short grass or pasture, satisfying the situation in the HRC. However, the relationship between the annual evapotranspiration ratio and the annual aridity index in the shallow groundwater zone definitely could not be explained by any of the ~~existing normal~~ standard Budyko formulas, because all the annual F values for the Zone-2 are higher than 1.0. The E_2/P value increases from 1 to 7 when the ϕ value increases from 1.5 to 9.8, approximately following a linear trend. This trend agrees with the relationship between E_2 and E_0 ($E_2 \propto E_0$) that described in Eq. (~~16~~14). When the groundwater storage, G, is relatively stable, the annual E_2/P value would be proportional to the annual E_0/P value and the slope is represented by the annual mean value of gG. In the HRC, the annual mean value of gG is 0.65 according to the 'natural' model. Thus, the annual E_2/P value must be higher than 1.0 when ϕ is higher than 1.5. Such a groundwater dependent evapotranspiration process is the reason for the cases of F>1 occurred at the catchment scale in the HRC. Note that in the original Budyko framework, the $F=\phi$ case denotes an energy limited condition when water supply (only precipitaiton for mean annual water balance) is sufficient for the evapotranspiration process. The slope of the E_2/P trend (≈0.5) in Figure 7b is less than 1 but is closer to the $F=\phi$ line than the Budyko curve for the ϕ>1 situation. It indicates that in the Zone-2 the evapotranspiration process is in a quasi-energy limited condition, rather than in a water limited condition, because sallow groundwater can effectively ~~role~~serve as an external source of water supply.

5 Discussions

5.1 Controls on F >1 cases

It has been demonstrated in Fig. 7a that the annual evapotranspiation ratio, F, would be usually higher than 1.0 when the aridity index, ϕ, is larger than 4.0 in the HRC. In the literature, the F>1 cases were also observed when ϕ is just higher than 1.0 (Cheng et al., 2011; Wang, 2012; Chen et al, 2013). Thus, it is interesting to discuss how the occurrence of the F>1 cases is controlled by the catchment properties when shallow groundwater plays an important role.

The equation for the annual evapotranspiation ratio can be derived from Eqs. (15) and (19) as follows

$$F = (1-\alpha)\frac{E_1}{P} + \alpha g \frac{E_0}{P}\sum_{m=1}^{12}\left(\frac{E_{0m}}{E_0}G_m\right), \qquad (\cancel{21}20)$$

where ~~E_1 is the annual evapotranspiation in the Zone 1 which is determined by the annual water balance in the soil water reservoir, E_0 and P are the annual potential evaporation and precipitation, respectively. T~~the term E_{0m}/E_0 denotes the proportion of monthly potential evaporation to the annual one with respect to the m-th month. It has been known that the relationship between E_1/P and ϕ in the HRC is similar to that predicted by the ~~conventional~~standard Budyko formulas, as shown in Fig. ~~8~~7b, where E_1/P is less than 1.0. For the groundwater dependent term, defining

$$G_a = \sum_{m=1}^{12}\left(\frac{E_{0m}}{E_0}G_m\right), \qquad (\cancel{22}21)$$

as the weighted average of the monthly groundwater storage, Eq. (~~21~~20) can be replaced by

$$F(\phi) = \frac{(1-\alpha)w\phi}{1+w\phi+\phi^{-1}} + \alpha g \phi G_a, \qquad (\cancel{23}22)$$

where E_1/P is represented by Eq. (~~5~~3). According to Eq. (~~23~~22), the function $F(\phi)$ is controlled by the parameters, g, w, α and the status of groundwater represented by G_a. As indicated in Eq. (~~16~~14), gG_a is a dimensionless parameter to describe the intensity of groundwater dependent evapotranspiration related to the potential evaporation. The recommended range of gG_a is 0.5-1.0. In Eq.(22), the term of E_1/P indicates the normal energy-water limited process in Zone-1, whereas the term of groundwater indicates the quasi-enegy limited process in Zone-2. The real F value is a mixed result of the different processes.

Typical F-ϕ curves obtained with Eq. (~~23~~22) are given in Fig. ~~9~~8. It can be seen that the proportion of shallow water table area (α) has large effect on the occurrence of the F>1 case. When the shallow water table area is small (α=0.1), the F>1 case occurs only during extreme dry years. When groundwater dependent evapotranspiration (gG_a) increases, the case F>1 occurs with smaller aridity index. The plant available water coefficient (w) also influences the occurrence of the F>1 case. A larger value of w shifts the F-ϕ curves (Fig. ~~9b~~8b) to the left side indicating that the F>1 case could occur with smaller aridity index.

5.2 Using effective precipitation and modified Budyko space

~~For mean annual water balance, the evapotranspiration ratio is less than 1.0, meaning on long-term average, mean annual evaporation is smaller than mean annual precipitation. However, for the inter-annual and intra-annual water balance, the evapotranspiration ratio is larger than 1.0 during the extreme dry years since groundwater storage contributes to excess evapotranspiration.~~ The standard Budyko space ~~was settled under the assumption~~assumes that the potential water supply for evapotranspiration is only rainfall in a catchment. This is ~~reasonable~~true for the long-term average water balance, but ~~would be generally false~~exceptions might exist for the annual or intra-annual behaviors. Wang (2012) and Chen et al. (2013) argued that the reduction of storage in a period should be regarded as one of the water supply components and suggested~~it is reasonable~~an approach to replace the evapotranspiration ratio and the dryness index by $E/(P-\Delta S)$ and $E_0/(P-\Delta S)$, respectively, where ΔS is the storage ~~increment~~ depletion in a studied period and $P-\Delta S$ ~~roles~~regarded as the effective precipitation. ~~The plots of the annual or seasonal water balances would follow the normal shape i~~In this modified Budyko space, evapotranspiration is always less than the water supply so that the original Budyko hypothesis could be applied for small time-scale problems. ~~Thus, i~~In this ~~study~~ section we attempt to check the characteristics of the annual water balance data in the HRC using such a modified Budyko space. ~~For~~ With the results of the ABCD-GE model, the total change in storage for a year ~~was~~ can be estimated as

$$\Delta S=\sum_{m=1}^{12}[(1-\alpha)(W_m+V_m-W_{m-1}-V_{m-1})+(G_m-G_{m-1})], \qquad (~~24~~23)$$

where m is the number of the months in the year, ~~m~~W_0, V_0 and G_0 ~~1~~ for m=0 denot~~e~~ings the respective storage components at the end of the last year. Results are shown in Fig. ~~10~~9. It can be seen ~~that~~ in the modified Budyko space that the annual water balance data fall into the zone below the limitation: $E/(P-\Delta S)<1$, even below the modified Budyko curve obtained with Eq. (2) using the newly defined evapotranspiration ratio and dryness index. The shift path of the data points can not be captured by a single Budyko curve in the modified Budyko space with a constant value of the specific parameter. Such as shown in Fig. 9, the rising trend of $E/(P-\Delta S)$ with the increasing $E_0/(P-\Delta S)$ seems too weak in comparison with any one of the normal Budyko curves determined by the formula of Zhang et al. (2001). Furthermore, the $E/(P-\Delta S)$ value approaches a stable value around 0.90 with the ~~varying~~ very high $E_0/(P-\Delta S)$ values. It indicates that at least 10% of $P-\Delta S$ is contributed to the annual runoff, in terms of $Q/(P-\Delta S)$. This portion of the water supply seems to be inaccessible for the annual evapotranspiration process.

The ~~trouble~~difficulty ~~caused by~~using the effective precipitation defined in Wang (2012) and Chen et al. (2013) is the unkown ΔS for an investigated time step and the difficulty in determin~~e~~ing what is the accessible part of ΔS for evapotranspiration. Consequently, the estimation of $E/(P-\Delta S)$ ~~result~~value ~~estimated by the normal Budyko formulas including the effective precipitation could not be the~~ is not straightforward, ~~estimation of the actual evapotranspiration~~ but requires a complex iteration process. In the original Budyko framework for steady state water balance, the water supply (only precipitation) does not depend on evapotranspiration and runoff so that the aridity index is an independent variable in assessing the behaviors of the catchments. However, the water supply represented by the effective precipitation ~~would be~~is influenced by the evapotranspiration-runoff processes due to the feedback mechanism. This cross-dependency between the water supply and loss significantly reduces the efficiency of using the modified Budyko space in analyzing the shift of annual water balance with the climate change. In contrast, it would be an efficient and straightforward approach to extend formulas for annual water balance in the standard Budyko space, such as Eq. (22), keeping an independent index (ϕ) for the climatic conditions.

5.3 Landscape-driven and human-controlled shifts of annual water balance

As illustrated in Figure 6d, the actual evapotranspiration in the HRC has been enhanced by the human activities. This impact might exist in both the shallow and deep groundwater zones~~ but on different levels~~. Crops in the HRC are mainly planted in the depressions and terrace lands with shallow groundwater, especially in the river valley. Crops require much more water than the precipitation for growing. For example, maize could consume more than 3 times of rainfall water in growing seasons (Zhou et al., 2013). Thus, irrigation is necessary to maintain the agricultural production. In the farmlands far away from the rivers, groundwater was abstracted from wells for irrigation. In the river valley, irrigation was realized with diversions and channels. Therefore, increasing in evapotranspiration in the shallow groundwater zone ~~was~~is dominated by ~~growing~~ irrigation.~~ (expanding croplands).~~ Along the river, the area of the surface water body was significantly enlarged in reservoirs~~ and before diversions,~~ leading to increase in surface water evapotranspiration loss. It is equivalent to increase in groundwater dependent evapotranspiration in this study because surface water is also included in the shallow groundwater zone. As a result, the shift of the annual water balance in the Budyko spapce was partly ~~triggered~~caused by change in land use and controlled by regulation of river water for irrigation.

Recently, Jaramillo and Destouni (2014) developed a method to assess the landscape-driven change in the mean evapotranspiration ratio using the difference between the actual change in the F value and the climate-driven change in the F value following the Budyko framework. In this section, we extend their method to assess the landscape-driven change in annual water balance in the HRC. The years between 1957-1966 is selected from Table 1 as the reference period. Changes ~~are accounting for with~~were evaluated for the different average values of the annual E/P data in the different periods listed in Table 1. The climate-driven change is estimated with the annual E_{NAT} values obtained from the 'natural' model, using a formula similar to Jaramillo and Destouni (2014), as follows

$$\Delta\left(\frac{E_{LD}}{P}\right) = \Delta\left(\frac{E_{ACT}}{P}\right) - \Delta\left(\frac{E_{NAT}}{P}\right), \qquad (24)$$

where $\Delta\,(E_{LD}/P)$ denotes the landscape-driven change in comparison with the 1957-1966 period. However, this quantity index includes the landscape changes driven by both climatic force and human activities. To check how this index is correlated with the increasing impacts from the reservoirs and diversions, following Jaramillo and Destouni (2015), the intra-annual variability of the monthly runoff (CV_Q) ~~is~~was applied. The CV_Q/CV_P value was estimated to reveal the separate influence of such a human-controlled flow regulation from the mixed human-climate controlling, where CV_P is the intra-annual variability of the monthly rainfall.

Results of the $\Delta(E_{LD}/P)$ and $\Delta(CV_Q/CV_P)$ data for the three periods after 1966 are shown in Figure 10. The $\Delta(E_{LD}/P)$ values of the periods are all positive but not big (less than 6%), indicating a slight increase in the evapotranspiration ratio after 1966 driven by changes in natural landscape and human controlled land use. The $\Delta(CV_Q/CV_P)$ values show a significant fluctuation around zero but also limited in a small range (±5%). Both the $\Delta(E_{LD}/P)$ and $\Delta(CV_Q/CV_P)$ values reach to the maximum during 1968-1987. Fluctuations of these data could not be fully explained by the increasing number of diversions in the rivers. The negative $\Delta(CV_Q/CV_P)$ value in the 1957-1967 period may be due to construction of the two reservoirs since reservoirs commonly smooth the variation of streamflow. During 1968-1987, the $\Delta(CV_Q/CV_P)$ value turned to positive when 5 new diversions was built, indicating the ~~a~~opposite impacts of the reservoirs and diversions. It is possible that the streamflow was disturbed by the ~~random~~ regulation of water for irrigation on these diversions with small overflow dams. Decrease in the $\Delta(CV_Q/CV_P)$ value during 1988-2010 may be caused by the control of river water use under some government to prevent the desertification (Yang et al., 2012; Zhou et al., 2015). The following decrease in $\Delta(E_{LD}/P)$ value for the 1988-2010 period is not significant, seems indicating alternative irrigation ~~forms~~practice in farmlands (for example pumping groundwater) so that the real water consumption was reduced but still on a high level. As a result, utilizations surface water and groundwater for irrigation can increase the frequency of the F>1 cases.

5.4 Limitation Remarks

Attention should be paid to the simplifications in the conceptual ~~models~~ model extended from the ABCD model, when the equations and formulas are applied in complicated catchments. The ABCD model assumes that the storage-evapotranspiration relationship is controlled by the parameters a and b whereas the physical interpretation of them is difficult (Alley, 1984). Equation (~~11~~8) in the ABCD model is also hypothesized from a simplified storage-loss process that controlled by the parameter b (Thomas, 1981). Sankarasubramanian and Vogel (2002) suggested that the b value for annual water balance could be approximately represented by the maximum soil moisture field capacity plus maximum E_0 for $\phi<1$ or maximum P for $\phi \geq 1$. The a value is generally estimated in a small range between 0.95 and 1.0. In this study, the model output is not sensitive to the a value. The correlation between a and b may exist because both of them are positively related with E_m+~~S_m~~-W_m in ~~equation~~ Eq. (~~10~~7). The ABCD model neglects the possibility of groundwater-dependent evapotranpiration which has been incorporated in the ABCD-GE model. The ABCD-~~GDE~~ GE model ~~clearly~~ divides the area into shallow and deep groundwater zones, without considering a complicated spatial distribution of groundwater depth. For the shallow groundwater zone, the evapotranspiration is assumed to be proportional to groundwater storage. Nonlinear behavior in groundwater dependent evapotranspiration could be further included if it ~~has been~~can be successfully parameterized. Linear groundwater storage-discharge relationship is adopted in both of the ABCD and ABCD-GE models. These simplifications could cause systematic errors in modeling a catchment where the nonlinear behaviors in the hydrological processes are significant.

In fact, when the Budyko framework is applied for small time-scale water balance in a catchment, ~~much more~~ the other additional sources of water supply should be ~~take care of~~considered, ~~rather than~~apart from groundwater. Significant changes in soil moisture, snow cover or frozen water in cold regions ~~–~~could also cause 'abnormal' shift of annual water balance for a catchment in the Budyko space. The ~~roles~~effects of these storage components are ignorable in the HRC but may be essential in other study areas. In particular, the special processes in cold regions are not included in ~~The~~ the ABCD-GE model~~s ignore the snow cover process~~. However, ~~For catchments in cold region~~ one can refer to Martinez and Gupta (2010) who proposed the snow-augmented ABCD model, which is easy to be incorporated into an extension of the ABCD-GE model.

6 Conclusions

The Budyko framework was developed for long-term mean annual water balance in catchments, which estimates ~~hypothesis assumes that~~ the evapotranspiration ratio (F) as a function of ~~is less than 1 and varies with~~ the aridity index (ϕ). It can be represented by curves for the F-ϕ relationship in the standard Budyko space that were determined by the original Budyko formula without any parameter or formulas with a catchment specific parameter. It is ~~attractive~~interesting to investigate whether the Budyko space can be also applied to capture the annual water balance in a catchment with the varying dryness. However, ~~The~~ the shift of annual water balance ~~plot for a catchment~~ in the standard Budyko space could be significantly different from that presumed from the normal Budyko curves, in particular, when the cases of *F*>1 occur as that have been observed in a number of catchments.

In this study, we highlighted the effects of groundwater dependent evapotranspiration in triggering the abnormal shift of annual water balance in the standard Budyko space ~~in comparison with traditional Budyko curves~~. A conceptual monthly hydrological model, the ABCD-GE model, was developed from the widely used ABCD model to incorporate the groundwater-dependent evapotranspiration in the zone with shallow water table and delayed groundwater recharge in the zone with deep water table. The model was successfully applied to analyze the shift of annual water balance in the Hailiutu River Catchment (HRC) ~~in~~, China, where 16% of the area is occupied with shallow groundwater (depth to water table is less than 2 m). ~~53 years data of runoff and groundwater discharge are available~~.

The results show that the ~~traditional~~ normal Budyko ~~hypothesis~~ formulas ~~is~~ are not ~~valid~~ applicable for the interannual variability of catchment water balance in the standard Budyko space ~~with~~ when groundwater dependent evapotranspiration is significant. The shift of ~~the~~ annual water balance in the F-ϕ ~~Budyko~~ space is a combination of the Budyko-type response in the deep groundwater zone and ~~more stable evapotranspiration~~the quasi-energy limited condition in the shallow groundwater zone. Shallow ~~Groundwater~~ groundwater ~~storage~~ supplies excess evapotranspiration during extreme dry years, leading to *F*>1 cases. The occurrence of the ~~*E/P*~~*F*>1 cases depends on the proportion area of the shallow groundwater zone, the intensity of groundwater dependent evapotranspiration and the catchment properties determining the ~~normal~~ Budyko-type trend in the deep groundwater zone. Water utilization for irrigation may enhance this excess evapotranspiration phenomenon. The modified Budyko space with the effective precipitation incorporating the change in storage can force *F* values below 1.0.~~remedy the bound of evapotranspiration.~~ However, the computation is tidious in dealing with ~~it meets the trouble of~~ the feedback between the water supply and evapotranspiration loss as well as the existence of inaccessible storage for evapotranspiration. ~~Instead, t~~The empirical formula proposed in this study for the standard Budyko space provides ~~yields~~ a straightforward ~~way~~method to predict the trend of annual water balance with the varying dryness.

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Table 1. Mean annual fluxes in the Hailiutu River catchment (HRC) in different periods

Periods	P (mm)	E_0 (mm)	Q (mm)	Number Of Diversions(reservoirs)†
1957-1966	387.0	1230.2	42.3	0(0)
1967-1987	337.0	1269.6	32.6	4(2)
1988-1997	329.9	1240.2	23.4	9(2)
1998-2010	352.8	1234.0	28.0	10(2)

† According to Yang et al. (2012).

Table 2. Best fitting parameters of the 'natural' model for the HRC.

Period	a	b	c	d	g	k	α	Error[†]	NSE
		mm		$\times10^{-2}$	$\times10^{-2}$ m^{-1}	$\times10^{-2}$		(%)	
1957-1966	0.97	33	0.92	4.53	1.00	1.68	0.21	13.9	0.51

[†] Mean standard errors of the monthly runoff and groundwater discharge

Figure Captions:

Figure ~~2~~1. Geographic information of the study site: (a) location of the study area in north central China; (b) Distribution of meteorological stations in the Erdos Plateau (green points) and contours of mean annual precipitation plotted from 1-km resolution gridded precipitation data; (c) Characteristics of landscape ~~Topography of the Hailiutu River catchment represented using a 30-m gridded DEM~~according to Lv et al. (2013).

Figure ~~4~~2. The monthly meteorological data (a) and streamflow-baseflow data (b) from 1957 to 2010 in the HRC.

Figure 3. The plots of the annual *Q*/*P* data (a) and (*P*−*Q*)/*P* data (b) versus the aridity index in the HRC. The dashed lines are determined with the original Budyko formula, Eq. (2). The solid lines are the correlation curves of the scatter data points.

Figure ~~1~~4. Schematic representations of the ABCD model (a) and ABCD-GE model (b). ~~*S*~~ *W* and *V* are the effective soil water storage and the effective storage in the transition vadose zone, respectively. *G* is the effective groundwater storage.

~~Figure 3. Historgram of requency for groundwater depth in the HRC according to the gridded data of groundwater level in Lv et al. (2013).~~

Figure 5. Correlation plots of the observed and simulated monthly (a) and annual (b) results for the runoff data in 1957-~~1966~~2010~~ period~~. The simulated results are obtianed with the 'natural' model calibrated with the observation data during 1957-1966 when the impacts of human activities are minimum. Both data of total runoff and groundwater discharge are applied for the correlation analysis without bias.

Figure 6. Simulated results of the 'natural' ABCD-GE model in comparison with the observation data in the HRC from 1957 to 2010, including: Monthly runoff (a), groundwater

discharge (b), annual runoff (c) and annual evapotranspiration (d). ~~The 'natural' model is calibrated with observation data during 1957-1966 when the impacts of human activities are minimum.~~ The actual evapotranspiration in (d) was estimated with Eq. (~~20~~18).

Figure 7. Plots of the annual evapotranpiration ratio in the HRC versus the annual aridity index in the standard Budyko space: (a) using the E_{NAT} data estimated with the 'natural' model and the E_{ACT} data estimated with Eq. (18); (b) using the E_1 data for the Zone-1 and the E_2 data for the Zone-2 that estimated with Eq. (19) on the basis of the 'natural' model ~~and the annual runoff ratio versus the annual aridity index (b)~~. The dashed lines are the linear correlation curves for the 'natural' model data. The $F=\phi$ line represents the energy-limited condition.

~~Figure 8. Plots of the annual evapotranpiration ratio in the HRC versus the annual aridity index in the Budyko space for Zone-1 and Zone-2 based on the 'natural' model. The dashed line is the linear correlation curve for the Zone-2 data. The red curve is obtained with Eq. (5) where w=0.5.~~

Figure ~~9~~8. The typical F-ϕ curves for annual water balance in the standard Budyko space determined with Eq. (~~23~~22) when w=0.5 (a) and w=2.0 (b). The solid and dashed line curves are estimated using gG_a=0.5 and gG_a=1.0, respectively. The gray blocks denote the potential F>1 zones. The actual data of the HRC are shown as the scatter points.

Figure ~~10~~9. Annual water balance data in the modified Budyko space with the effective precipitation defined by Wang (2012). Dots are the data obtained for the HRC using the 'natural' model. The curve represents the normal ~~result of~~ Budyko ~~equation~~ curves determined with Eq.(3)~~(Budyko, 1958)~~ ~~with~~ using $E_0/(P-\Delta S)$ and $E/(P-\Delta S)$, respectively, instead of ~~E_0/P~~F and ϕ ~~E/P~~. The dashed line approximately represents the actual bound of the $E/(P-\Delta S)$ data.

Figure 10. Historgram of the $\Delta(E_{LD}/P)$ data determined with Eq. (24) and the $\Delta(CV_Q/CV_P)$ data determined with the intra-annual variabilities of the monthly runoff (CV_Q) and rainfall

(CV_P) for the different periods in the HRC. The numbers of diversions(reservoirs) are shown on the top of the blocks according to Table 1.