1-1-2012

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Recommended Citation

Cheng, Lei; Xu, Zongxue; Wang, Dingbao; and Cai, Ximing, "Reply to comment by Jozsef Szilagyi on "Assessing interannual variability of evapotranspiration at the catchment scale using satellite-based evapotranspiration data sets"" (2012). *Faculty Bibliography 2010s*. 2409.
https://stars.library.ucf.edu/facultybib2010/2409

WATER RESOURCES RESEARCH, VOL. 48, W03802, doi:10.1029/2011WR011799, 2012

Reply to comment by Jozsef Szilagyi on "Assessing interannual variability of evapotranspiration at the catchment scale using satellite-based evapotranspiration data sets"

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Received 29 December 2011; accepted 13 February 2012; published 21 March 2012.

Citation: Cheng, L., Z. Xu, D. Wang, and X. Cai (2012), Reply to comment by Jozsef Szilagyi on "Assessing interannual variability of evapotranspiration at the catchment scale using satellite-based evapotranspiration data sets" *Water Resour. Res.*, *48*, W03802, doi:10.1029/2011WR011799.

1. Introduction

[1] We would like to thank J. Szilagyi for his comment [*Szilagyi*, 2012] and for providing us an opportunity to restate the ideas of our paper [*Cheng et al.*, 2011] about the interannual ET variability at the catchment scale. Using satellite-based evapotranspiration (ET) data sets, we found that a linear relationship can better characterize the interannual relationship between ET/P and PET/P (where P is annual precipitation, ET is evapotranspiration, and PET is annual potential ET estimated by *Priestley and Taylor* [1972]) than a nonlinear single-parameter Budyko-type curve for a particular catchment [*Budyko*, 1958]. Furthermore, we discussed the main controlling factors of the linear relationship, including filter effect of soil water, physiological responses of vegetation to climatic variability, and human interferences to the catchment water cycle.

[2] The major argument of *Szilagyi* [2012] is that the linear relationship can be derived directly from the complementary relationship (CR), and thus the linear relationship may not be considered a new contribution in our recent paper [*Cheng et al.*, 2011]. However, we do not agree with this. *Szilagyi* [2012] also expressed doubt regarding the satellite-based ET data sets used in our studies; we disagree with this as well. In addition, *Szilagyi* [2012] pointed out some terminology issues in the water mass balance equations [*Cheng et al.*, 2011, equations (1) and (3)]. We find his discussion on these equations help clarify our point about water balance at the catchment scale.

2. Differences Between the Linear Relationship Derived From the Budyko Framework and That From the CR for Annual Water Balance

[3] The fundamentals of the Budyko framework for water-energy balance, namely, the relationship between ET/P and PET/P, and the differences between the framework and the CR have been discussed by *Zhang et al.* [2004] and *Yang et al.* [2006]. Essentially, at the annual time scale, the Budyko framework postulates that the actual ET not only has a complementary relationship with residual potential evapotranspiration (i.e., PET minus ET), given potential ET is constant, but also has a complementary relationship with residual precipitation (i.e., P minus ET), given precipitation is constant. However, CR assumes that actual ET and PET are symmetric around the wet environment evaporation [*Bouchet*, 1963; *Brutsaert and Stricker*, 1979; *Morton*, 1983], which means that actual ET only has a complementary relationship with residual energy supply. As we know, in humid regions, ET is constrained by energy supply; while in arid regions, it is limited by water supply. Therefore, the Budyko framework provides a more general description of the partitioning of precipitation [*Zhang et al.*, 2004; *Yang et al.*, 2006], which characterizes the complementary relationship between actual ET and both water and energy supply.

[4] In our paper, we estimated the interannual variability of ET at the catchment scale using the Budyko framework and proposed the following relationship:

$$\frac{\mathrm{ET}}{P} = \alpha\frac{\mathrm{PET}}{P} + \beta \tag{1}$$

in which, the slope (α) and the intercept (β) reflect different controls of PET and P on annual ET in different climate regions as discussed by *Cheng et al.* [2011]. It should be noted that this relationship is fundamentally different from the equation presented by *Szilagyi and Jozsa* [2009] and *Szilagyi* [2012], i.e.,

$$\frac{\mathrm{ET}}{P} = \frac{\left(2 - \frac{\mathrm{PET_{PM}}}{\mathrm{PET}}\right)\mathrm{PET}}{P} \tag{2}$$

where PET is derived by *Priestley and Taylor* [1972] and $\mathrm{PET_{PM}}$ is derived by *Penman* [1948]. We disagree with *Szilagyi*'s [2012] claim that equation (1) is implied by equation (2) because of the following two arguments. First,

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equation (2) essentially represents a linear correlation between actual ET and residual energy for ET, which is applicable to an energy-limited environment. However, in a water-limited environment where actual ET is mainly controlled by the water supply rather than energy supply, a linear relationship using equation (2) for the interannual relationship between ET/*P* and PET/*P* possibly is not strong [*Yang et al.*, 2006]. Second, even though CR may infer a linear relationship of annual water-energy balance for a specific catchment located in an energy-limited environment, the two linear relationships for annual water-energy balance derived directly from CR by *Szilagyi and Jozsa* [2009] and proposed by *Cheng et al.* [2011] are fundamentally different. Equation (1), which is based on the Budyko framework, has a nonzero intercept term, but equation (2) from CR does not. A zero-intercept term means that the annual ET is only related to energy (PET). The intercept reflects that the relative magnitude of the annual variability of precipitation could cascade into the annual variation of ET. In fact, in a humid region, the response of vegetation to climate variability and carryover soil water between years could introduce the variability of precipitation into variability of ET, as discussed by *Cheng et al.* [2011]. We have shown that β in equation (1) in the humid region is close to but not equal to zero. While, as shown by equation (2), the intercept is zero and cannot take interannual precipitation variability into account explicitly. Moreover, *Szilagyi and Jozsa* [2009] mainly discuss long-term mean water balance (10 years interval) using CR, where the ET was aggregated from daily estimates but not at the annual time scale.

[5] *Cheng et al.*'s [2011] purpose was to investigate the coupling relationship of annual water-energy at the catchment scale in a top-down manner under the Budyko framework (i.e., from a general theory applied to the behavior of all catchments across different climate zones at mean annual time scale to the study on a particular catchment at annual time scale). Recently, the Budyko framework has been applied to quantifying climate variability in catchment water balance, which has bridged the knowledge gap on the impact of changing climate and human interferences on water resources to some extent [*Zhang et al.*, 2001, 2004; *Ma et al.*, 2008; *Y. Zhang et al.*, 2010; *Roderick and Farquhar*, 2011; *Donohue et al.*, 2011; *Wang and Hejazi*, 2011]. Equation (1), as a further extent of the Budyko framework, can be used to analyze the impact of climate variability on the interannual water-energy balance for individual catchments, although accurate catchment annual ET may not be estimated using equation (1) [*Cheng et al.*, 2011].

[6] In summary, the linear relationship of the annual water-energy balance derived from CR [*Szilagyi and Jozsa*, 2009, equation (2)] and the Budyko framework [*Cheng et al.*, 2011, equation (1)] are fundamentally different. Equation (1) suggests a general coupling relationship of annual water-energy balance at the catchment scale. Thus, the statement by *Szilagyi* [2012] that the findings of *Cheng et al.* [2011] are simply an empirical proof of CR is incorrect, although our findings can be partly explained by CR.

3. The Satellite-Based ET Data Sets

[7] *Szilagyi* [2012] claimed that it was superfluous for us to use satellite-based ET estimates to address annual water-energy balance issues. We understand the concern on the accuracy and completeness of remotely sensed data. The bias in the satellite-based ET estimates could be introduced by algorithms, remotely sensing (RS) products, scaling issues, parameter calibration, etc. [*Kalma et al.*, 2008; *Wu and Li*, 2009; *Tang et al.*, 2009a]. This issue is beyond the scope of our work. However, on the basis of our knowledge of satellite-based ET, we cannot accept the claim of *Szilagyi* [2012]. Actually, the advantages of the satellite-based ET has been demonstrated by numerous efforts using different RS products [*Bastiaanssen et al.*, 1998; *Allen et al.*, 2007; *Kalma et al.*, 2008; *Schmidt et al.*, 2008; *Li et al.*, 2009; *Tang et al.*, 2009a; *Jung et al.*, 2010; *K. Zhang et al.*, 2010; *Miralles*, 2011; *Mu et al.*, 2011]. We have compared different methods to estimate areal averaged ET over a catchment [*Cheng et al.*, 2011, section 2.1] and pointed out why we chose the satellite-based ET to carry out the investigation.

[8] Particularly, the satellite-based ET data set (UM_ET) used in our paper is not the one developed by *Mu et al.* [2011] on the basis of MODIS data sets. The data set we used was developed by *K. Zhang et al.* [2010] and is based on an AVHRR normalized differences vegetation index (NDVI) canopy conductance algorithm incorporating meteorological observations. This data set has been demonstrated to have a good performance globally, especially in the United States [*Jung et al.*, 2010; *K. Zhang et al.*, 2010]. According to the producers of both data sets (UM_ET and UW_ET) [*Tang et al.*, 2009a; *K. Zhang et al.*, 2010], both spatial and temporal accuracy have been improved at the annual time scale and can capture the interannual variability. Furthermore, our study focused on the interannual variability rather than accurate quantities of ET.

4. The Water Balance Equations

[9] *Szilagyi* [2012] questioned the validity of equation (1) and (3) of *Cheng et al.* [2011] (hereinafter, the equation numbers denote the equations of *Cheng et al.* [2011], not the equations in this reply). He suggested using a very rigorous water balance equation for combined unsaturated and saturated zones of a watershed underlying an impervious layer. Basically, we followed what he suggested. *G* in equation (1) represents the percolation to deep groundwater in equation (1). We admit that the use of the phrase "groundwater recharge" may cause confusion to readers.

[10] In terms of equation (3), as we stated "For watersheds with intensive irrigation diverted from other catchments or pumped from deep groundwater, irrigation water (I) as an external source should be added to equation (1)." If the groundwater is pumped from a shallow unconfined aquifer, irrigation indeed cannot be included in equation (3). We believe this is not in conflict with what *Szilagyi* [2012] suggested.

[11] We use the water balance equations to illustrate (1) how to estimate mean annual ET (equation (2)), (2) the possible biases that may arise from this method when it is applied to the interannual time scale, and (3) human interferences (over pumping of deep groundwater) to the water balance (equation (3)). In fact, the water balance equation can have different forms for different considerations. In surface hydrology, when catchment water balance is modeled

in a lumped form (without an explicit definition of groundwater and underlying a pervious layer), water balance can be accounted considering precipitation (P) as an input; and water depleted from the catchment system including ET to the atmosphere, runoff (R, fast flow and slow flow gauged at the outlet), and deep percolation to a confined aquifer (G, soil water out of the watershed that does not though gauged outlet) as outputs. Hence, equation (1) could be derived with an additional soil water storage variation term (ΔS). The parameterization of equation (1) is also applied in some hydrological models for water balance accounting [*Singh*, 1995]. Actually, almost all the 547 catchments used by *Cheng et al.* [2011] are in headwater zones. Since we use the annual time interval, it is reasonable for us to use equation (1) and introduce an additional groundwater pumping item to equation (3) considering the disequilibrium condition of a confined aquifer system (where there exists over pumping for a long period, e.g., the Republican River basin).

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