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# Comment on "Assessing interannual variability of evapotranspiration at the catchment scale using satellite-based evapotranspiration data sets" by Lei Cheng et al.

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[1] *Cheng et al.* [2011] analyze annual water and energy balance data of 547 watersheds within the United States in a *Budyko* [1958] framework. Some problems with their water balance equations (equations (1) and (3)) written for the unsaturated zone, should be discussed first.

[2] Equation (1) of *Cheng et al.* [2011] cannot be written for any time period as they claim to obtain the catchment water balance because for longer time periods (e.g., a year, their chosen time period of analysis) the runoff ($R$) values (i.e., stream discharge) will contain a certain part of the recharge values due to base flow. Therefore, a significant percentage of the groundwater recharge value can and will appear twice in the equation, once as part of recharge and once as runoff. If, indeed, $R$ means only surface runoff (which is not known because the authors do not elaborate on it), then measured discharge at the watershed cannot be decomposed into this $R$ and recharge at an annual basis since not all the recharged water will leave the watershed in the same year at larger catchments. The solution of the problem is to write the water balance for the combined unsaturated-saturated zone of the watershed, with the water storage term ($\Delta S$) defined for the combined system. This way the recharge term disappears from the equation and evapotranspiration (ET) becomes equal to precipitation ($P$) less runoff plus the change in water storage, provided net lateral groundwater fluxes are negligible and the watershed is underlain by an impervious layer.

[3] The problem with equation (3) of *Cheng et al.* [2011], in addition to the above, is that irrigation water ought to be included in the equation only if it is from a source outside the catchment. In the Republican River basin in their example, most of the irrigated water comes from center pivot systems, where the water is pumped from within the catchment, thus reducing water storage and runoff (in fact, a serious problem in many prairie states); consequently, a certain part of the irrigated water is counted twice in the equation, once as a measured reduced runoff value and once as additional "precipitation", leading to an overestimation of ET. The solution is the same as above, i.e., $\mathrm{ET} = P - R + \Delta S$ (written for the unsaturated-saturated system) is the correct form of the water balance equation for estimating annual ET for center-pivot irrigated catchments, similarly to watersheds without irrigation.

[4] Focusing now on the core issue of the present comment, *Cheng et al.* [2011] found linear relationships between two ratios, ET/$P$ and PET/$P$ (where PET is the *Priestley and Taylor* [1972] evaporation rate and $P$ is precipitation), for the catchments analyzed. They show that these linear relationships are strong in humid regions while less strong (but still statistically significant) in semiarid ones. However, what the authors overlook is that they see yet another empirical proof of the complementary relationship (CR), originally from *Bouchet* [1963] and later reformulated by *Brutsaert and Stricker* [1979] in their advection-aridity (AA) model and by *Morton* [1983] in his WREVAP model, to name just the two most widely used versions of the CR. Figure 1 displays the AA-estimated 10 year average ET rates plotted against the water balance–derived ET values ($\mathrm{ET} = P - R$) for 23 catchments [*Szilagyi and Jozsa*, 2009] across the United States that were, supposedly, only minimally affected by human activity for the 1961–1990 period.

[5] *Szilagyi and Jozsa* [2009] demonstrate that by dividing both sides of the AA Formulation of the CR, i.e.,

$$\mathrm{ET} = 2\mathrm{PET} - \mathrm{PET}_{\mathrm{PM}} \qquad (1)$$

where $\mathrm{PET}_{\mathrm{PM}}$ is the *Penman* [1948] evaporation rate, by $P$, one obtains the following simple relationship between the two ratios (i.e., ET/$P$ and PET/$P$):

$$\mathrm{ET}/P = (2 - \mathrm{PET}_{\mathrm{PM}}/\mathrm{PET})\mathrm{PET}/P \qquad (2)$$

[6] The $\mathrm{PET}_{\mathrm{PM}}$/PET ratio varies between unity and two, thus in the former case one obtains the limiting 1:1 line of the Budyko curve (Figure 2), while in the latter, when the ratio approximates two, one reaches the unity (for catchments with no irrigation) upper limit line of the Budyko curve. The importance of (2) is that it clearly defines the relationship between the two ratios, ET/$P$ and PET/$P$, via the $\mathrm{PET}_{\mathrm{PM}}$/PET term without the need for empirical equation fitting as done by *Cheng et al.* [2011]. The linear equations of *Cheng et al.* [2011] follow from the ET/$P$ curve (similar to the Budyko curve, but better fits the observed data) of Figure 2. For any given catchment, the aridity

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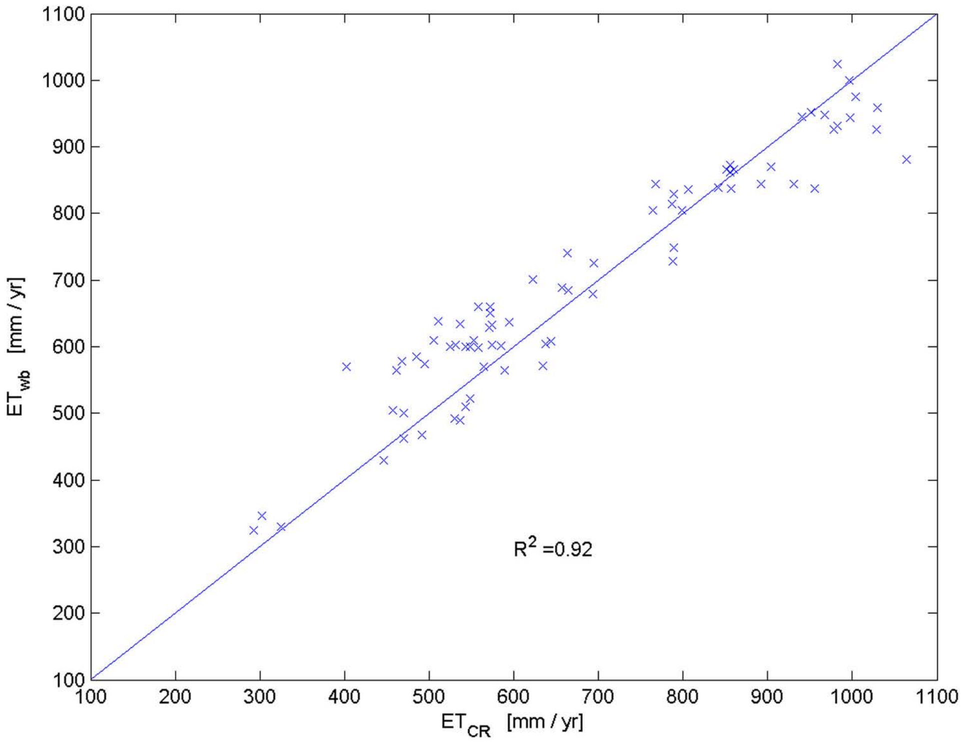

**Figure 1.** Ten year average water balance and complementary relationship (CR) derived annual evapotranspiration (ET) rates for 23 U.S. catchments [*Szilagyi and Jozsa*, 2009] assumed to be minimally affected by human activity for the 1961–1990 period. Mean of $ET_{wb}$ is 698 mm yr$^{-1}$, and mean of $ET_{CR}$ is 683 mm yr$^{-1}$, a difference of 2%.

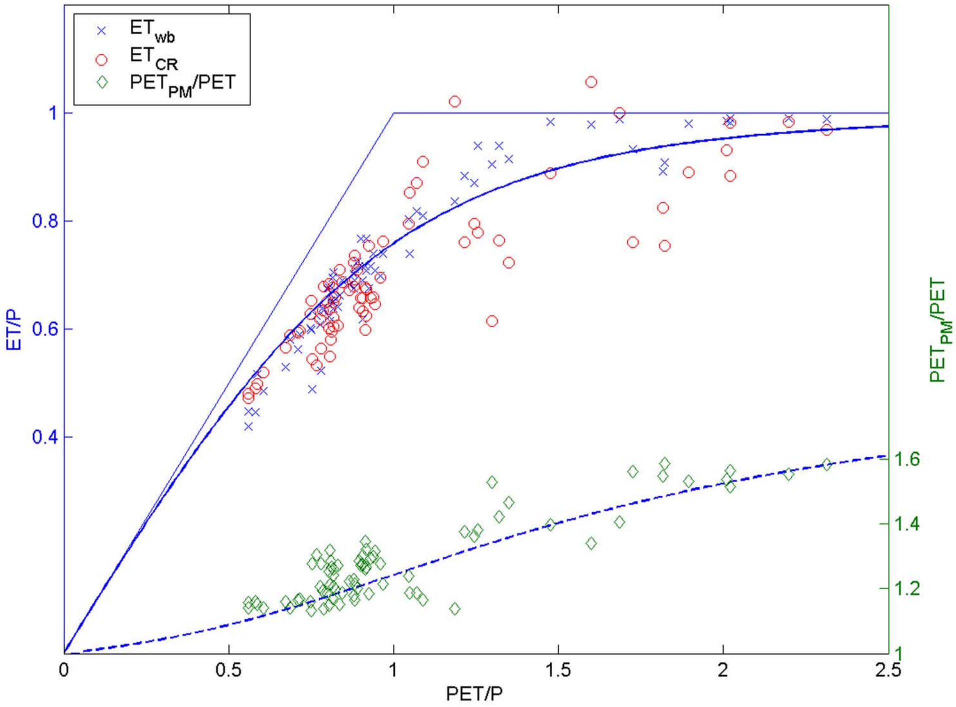

**Figure 2.** Ten year average ET/$P$ and $PET_{PM}$/PET ratios plotted against the PET/$P$ ratio for the 23 catchments in Figure 1. $ET_{wb}$, water balance; $ET_{CR}$, advection-aridity model. PET is the Priestley-Taylor evaporation rate with a coefficient of 1.31; $PET_{PM}$ is the Penman evaporation rate employing the Rome wind function, $f(u)$ $(0.26(1 + 0.54u_2))$, where $u_2$ is the mean wind speed in m s$^{-1}$ at 2 m. The two curves are the best fit one-parameter curves of *Porporato et al.* [2004] as discussed by *Szilagyi and Jozsa* [2009].

(i.e., expressed as PET/$P$) value changes within a relatively short range between the years (because of the given climate); thus, one always sees only a portion of the whole curve, and consequently, the curve can be substituted by a straight line segment over these short PET/$P$ ranges. The humid watersheds fall on the steeper side of the curve where the interannual variability of the $\mathrm{PET_{PM}}$/PET ratio (which regulates the linear fit) at a given catchment is much reduced, because in humid climates the predominant part of the $\mathrm{PET_{PM}}$ value comes from the available energy at the surface, just as for the PET value. The second term of the Penman equation, the so-called "drying power of air", which depends on the wind and the vapor pressure deficit (VPD) of the air, is typically small in humid climates compared to the first term because of the abundance of rain and, consequently, high humidity of air (which is why in Figure 2 the ratio is close to unity in humid regions), from which term any, even significant, interannual variation becomes very suppressed when added to a much larger quantity and divided by a similarly large quantity (i.e., PET), consequently yielding reduced variation in the $\mathrm{PET_{PM}}$/PET ratio and therefore a better linear fit, as correctly observed by *Cheng et al.* [2011]. As aridity increases, the ET/$P$ curve becomes less steep and so do the fitted lines of *Cheng et al.* [2011] with interannual variability increasing. In more arid climates the same interannual variability in the drying power of air term of the Penman equation found in humid climates becomes more pronounced in the $\mathrm{PET_{PM}}$/PET ratio, because the value of this term increases (since VPD is larger) compared to the first, energy-dependent term. Naturally, when one takes multiyear averages, as in Figure 2, the variance, displayed by the water balance–derived ET values, does not increase significantly (if at all) with aridity since over longer intervals these catchments stay almost equally dry; that is, they evaporate almost all the precipitation they receive.

[7] In summary, the relationships between the annual $E/P$ and PET/$P$ values found by *Cheng et al.* [2011] are yet another empirical proof of the CR (for additional empirical proofs other than those of *Bouchet* [1963], *Brutsaert and Stricker* [1979], and *Morton* [1983], see, e.g., *Hobbins et al.* [2001a, 2001b], *Ramirez et al.* [2005], *Szilagyi and Jozsa* [2009], and *Szilagyi et al.* [2009]). The fitted empirical linear lines of *Cheng et al.* [2011] themselves are of little value since they smooth out the interannual variability, the same variability Cheng et al. set out to investigate and which is, indeed, very important for the management and planning of water resources. On the other hand, with the additional (to precipitation, as well as air temperature and global radiation, the latter necessary for obtaining the Priestley-Taylor PET values) measurements of humidity (since the WREVAP program does not require wind velocity measurements, as the AA model) one can immediately capture this interannual variability with the application of the complementary relationship of evaporation. The data displayed in Figures 1 and 2 representing entire watersheds came from single (typically one station per catchment) point measurements of precipitation, air temperature, humidity, global radiation, and wind velocity. Many of these variables are now available as field values, expected to further reduce the variability of the CR-derived ET estimates displayed in Figures 1 and 2. Application of the CR for defining watershed representative ET rates on a monthly, annual or multiannual basis thus require only basic atmospheric and radiation variables without the need of applying remotely sensed or even precipitation or streamflow data. Remote sensing–based global ET estimates may currently contain significant errors when applied at the watershed scale, as was found for the University of Montana ET values [*Mu et al.*, 2011] at the Republican River watershed by the present author where mean annual ET for the 2000–2009 period is underestimated by about 40%.

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