

COMMENT

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This article is a comment on Crago et al. [2016], doi:10.1002/2016WR019753.

Key Points:

- Evaluation of a revised complementary relationship model in estimating land surface evapotranspiration
- The  $x_{min}$  proposed by C16 may lose its physical meaning under the conditions of strong available energy but weak winds
- The Penman-based method is more appropriate than mass-transfer-based method in deriving the  $E_{pads}$  to rescale the CR with  $x_{min}$

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Comment on "Rescaling the complementary relationship for land surface evaporation" by R. Crago et al.

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**Abstract** The generalized complementary relationship (GCR) model of Brutsaert (2015) has been widely applied to estimate land surface evapotranspiration ( $E$ ) over Chinese eastern monsoon region, Loess Plateau and Australia. However, Crago et al. (2016, hereinafter C16) recently noted a deficiency in one of his boundary conditions and proposed a novel approach to improve it. The key of this approach is to determine the ratio ( $x_{min}$ ) of the potential evapotranspiration ( $E_{po}$ ) to the apparent potential evapotranspiration for an entirely dry surface ( $E_{pads}$ ) at which  $E$  tends to be vanishing. As seen, the physically reasonable range of  $x_{min}$  should be between 0 and 1. The present comment reports that the  $x_{min}$  in C16 may become invalid under conditions of relatively strong available energy but weak winds if  $E_{pads}$  is calculated by the mass-transfer-based method, thereby causing unrealistic estimation of  $E$ . A more preferable way to determine  $E_{pads}$  is still based on the traditional Penman-based equation with consideration of the characteristics of dry air in which  $E_{pads}$  occurs.

1. Introduction

Recently, Crago et al. [2016, hereinafter C16] drew attention to one of the boundary conditions of Brutsaert's [2015] generalized complementary relationship (GCR) model, which may be problematic because of an ill-defined physical constraint. That is, the absence of actual evapotranspiration ( $E$ ) does not suggest that the ratio of the potential evapotranspiration ( $E_{po}$ ) to the apparent potential evapotranspiration ( $E_{pa}$ ) approaches zero. The latter is due to, as supposed by Brutsaert [2015], either a diminishing  $E_{po}$  or an infinite  $E_{pa}$ . Owing to solar and wind's natural properties, we agree with C16 that the " $ET_p \rightarrow 0$ " may be questionable since the available energy and the vapor transfer in the atmospheric boundary layer are not infinite. In this way, C16 proposed a maximum value as the upper limit of  $E_{pa}$  (i.e.,  $E_{pads}$ )—"the value  $E_{pa}$  would have if the regional surface was devoid of all moisture"—to normalize  $E_{po}$  as  $x_{min}$ , thereby replacing the low boundary of  $x = 0$  in Brutsaert [2015]; specifically,

$$x_{min} = \frac{E_{po}}{E_{pads}} \tag{1}$$

$$E_{po} = \alpha \frac{\Delta(T_{ws})}{\Delta(T_{ws}) + \gamma} Q_n \tag{2}$$

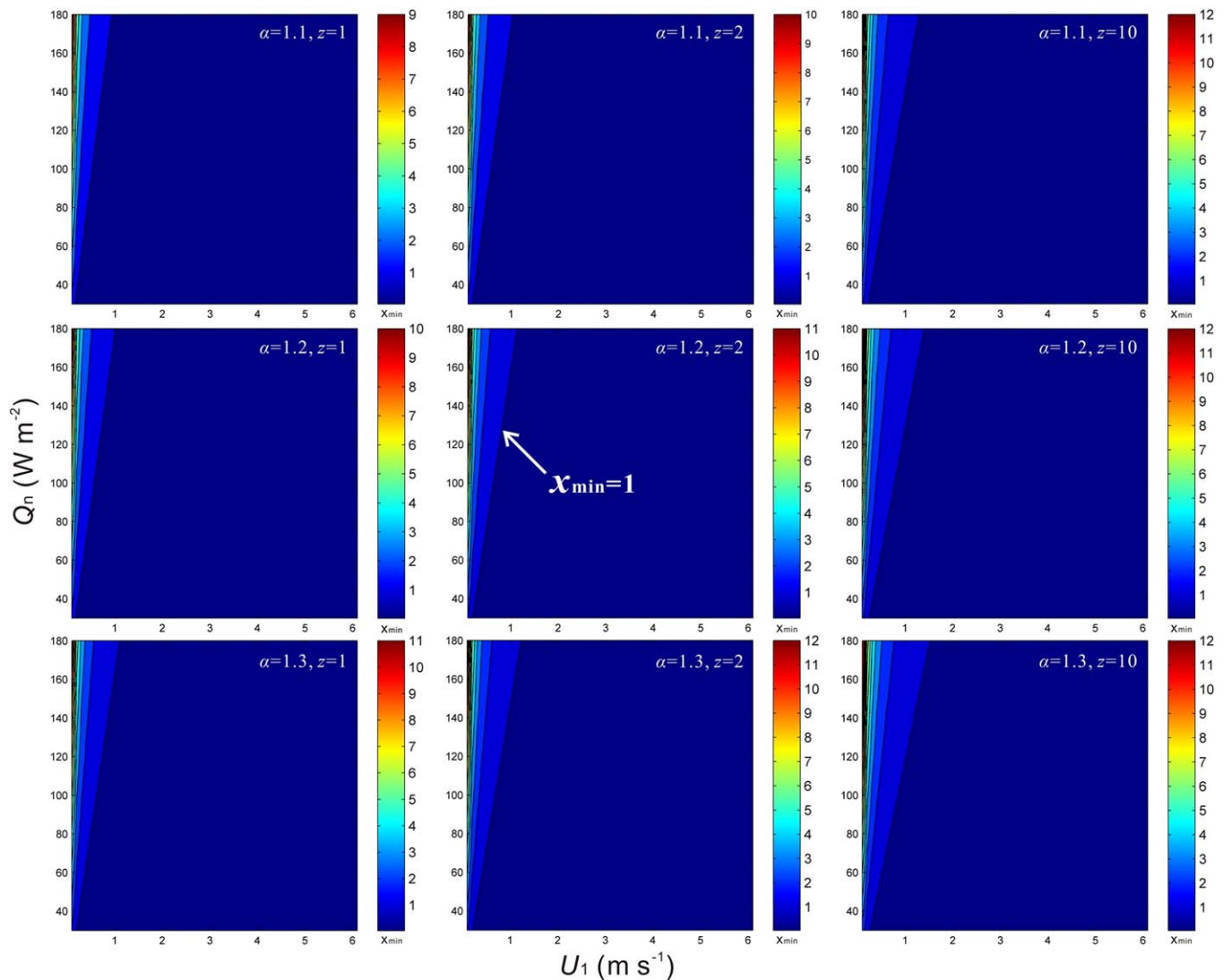
$$E_{pads} = \frac{Le[q^*(T_{ws}) - 0] \rho k^2 U_1}{\ln\left(\frac{z-d_a}{z_{ov}}\right) \ln\left(\frac{z_1-d_a}{z_{om}}\right)} \tag{3}$$

where  $Q_n$  is the available energy that is equal to the net radiation less the ground heat flux. All other variables in equations (1)–(3) have been carefully defined in C16 (notice that all of them are based on a daily scale). In particular, the dimensionless Priestley and Taylor [1972] coefficient  $\alpha$  in equation (2), which typically ranges from 1.1 to 1.32 [Szilagyi et al., 2017], must be calibrated using the measured  $E$  and a given complementary relationship (CR) model, as illustrated in C16 or Brutsaert [2015]. C16 also noted that the height of  $z$  should be low without consideration of atmospheric stability on a daily scale (i.e., neutral conditions). This is valid since equation (3) is derived from the logarithmic profile of wind and humidity within the dynamic sublayer (i.e., entirely turbulent), which normally spans an order of  $10^0$ – $10^1$  m [Brutsaert, 1982, p.54].

## 2. Issue With the Rescaling Using $x_{min}$

By virtue of the invariability of  $T_{ws}$  [Szilagyi and Schepers, 2014],  $E_{pads}$  is the maximum evapotranspiration that would occur from a small wet patch surrounded by a nonpotential environment. Except for the state of exhausted air humidity (i.e., 0) in the present equation, which reflects “no source of moisture”, equation (3) is almost identical to the EP5 of Granger [1989] and the equation (8) (with  $e^*_1$  taken as  $e^*_s$ ) of Crago and Crowley [2005]. Although Granger [1989] stated theoretically that  $EP5 > EP2$ , he did not provide any observational evidence to support it. Further, although C16 noted that “ $E_{po}$  is primarily a function of available energy and  $E_{pads}$  is largely a function of the efficiency of mass transfer”, this does not necessarily mean that  $E_{pads} > E_{po}$  indefinitely, due to their different governing factors. Indeed, as shown below,  $x_{min}$  may be  $\geq 1$  under conditions of weak winds but strong available energy if  $E_{pads}$  is calculated by mass-transfer-based equation (3), which then loses its original physical meaning introduced by C16.

To illustrate, imagine a common homogeneous terrain with a mean plant height of 10 cm, air pressure of 101.3 kPa, and  $T_{ws}$  of 10°C. With the settings above, one can derive  $E_{po}$  and  $E_{pads}$  using given  $Q_n$  and  $U_1$  (for convenience the wind speed at 2 m high is used here) values from either ground measurements or reanalysis data sets. Although it is not easy to determine the upper limit of air flow velocity without any



**Figure 1.**  $x_{min}$  values (equation (1)) under different conditions of available energy ( $Q_n$ ) and 2 m high wind speed ( $U_1$ ), where  $\alpha = 1.1, 1.2$  and  $1.3$  in equation (2), respectively; and  $z = 1, 2$  and  $10$  m in equation (3), respectively. The rightmost isoline in every panel (as exemplified in the center panel) indicates  $x_{min} = 1$ , with the values to the left of this line representing  $x_{min} > 1$ .

information on weather and topography, common sense suggests that  $U_1 \geq 0$ . Besides, a value of  $180 \text{ W m}^{-2}$  for the maximum daily  $Q_n$  over most mid- and low-latitudes is undoubtedly realistic, as evidenced by a variety of in-situ observations [e.g., Baldocchi et al., 2004; Giambelluca et al., 2016; Scott et al., 2004; Timm et al., 2014; You et al., 2017]. Therefore, we uniformly sampled  $Q_n$  in the range of  $30\text{--}180 \text{ W m}^{-2}$  (intervals of  $2.5 \text{ W m}^{-2}$ ) and  $U_1$  in the range of  $0.1\text{--}6.1 \text{ m s}^{-1}$  (intervals of  $0.1 \text{ m s}^{-1}$ ) to calculate all possible  $x_{min}$  values under different  $Q_n$  and  $U_1$  scenarios. (It is worthwhile to emphasize that we are not intended to show how  $x_{min}$  would vary with changes of  $Q_n$  and  $U_1$  since C16 has already assumed that “holding available energy, wind speed, and  $T_{ws}$  constant” in defining  $E_{pads}$ ; rather, our aim is to quantify  $x_{min}$  values for any  $Q_n$  and  $U_1$  combination.)

Considering the possible ranges of  $\alpha$  (equation (2)) and  $z$  (equation (3)) mentioned previously, we directly tested  $\alpha$  values of 1.1, 1.2, and 1.3. In addition to a height of 2 m used by C16, other heights were also examined (i.e.,  $z = 1$  and 10 m) because of possible changes of the dynamic sublayer. Figure 1 shows  $x_{min}$  values under different  $Q_n$  and  $U_1$  conditions. The results in Figure 1 suggest that  $x_{min}$  adopts values  $> 1$  during relatively low  $U_1$  and high  $Q_n$  conditions. Taking  $z = 2$  m and  $\alpha = 1.3$  as an example, a  $U_1 \leq 1 \text{ m s}^{-1}$  would result in a failure of equations (1–3) to represent the minimum realistic value of  $x$  of Brutsaert [2015] as long as  $Q_n > 145 \text{ W m}^{-2}$ . For a given  $U_1$ , the threshold of  $Q_n$ , which yields an  $x_{min} > 1$ , decreases as  $\alpha$  and  $z$  increase. This ultimately causes the calculated  $E$  to become unrealistically negative according to the equation (14) of C16.

### 3. Summary

In short, the present comment is to caution the possible deficiency of using the C16 approach to estimate  $E$ . This is particularly important during summer when the solar radiation usually appears to be intense, while the wind speed does not necessarily behave similarly at the same time. Moreover, given that terrestrial wind stilling is globally widespread [McVicar et al., 2012], one would need to pay more attention on future model application. To clarify, we think it may be safe to implement the new boundary with  $x_{min}$  (equation (1)) in the CR model of C16 for relatively higher wind velocities or much rougher surfaces, which dramatically increase the bulk transfer efficiency.

The primary idea of normalizing  $E_{po}$  for a physically reasonable  $x_{min}$  at which  $E$  approaches zero is to determine the theoretical maximum  $E_{pa}$ . In this context, a more appropriate manner is still applying the Penman-based equation [Penman, 1948] and considering the properties of completely dry air above the evaporating surface, as was done by Szilagyi et al. [2017].

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