Comment on "Revised coefficients for Priestley-Taylor and Makkink-Hansen equations for estimating daily reference evapotranspiration" by N.C. Cristea, S. K. Kampf, and S. J. Burges published in Journal of Hydrologic Engineering, 18(10), 1289-1300

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Abstract: Correlation of the Priestley-Taylor coefficient value, α, with air humidity and wind speed for obtaining evapotranspiration (ET) values similar to those by the Penman-Monteith equation maybe justified from a strictly utilitarian viewpoint in cases when wind measurements are lacking. However, by doing so, a conflict of scale arises, which leaves ample room for incorrect generalization about the behavior of the Priestley-Taylor α value at the original, regional scale, it was designed for. Such improper generalizations are misleading and obstructive to further ET research, as this author experienced more than once (and thus prompting the recent comment) when he was pointed to the work of Cristea et al (2013) on how the PTE α is expected to behave.

Keywords: *Priestley-Taylor equation, Priestley-Taylor coefficient, Penman-Monteith equation, wet-environment evaporation, spatial scale, oasis effect.*

Technical Note

The authors calibrate the single parameter, α (-), of the Priestley-Taylor (1972) equation (PTE)

$$ET = \alpha \frac{\Delta}{\Delta+\gamma} R_n \tag{1}$$

with the help of the FAO-56 version of the Penman-Monteith (PM) equation (Allen et al., 1998) in order to estimate daily reference evapotranspiration. Here ET (mm day^{-1}) is the evapotranspiration rate of an extensive wet surface, R_n is the net radiation expressed in water depth equivalent of mm day^{-1}, γ is the psychrometric constant (hPa K^{-1}), and Δ (hPa K^{-1}) the slope of the saturation vapor pressure curve to be evaluated at the air temperature (T_{wa}) above the wet surface (Priestley and Taylor, 1972).

According to the authors, the rationale of calibrating α is that the PTE does not require wind velocity (u) measurements unlike the PM equation, therefore, after calibration, it may become a more flexible tool than the latter since wind velocities are not measured as widely as more basic meteorological variables, such as air temperature (T_a), humidity, and perhaps solar radiation (R_s). Then the authors regress the obtained α values against air humidity [i.e., relative humidity (RH) and vapor pressure deficit (VPD)] and wind speed. Finally, they create a map of α (as well as RH and u) values across the conterminous U.S. by spatial interpolation.

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The core idea of the paper is a practical one: the application of a simpler equation for performing the job of a more complex and data intensive one. However, two problems with this approach exist. First, the complete overlook of scale, the second which derives from the first, is the room left for incorrect generalizations.

The FAO-56 version of the PM equation was meant to be used in agriculture (hence the Food and Agricultural Organization acronym, FAO), therefore the scale the equation is valid for is the size of the typical agricultural plot, i.e., in the order of a couple of hundred meters. In contrast, the scale the PTE is valid for is at least a magnitude larger, a couple of kilometers to tens or even hundreds of kilometers, depending on how fast the local advection term (i.e., the second term that contains the vapor pressure deficit) of the PM equation approaches zero as one moves along the wet and vegetated land surface and the air becomes closer and closer to saturation (Brutsaert, 1982) due to evaporation from the wet surface. A quote from Priestley and Taylor's original (1972) article: "We shall consider the minimum requirements to be the daily rates ... with a spatial resolution... on the order of several hundreds of kilometers."

Typically, the more humid the climate, the less is the difference in air temperature and humidity between the land and a permanently wet vegetated surface, therefore, the less significant this local advection of hotter and drier air becomes. Then the classical PTE (with its typically employed constant α value of 1.26) yields ET rates close to the PM-calibrated PTE (i.e., α varies by location), as illustrated in Figure 1. Note that with only one single exception, the PM-calibrated PTE ET rates are larger than the corresponding classical PTE ET values.

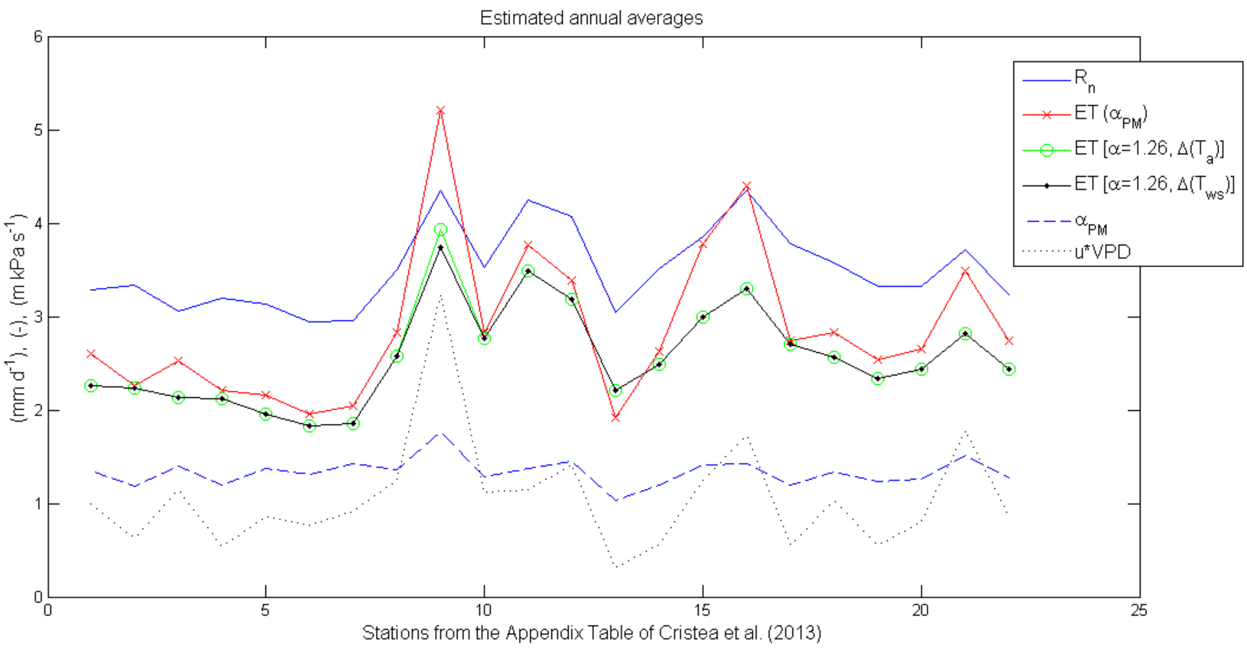

Figure 1 ET rates (mm d^{-1}) of the PTE when a) α was calibrated via RH and u in the FAO-56 PM equation; b) α = 1.26 and Δ is evaluated at T_a; c) α = 1.26 and Δ is evaluated at T_{ws}, provided $T_{ws} < T_a$. T_{ws} is the Szilagyi and Jozsa (2008) estimated wet surface temperature. R_n is in mm d^{-1}, u in m s^{-1}, and VPD in kPa. The product of u and VPD is proportional to the advection term of both the FAO-56 PM and Penman (1948) equations

Figure 1 employs the annual mean values of the Appendix Table of Cristea et al. (2013) in the same station order. R_n was obtained by using the regression equation they provide for Makkink-Hansen C and α, via the solar radiation values of the Table. As the PTE was parameterized under actual wet environmental conditions (Priestley and Taylor, 1972), it expects the wet environment air temperature, T_{wa}, for Δ. However, the PTE is typically employed under drying conditions (as in Figure 1), resulting in that Δ is evaluated at T_a and not at the required T_{wa}. Since the latter is unknown under drying conditions, it can be approximated by the wet surface temperature, T_{ws}, which is easier to estimate than T_{wa} (Szilagyi and Jozsa, 2008; Szilagyi et al., 2009). In more humid climates where the difference in T_a and T_{wa} is typically small, T_{ws} can be larger than T_a. Therefore, in such cases it is better to use the cooler actual air temperature as an estimate of T_{wa} (which is always smaller than T_{ws} under equilibrium-flux conditions). This is the case at 21 out of the 22 stations of Figure 1 (and so the T_a and T_{ws} ET values overlap), except at station #9, in Oasis, California, where $T_{ws} < T_a$. Note that on a daily basis (rather than on an annual mean basis of Figure 1) and especially in the summer when RH is typically smaller, T_{ws} would be more frequently below T_a, and so the two ET rates would differ more.

What is important, however, at the Oasis station is that the PM-calibrated α value yields an ET rate significantly larger than the energy (R_n) available for sensible and latent heat fluxes at the surface. Note that over an extended wet surface the PTE is valid for, equilibrium fluxes develop (Priestley and Taylor, 1972; Brutsaert, 1982), meaning that both latent and sensible heat fluxes are constant with elevation from the ground in the lowest couple of tens of meters at least. This is only possible if both specific humidity and the potential temperature profiles are monotonically decreasing with height above the ground, and both of the resulting fluxes thus are directed from the surface toward the air. From this it follows that the equilibrium latent heat flux must be smaller than the available energy at the surface. What we see at Oasis is that the PM-calibrated α value yields a latent heat flux much larger than the available energy. How is it possible?

It is possible exactly because of the scale the FAO-56 PM equation is valid at and was parameterized for. Namely, in strong local advective conditions, such as those that no doubt exist at Oasis, CA (the name is telling), the ET rate of a wet plot (may the plot be 'extensive' in agricultural term, but still not reaching the scale required by the PTE) is boosted significantly by the advected energy of the hot and drier air of the region. So at Oasis, the PM-calibrated PTE gives a plot-sized ET rate (via an artificially boosted α value) larger than the available energy and thus much larger than the ET rate of a truly expansive wet surface (with the standard α value of 1.26) over which these local advection effects are negligible. Therefore, by tweaking the α value of the PTE, it is possible to estimate plot-sized wet surface ET, but then it must be acknowledged that the PTE is not used as it was intended to be used, and most importantly, one must not generalize the results as if the inflated α values were the norm and that is how the PTE α behaves. What Cristea et al. (2013) do is simply this tweaking of the α value to artificially account for advection effects, the PTE was never meant to be applied for, in fact, it was deliberately derived to exclude such effects. From a strictly utilitarian and practical point of view what they do may be justifiable – since this way one does not need wind velocity values (once α is calibrated for the study region), as one does in the PM equation. But then one should fully recognize and acknowledge what is done in the paper.

From Figure 1 it is evident that whenever energy advection (proportional to u times VPD, since the larger VPD the larger the T_a-T_{ws} difference) peaks, so does the PM-calibrated α value, and also the larger the resulting ET rate becomes in comparison to the constant α case. It is also interesting to note why it is that at Puyallup, WA, close to the cold water of Puget Sound, the opposite is taking place, i.e., the PM-calibrated α value is much smaller than 1.26 (close to unity). It is because here relative humidity is the largest of the stations, and the humid and cool air coming from the sound by the prevalent wind exerts a) a possible negative advection effect by cooling the warmer wet surface and thus suppressing ET, or; b) advection effect is indeed negligible but the FAO-56 PM equation may have been calibrated in predominantly drier and warmer climates (for irrigation purposes) where local energy advection at the plot scale it was designed for is always significant, thus when it is supplied by a significantly depressed VPD value, it undershoots.

The mean ET rate of Figure 1 with the PM-calibrated values is 2.89 mm day^{-1}; by a replacement of the Oasis value with R_n, it becomes 2.85 mm day^{-1}, which is still 10% larger than the constant α = 1.26 case of 2.57 mm day^{-1}. So on average, local energy advection boosted ET rates by about 10% at the stations of Figure 1. But this boost is not even – at dry and hot stations it becomes much larger.

As a consequence, the PM-calibrated α value becomes correlated with air humidity and wind speed [as Cristea et al. (2013) conclude], as it indeed should at the plot scale, for the above reasons. Unfortunately, Cristea et al. (2013) never mention this scale conflict in their work, which leaves ample room for incorrect generalization by other workers about the behavior of the PTE α value at the proper, more regional scale, it was designed for. Such generalizations are misleading and obstructive to further ET research, as this author experienced more than once (and thus prompting the recent comment) when he was pointed to the work of Cristea et al (2013) on how the PTE α is expected to behave.

It is true, however, that the larger than unity α value of the PTE involves certain advection effects, but it is regarded by most workers as largely the result of the entrainment of drier air from the free troposphere into the daytime developing convective boundary layer (Brutsaert, 1982; de Bruin, 1983; Culf, 1994; Lhomme, 1997; Heerwaarden et al., 2009). Local energy advection at the plot scale however should not be washed together with the latter. The former takes place even in the middle of the oceans, while the latter, local advection, mainly over (or near the shore, see sea-land breeze systems) the land along soil moisture gradients.

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