What is the Priestley-Taylor Wet-Surface Evaporation Parameter? Testing Four Hypotheses

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Abstract. This study compares four different hypotheses regarding the nature of the Priestley-Taylor parameter α. They are:
1) α is a universal constant; 2) the Bowen ratio (H/LE, where H is the sensible and LE is the latent heat flux) for equilibrium
15 (i.e. saturated air column near the surface) evaporation is a constant times the Bowen ratio at minimal advection (Andreas et
al., 2013); 3) minimal advection over a wet surface corresponds to a particular relative humidity value, and 4) α is a constant
fraction of the difference from the minimum value of one to the maximum value of α proposed by Priestley and Taylor (1972).
Formulas for α are developed for the last three hypotheses. Weather, radiation and surface energy flux data from 171
FLUXNET eddy covariance stations were used. The condition $LE_{ref}/LE_p > 0.90$, was taken as the criterion for nearly-saturated
20 conditions (where LE_{ref} is the reference and LE_p is the apparent potential evaporation rate from the Penman (1948) equation).
Daily and monthly average data from the sites were obtained. All formulations for α include one model parameter which is
optimized such that the root mean square error of the target variable was minimized. For each model, separate optimizations
were done for predictions of the target variables α, wet surface evaporation (α multiplied by equilibrium evaporation rate) and
actual evaporation (the latter using a highly-successful version of the complementary relationship of evaporation). Overall, the
25 second and fourth hypotheses received the best support from the data.

1 Introduction

On a globe dominated by ocean surfaces, wet surface evaporation has obvious global importance (e.g., Brutsaert, 1982, 2005;
Andreas, 2013; McMahon et al. 2013; Szilagyi et al., 2014; Yang and Roderick, 2019). But estimates of wet surface
evaporation can be valuable over land surfaces as well. For example, the GLEAM evaporation product (Miralles et al., 2011,
30 Martens et al., 2017) uses the Priestley and Taylor (1972) wet surface evaporation equation as the starting point for land surface
evaporation. While climatic influences on wet surface evaporation rates can differ from those on transpiration (e.g.,
Schymanski and Or, 2015), in the GLEAM model, adjustments for water stress are made using a "multiplicative stress factor"

(Martens et al., 2017). Many other models and data products use some form of the Penman (1948) or the related Penman-Monteith equation (Monteith, 1965; Allen et al., 1998; McMahon et al., 2013). The advection-aridity version (Brutsaert and

35 Stricker, 1979) of Bouchet's (1962) Complementary Relationship (CR) between actual and apparent potential evaporation (Brutsaert, 2005) makes use of both the Priestley-Taylor and the Penman equation to estimate actual land-surface evaporation from non-saturated surfaces.

Both the Penman (1948) and the Priestley-Taylor (1972) equation are estimates of potential evaporation, the hypothetical

40 evaporation rate that one would get from a land surface if the surface was saturated (e.g., Brutsaert, 1982; 2005). The Penman equation consists of a radiative term and an advective term. Slatyer and McIlroy (1961) noted that the advective term would be zero if the surface and the lower atmosphere were fully saturated (see further discussion in section 2.1). Evaporation under this condition is known as equilibrium evaporation. The Priestley-Taylor equation multiplies the equilibrium evaporation rate by a factor α (where α >1) to account for the presence of some vapor pressure deficit even under conditions of minimal

45 advection--what Priestley and Taylor (1972) termed "the absence of advection".

Some work regarding α for wet surfaces treated it as a global constant to be found through field experiments (e.g., Priestley and Taylor, 1972). Other work made use of mixed-layer models of the atmospheric boundary layer (ABL), linked to a surface layer model in order to assess the role of ABL development on the value of α (de Bruin, 1983; McNaughton, 1976;

50 McNaughton and Spriggs, 1989; Lhomme, 1997a,b, c.f., Raupach 2000). As a whole, this work suggests that ABL processes result in variability of the value of α. Since Priestley and Taylor (1972) found a single central value for α, such variability could cast doubt on the concept of a minimal-advection, wet-surface evaporation rate that can be reliably estimated. Eichinger et al. (1996) derived an explicit equation for α. Szilagyi et al. (2014) and Yang and Roderick (2019) used global ocean data products to investigate α over the oceans of the world. They found a discernible relationship between α and temperature.

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The context of this work is the estimation of wet-surface evaporation, whether under actually-wet conditions or the hypothetical evaporation rate if an unsaturated surface was actually saturated. Such hypothetical wet-surface evaporation estimates are commonly used, particularly in models based on the CR (e.g., Brutsaert and Stricker, 1979; Szilagyi and Josza, 2008; Crago et al. 2016; Han and Tian, 2018, 2020). In this context, it is not immediately apparent whether formulae derived from wet

60 surfaces will also provide good results from unsaturated surfaces. A different context is sometimes seen in the literature, in which α is essentially a moisture-availability factor (e.g., De Bruin, 1983). This latter use of α will not be further considered here.

The objective here is similar to that of Crago and Qualls (2013), that is, to gain a better conceptual understanding of α. Similar

65 to the limitations applied by Priestley and Taylor (1972), only cases where both sensible and latent heat fluxes are positive will be considered.

Four hypotheses regarding α will be examined:

70   Hypothesis 1: The ratio (α) between wet-surface evaporation under minimally-advective conditions and under equilibrium conditions (i.e., a saturated atmospheric column near the wet surface) is a global constant.

  Hypothesis 2: There is a globally-constant ratio (Andreas et al., 2013; Yang and Roderick, 2019) between: 1) The Bowen ratio that occurs under minimal advection with a saturated surface and 2) the Bowen ratio that would occur under equilibrium 75   evaporation conditions, and α can be derived using this constant ratio.

  Hypothesis 3: There is a globally-constant relative humidity value that can be used to derive an estimate of α that corresponds to minimally-advective conditions

80   Hypothesis 4: The parameter α is a globally-constant fraction of the gap between the minimum value of one and the maximum-allowable value of α proposed by Priestley and Taylor (1972) .

  All four hypotheses will be examined under actually-saturated conditions, but they will also be evaluated under unsaturated conditions. Because there is no measured or reference value for the hypothetical wet-surface evaporation rate, instead the 85   hypothetical rate will be included in a well-tested CR model for actual evaporation. That is, the CR model accuracy will be taken as an indirect measure of the method's ability to estimate the hypothetical wet-surface evaporation rate.

2 Theoretical Background

2.1 Wet surface evaporation equations

Latent heat flux LE (W m^{-2}) is related to evaporation rate E (kg m^{-2} s^{-1}) as $LE=l_vE$, where l_v is the latent heat of evaporation (J 90   kg^{-1}). Penman's (1948) equation for apparent potential evaporation (LE_p) from a wet surface can be written:

$$LE_p = \frac{\Delta}{\Delta + \gamma}(R_n - G) + l_v\frac{\gamma}{\Delta + \gamma}E_A , \qquad (1)$$

where $\Delta=\mathrm{d}e^*/\mathrm{d}T$ (Pa K^{-1}) is evaluated at the air temperature T_a (K) at height z_T (m), e (Pa) is vapor pressure, and e^* (Pa) is saturated vapor pressure, where both e and e^* are calculated using the formulations given by Andreas et al. (2013) which arefi valid for temperatures both above and below freezing. The net radiation is R_n (W m^{-2}), G (W m^{-2}) is the ground heat flux, the 95   latent heat of evaporation, l_v, is also calculated with a formulation given by Andreas (2013), $\gamma=c_pp/(0.622l_v)$ (Pa K^{-1}) is the psychrometric constant, p (Pa) is atmospheric pressure, and c_p is specific heat of air at constant pressure (J kg^{-1} K^{-1}). The

formulae adapted from Andreas et al. (2013) have been included in the Supplement. The drying power of the air E_A (kg m^{-2} s^{-1}) is defined by:

$$E_A = f(u)[e^*(T_a) - e_a]. \qquad (2)$$

100 Where e_a is the vapor pressure at height z_T and $f(u)$ (s/m) is a function of wind speed. The wind function can be calculated (Brutsaert, 1982, 2005, 2015) using Monin-Obukhov Similarity theory (MOS theory):

$$f(u) = \frac{0.622 \, k^2 u}{R_d T_a ln[(z_T - d_0)/z_{0v}] ln[(z_u - d_0)/z_0]} , \qquad (3)$$

where k=0.4 (dimensionless) is von Karman's constant, R_d (J kg^{-1} K^{-1}) is the ideal gas constant of dry air, u (m s^{-1}) is wind speed measured at height z_T, d_0 (m) is the displacement height, and z_0 (m) and z_{0v} (m) are the roughness lengths for momentum

105 and sensible heat, respectively. Equation (3) is based on MOS theory, the standard formulation of flux-gradient relationships in the lower atmosphere (Stull, 1988, Brutsaert, 2005), but Penman (1948) recommended the form $f(u)=c_1(1+c_2 u_2)$ where c_1 and c_2 are empirical constants and u_2 (m s^{-1}) is wind speed at 2 m (m s^{-1}). This latter formulation (not used here) is preferred by some authors (e.g., Szilagyi et al (2019)) because information about the roughness of the surface (needed for z_0, z_{0v} and d_0) is not needed.

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Note that other versions of LE_p are available, including one (e.g., Qualls and Crago, 2020; Crago and Qualls, 2021) which is based on the surface energy budget with mass and energy transport functions for the latent and sensible heat fluxes, respectively. While (1)-(3) are based on the same principles, Penman's (1948) derivation involved his well-known approximation that Δ for a wet surface is approximately equal to the ratio of the difference in vapor pressure between the

115 surface and measurement height to the difference in temperature between the same two levels, which allowed the simple two-term equation (1). Only (1) will be used for LE_p in this project.

As described by Brutsaert (1982, 2005), air in the lowest layers blowing for a long distance over a wet surface would likely become increasingly humid. If it should approach saturation, the second term of (1) would go to zero, leaving the first term of

120 (1) as an effective lower limit for wet-surface evaporation; Slatyer and McIlroy (1961) termed this equilibrium evaporation (Brutsaert, 2005). Here, this lower limit LE_e (W m^{-2}) is calculated as:

$$LE_e = \frac{\Delta_{T0}}{\Delta_{T0} + \gamma} (R_n - G) . \qquad (4)$$

where Δ_{T0} is Δ evaluated at the wet surface temperature T_0 (to be defined shortly). While (4) is often written with Δ calculated at T_a, (4) corresponds to the definition of equilibrium evaporation suggested by Andreas et al. (2014) and Qualls and Crago

125 (2020). It is the lowest wet-surface evaporation rate possible for a given available energy value (R_n-G) with a surface temperature of T_0 (K). It is a minimum because lower evaporation rates would require the vapor pressure to exceed the saturation value (e.g., Philip, 1987; Andreas et al., 2013; Qualls and Crago, 2020). The fact that super-saturation cannot occur

during evaporation explains why wet surface evaporation is limited by (4) rather than simply by (R_n-G) (see Qualls and Crago, 2020). The Bowen ratio (Bo=H/LE; dimensionless) corresponding to (4) is $Bo^* = (R_n\text{-}G\text{-}LE_e)/LE_e$.

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Priestley and Taylor (1972) found that (4) nearly always underestimates the actual minimum-advection evaporation rate over saturated surfaces. They introduced the parameter α (dimensionless) so that:

$$LE_{PT} = \alpha LE_e \ , \qquad (5)$$

Where LE_{PT} (W m^{-2}) estimates minimum advection, wet-surface latent heat flux. Their data suggested that α is around 1.26.

135   Because $LE_{PT} \geq LE_e$ and $H \geq 0$, the limits on α are (Priestley and Taylor, 1972):

$$1 \ \leq \ \alpha \ \leq \ 1 + \frac{\gamma}{\Delta_{T0}} \qquad (6)$$

Hypothesis 1 suggests that (5), with α a global constant, defines minimal-advection wet-surface evaporation.

Andreas et al. (2013) examined thousands of measurements taken over extensive water and ice surfaces for which H>0 and

140   LE>0 and suggested that Bo is related to Bo^* by:

$$Bo = a_A Bo^* \, , \qquad (7)$$

where a_A (dimensionless) was found to be a global constant of about 0.4. This is equivalent to a Priestley-Taylor α of:

$$\alpha_A = \frac{\Delta_{T0} + \gamma}{\Delta_{T0} + a_A \gamma} \quad . \qquad (8)$$

In (8), a_A is a constant, and Δ is a function of the skin temperature T_0 so that a discernible relationship between α and T_0 is

145   implied by (8) (c.f., Szilagyi et al., 2014). Hypothesis 2 suggests that (8) captures the foundational concept of α.

Yang and Roderick (2019) made a similar proposal to (7), resulting in a_A=0.24 based on global ocean data products. However, they noted that, in practice, LE and R_n cannot be known independently of each other over oceans, since increased LE reduces the ocean surface skin temperature, which reduces outgoing longwave radiant fluxes, thereby increasing R_n. Their value of a_A

150   accounts for adjustments in the available energy resulting from this linkage. The present study assumes that R_n is known via measurements at each site.

Eichinger et al. (1996) had already proposed a dimensionless variable C=[$e^*(T_a)$-e_a]/[$e^*(T_0)$-e_a] for use in an explicit method (their equation 7) to estimate α for wet surfaces. Plans to include an additional hypothesis based on their equation (7) in this

155   study were abandoned when it became apparent that their C (taken as a constant model parameter rather than calculated with the definition given in the previous sentence) is mathematically-equivalent to (1-a_A). While we will refer to (8) as the Andreas et al (2013) formula, we acknowledge the prescient contribution of Eichinger et al. (1996).

As an alternative to (8), if there is minimum advection over a wet surface, both (1) and (5) should give the correct evaporation
160 rate. By setting them equal to each other, one arrives at:

$$\alpha_{RH} = 1 + \left(\frac{\gamma}{\Delta_{T0}}\right)\frac{l_v f(u) e^*(T_0)(1 - RH)}{R_n - G}.$$ (9)

where RH (dimensionless) is the relative humidity of the air and α_{RH} is dimensionless. The values of l_v, Δ_{T0} and e^* could all be
evaluated at the wet surface skin temperature T_0. Equation (9) gives the correct value of α within the accuracy of Penman's
(1948) assumption regarding Δ, provided RH is the measured relative humidity. However (9) is proposed here as a
165 parameterization of α for both actually- and hypothetically-saturated surfaces, where RH is the model parameter representing
the relative humidity under saturated surface and minimal advection conditions. Small values of (R_n-G) could result in
unreasonably-large values of α. Therefore, the limits given by (6) are applied to estimates of α_{RH}. That is, if $\alpha_{RH} > 1+\gamma/\Delta$, it is
set to $1+\gamma/\Delta$, and if $\alpha_{RH} < 1$, then it is set to 1.

170 The limits on α given by (6) suggest that perhaps α takes a constant intermediate position in between the limits. Thus, the
parameter m (dimensionless) is:

$$m = \frac{\alpha - 1}{\left(1 + \frac{\gamma}{\Delta_{T0}}\right) - 1}$$ (10)

Or,

$$\alpha = 1 + m\frac{\gamma}{\Delta_{T0}}.$$ (11)

175 Hypothesis 4 suggests that (11) is the best explanation of α.

Szilagyi and Jozsa (2008; see also Szilagyi and Schepers, 2014; Szilagyi et al., 2017) suggested T_0 could be found by setting
two expressions for the Bowen ratio equal to each other:

$$\frac{H}{LE_p} = \frac{R_n - G - LE_p}{LE_p} = \gamma\frac{T_0 - T_a}{e^*(T_0) - e_a}.$$ (12)

180 With (12), the wet surface temperature is T_0, which can be easily found with a numerical root finder. Equation (12) can find
the wet surface temperature T_0 from data taken from either saturated or unsaturated surfaces.

2.2 The Complementary relationship (CR) of Evaporation

In the Complementary Relationship (CR) between actual and potential evaporation (Bouchet, 1962), regional evaporation from
185 a saturated surface, the apparent-potential evaporation rate, and the actual evaporation rate are all identical (Brutsaert, 2015).
According to the advection-aridity approach (Brutsaert and Stricker, 1979), apparent potential evaporation corresponds to the
Penman equation (1) and the wet regional surface rate corresponds to the Priestley and Taylor (1972) equation (5). As the

surface dries, less water is available to evaporate, so actual evaporation decreases. This results in a drier lower atmosphere, which increases apparent potential evaporation. Thus, evaporation and apparent potential evaporation change in opposite directions—they complement each other.

As formulated by Brutsaert (2015), the CR can be formulated in terms of $x=LE_w/LE_p$ and $y=LE/LE_p$, where LE_w is given by (5) and LE_p by (1)-(3). Both x and y are dimensionless. Values of α to be used in (5) will be discussed in Section 3. Brutsaert (2015) used physical reasoning to suggest that at $x=0$, the boundary conditions are $y=0$ and $dy/dx=0$, while at $x=1$, they are $y=1$ and $dy/dx=1$. He used these boundary conditions to derive:

$$y_B = 2x^2 - x^3. \qquad (13)$$

where y_B is an estimate (i.e., y_{est}) of y. Crago et al. (2016) noted that y can approach zero when there is no water available to evaporate, but x cannot approach zero unless LE_w goes to zero. The smallest x can get is:

$$x_{min} = \frac{LE_w}{LE_{pmax}}, \qquad (14)$$

where LE_{pmax} (W m^{-2}) is given by

$$LE_{pmax} = \frac{\Delta_d}{\Delta_d + \gamma}(R_n - G) + l_v \frac{\gamma}{\Delta_d + \gamma} f(u)e^*(T_d). \qquad (15)$$

In (15), the subscript "d" means the variable is evaluated at T_d, the "dry air temperature" at which the isenthalp passing through (T_a, e_a) reaches $e_a=0$ (Szilagyi et al., 2017; Crago and Qualls, 2021). That is,

$$T_d = T_a + \frac{e_a}{\gamma} . \qquad (16)$$

Crago et al. (2016) suggested x could be "rescaled" through the transform:

$$X = \frac{x - x_{min}}{1 - x_{min}} \qquad (17)$$

Crago et al. (2022) considered several formulations for the CR. One formulation took the form of equation (13), but with X as the independent variable rather than x. Another formulation took the form:

$$y = X \qquad (18)$$

Crago et al. (2022) considered data from seven FLUXNET sites in Australia as well as global, gridded ERA5 data (Hersbach, 2020) produced by ECMWF (European Center for Medium-Range Weather Forecasts; https://www.ecmwf.int/). With the FLUXNET data, (18) consistently performed best at predicting reference (eddy covariance) latent heat fluxes while the version using (13) with x replaced by X performed best with the ERA5 data. Since FLUXNET data are used here as well, (18) will be the assumed CR formula for this study.

Equations (1) through (5) and CR methods are generally considered applicable at time scales ranging from daily to monthly, with monthly being most common (McMahon et al., 2013). Equations (1) through (5) require homogeneous surfaces

corresponding to the spatial extent of the flux footprint (e.g., Schuepp, 1990), typically corresponding to several hundred
220 meters, while CR formulations are best suited for homogeneous conditions at the "regional" scale (Brutsaert, 2005) of perhaps
tens of km.

3 Methodology

3.1 Data sources and processing

225 Monthly- and daily-average data pre-processed by FLUXNET were downloaded as csv files from their web site (fluxnet.org)
for 171 eddy covariance stations (listed in Table S1). At least minimally-adequate fetches are assumed at all sites included in
FLUXNET. Measurement heights, latitudes, longitudes, IGBP land classes (www.igbp.net), and canopy heights were provided
for these sites by Wang et al. (2020; see their supporting information). Wang et al. (2020) assumed $z_0=0.123h_c$, $d_0=0.67h_c$, and
$z_{0v}=0.1z_0$, where h_c (m) is the reported canopy height. These values were all adopted herein. Separate wind speed, temperature
230 and humidity measurement heights were not included by Wang et al. (2020), so it is assumed here that they are all measured
at the single given height. Net radiation, ground heat flux, sensible and latent heat fluxes, air pressure, air temperature, vapor
pressure deficit, and wind speed were included in the FLUXNET downloads. All variables employed some gap filling using
the MDS [Marginal Distribution Sampling (Reichstein, 2005)] method as described by Pastorello et al. (2020). Data flagging,
quality assurance and control for all the variables also followed the procedures outlined by Pastorello et al. (2020).

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The sensible and latent heat flux values used are also gap-filled using the MDS (Reichstein, 2005) method. The FLUXNET
dataset includes the variables "H_CORR" and "LE_CORR", which indicate corrected values, that is, values that correspond
to energy budget closure. However, the corresponding uncorrected variables ("LE_F_MDS" and "H_F_MDS") are available
for more sites and times. These latter surface fluxes were used for this study. Issues regarding energy budget closure with eddy
240 covariance fluxes are complicated, as discussed by Mauder et al. (2020). In this study, the downloaded values of sensible heat
flux are taken to be the final reference values H_{ref}, while downloaded latent heat flux values are adjusted so that monthly (or
daily for the daily averaging time) energy budget closure is obtained: $LE_{ref}=(R_n-G)-H_{ref}$. This was the procedure recommended
by Wang et al. (2020) who supplied the information found in the supplement. Only data for which monthly (or daily) $H_{ref}>0$,
$LE_{ref}>0$, and $R_n-G>0$ were further analysed; this eliminates periods of strong dry advection that result in negative H_{ref}. The
245 ground heat flux G was not measured at all for some of the sites, and missing values of G also occurred. When measurements
of G were not available, a value of zero was assumed. Over a 24-hour period, G "is often near zero" (Stull, 1988), so this
assumption is not unreasonable. Over the daily to monthly time-scales at which (1) and (5) are commonly used (McMahon,
2014) the assumption likely improves as the averaging time increases.

250 The decisions described above regarding data inclusion, screening, and correction reflect a desire to obtain a broad range of climates, land covers, and seasons, so as to test the four hypotheses under as wide a range of conditions as possible. While these decisions do entail some risk of including lower quality data, we think they are defendable as outlined above.

Eleven different IGBP land surface classes (e.g., Loveland et al., 1999) are in the original data. They include: Wooded

255 Savannas (WSA); Grasslands (GRA); Evergreen Broadleaf Forests (EBF); Crops (CRO); Evergreen Needleleaf Forests (ENF); Savannas (Sav); Deciduous Broadleaf Forests, (DBF); Closed Shrublands (CSH); Mixed Forests (MF); Open Shrublands (OSH); and Permanent Wetlands (WET). Classes for each site were provided by Wang et al. (2020).

3.2 Estimates of wet surface α

Saturated or nearly-saturated land surface conditions were assumed when $LE_{ref} > T*LE_p$ where T (dimensionless) is a threshold

260 value which had to be determined. A value of T was found such that the linear regression between LE_{ref} and LE_p (for data for which the condition above is met) falls nearly on the one-to-one line, and at the same time root mean square (RMS) errors between LE_{ref} and LE_p are very small.

Trial values of the parameters α_c, a_A, RH, and m, where α_c is a constant (global) value of α were selected randomly (chosen

265 within a realistic range of values) and used at all sites and times where the condition $LE_{ref} > T*LE_p$ was satisfied. Parameter values were used to estimate α_{est}: α_c; α_A from (8); α_{RH} from (9); and α_m from (11). These estimates were compared to $\alpha_{ref} = LE_{ref}/LE_e$. Trial parameter values that minimized the RMS difference between α_{est} and α_{ref} were considered optimal.

3.2 Estimates of wet surface evaporation

Random parameter values were also chosen to estimate α_c, α_A, α_{RH}, and α_m for use in (5) to estimate $LE_{est} = \alpha LE_e$, where α is

270 estimated from the parameter values using (8), (9), and (11). This was done for all sites for which the condition $LE_{ref} > T*LE_p$ was satisfied. Optimal parameter values were those giving minimum RMS difference between the resulting LE_{est} and LE_{ref}. The same optimal parameter values were used for all stations and all times.

3.3 Complementary relationship

New parameter values were determined for use in the CR. Again, random parameter values were used to find optimal values

275 for the parameters α, a_A, RH and m. Parameter values were substituted into (8), (9) or (11), and were used to calculate estimates of α. Those values were used in (1) through (5) along with (15) through (17) in the equation $y=X$, and finally in $LE_{est} = y*LE_p$. The rms error between LE_{est} and LE_{ref} was found. Parameter values (and LE_{est} estimates from them) which minimized the rms error were saved as the best estimates.

4 Results

280 For monthly averaging times, the wet surface threshold was established to be *T*=0.90, which resulted in a regression equation with slope of about 1 and intercept very near 0, while RMS errors were small (Figure 1, panel 3). The process by which this value of T was established is described using Figure 1, and the corresponding statistics for monthly and daily data are found in Table 1. The second row of text in each panel identifies the range of LE_{ref}/LE_p values incorporated into the graph. If the lower limit of accepted values was *T*, then in the left column (panels 1, 3, and 5) an upper limit of 2-*T* was imposed. In the

285 right column (panels 2, 4, and 6) no upper limit was imposed (as indicated by an upper limit denoted '-'). There seems to be no compelling reason to impose an upper limit on wet-surface LE_{ref}/LE_p, even though the upper limit improved many of the statistics (i.e., comparing panel 1 to 2; 3 to 4, and 5 to 6). In the right column, panel 2 has a slope somewhat below 1 and panel 6 has a large RMS difference. Panel e, where all points with LE_{ref}/LE_p>0.95 were included was taken as a reasonable compromise. As shown in panel 4, wet surface evaporation defined in this way occurred on 430 months and from 50 of the

290 sites. The sites included IGBP classes CRO, ENF, GRA, DBF, WET, OSH, and EBF. For daily averaging times, a similar process was followed (statistics included in Table 1). Wet surface evaporation (defined again by T=0.90) occurred on 22998 days, involving 158 of the 171 stations and included IGBP classes WSA, GRA, EBF, CRO, ENF, SAV, DBF, CSH, OSH, WET and MF. Figure 2 shows the location of sites having at least one month of wet surface measurements (top panel) and those having none (bottom panel).

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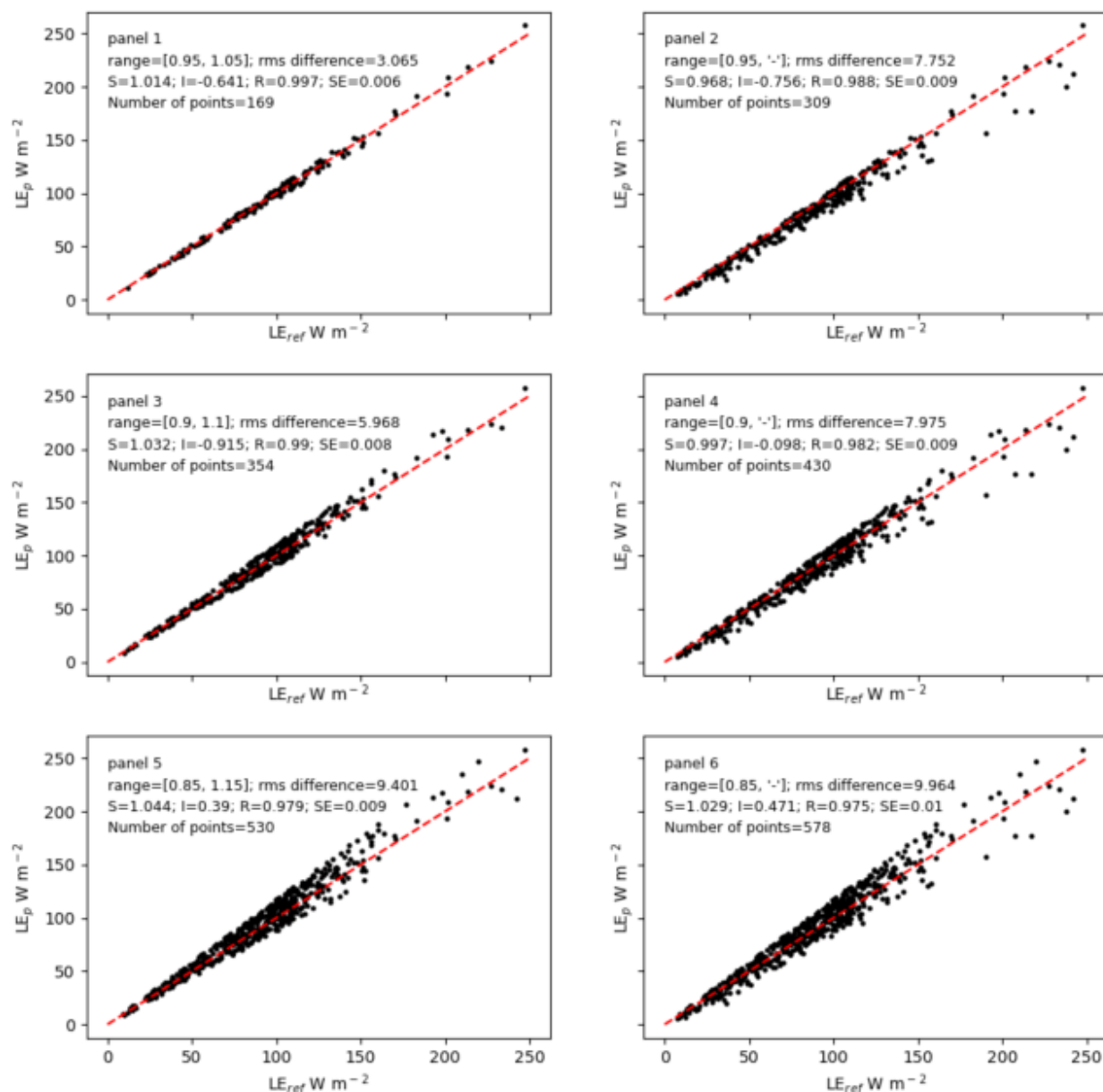
Figure 1. Comparison of reference values to estimates from equation (1) for various threshold (T) values to define wet surface conditions. The left column applies both upper and lower limits on LE_{ref}/LE_p, while the right column applies only a lower limit. Panel 4 was taken as the best compromise among large numbers of points, regression slopes and intercepts near zero, and low rms differences. A total (panel 4) of 430 months of wet surface evaporation were identified. The red line is one-to-one and the black line is the linear regression. 'rms' is root mean square error, R is correlation coefficient, and S and I are the slope and intercept in the linear regression equation.

Table 1. Results of regression between LE_p and LE_{ref} for various ranges of LE_{ref}/LE_p

Averaging time	Range of LE_{ref}/LE_p	No. points	R [1]	Slope [1]	Intercept [1] (W m^{-2})	NSE [1]	RMS [1] (W m^{-2})
Monthly	0.95-1.05	169	.997	1.014	-0.641	0.994	3.1
Monthly	0.90-1.10	354	0.99	1.032	-0.915	0.977	6.0
Monthly	0.85-1.15	530	0.979	1.044	0.39	0.946	9.4
Monthly	0.95-	309	0.988	0.968	-0.756	0.968	7.8
Monthly	0.90-	430	0.982	0.997	-0.098	0.964	8.0
Monthly	0.85-	578	0.975	1.029	0.471	0.946	10.0
Daily	0.95-1.05	7126	0.998	1.007	-0.202	0.996	3.0
Daily	0.90-1.10	14396	0.993	1.021	-0.406	0.985	6.2
Daily	0.85-1.15	21210	0.986	1.044	-0.744	0.968	9.4
Daily	0.95-	18456	0.983	0.961	-3.446	0.948	11.2
Daily	0.90-	22986	0.981	1.000	-3.648	0.957	10.8
Daily	0.85-	27796	0.977	1.036	-3.621	0.953	11.7

305   [1] R: correlation coefficient; Slope, Intercept: S and I in $LE_p=S*LE_{ref}+I$; NSE: Nash-Sutcliffe efficiency; RMS: root mean square difference.
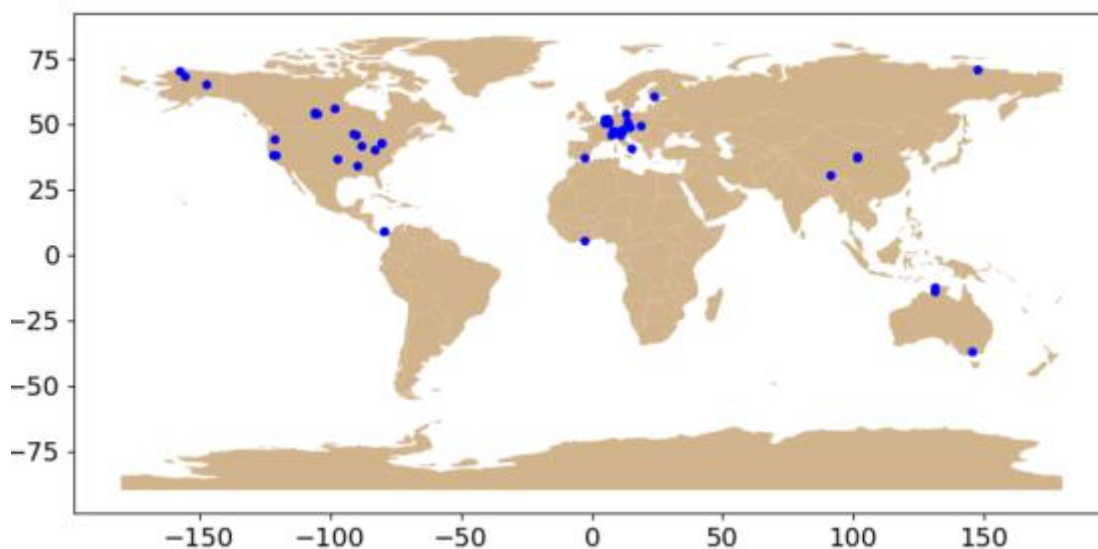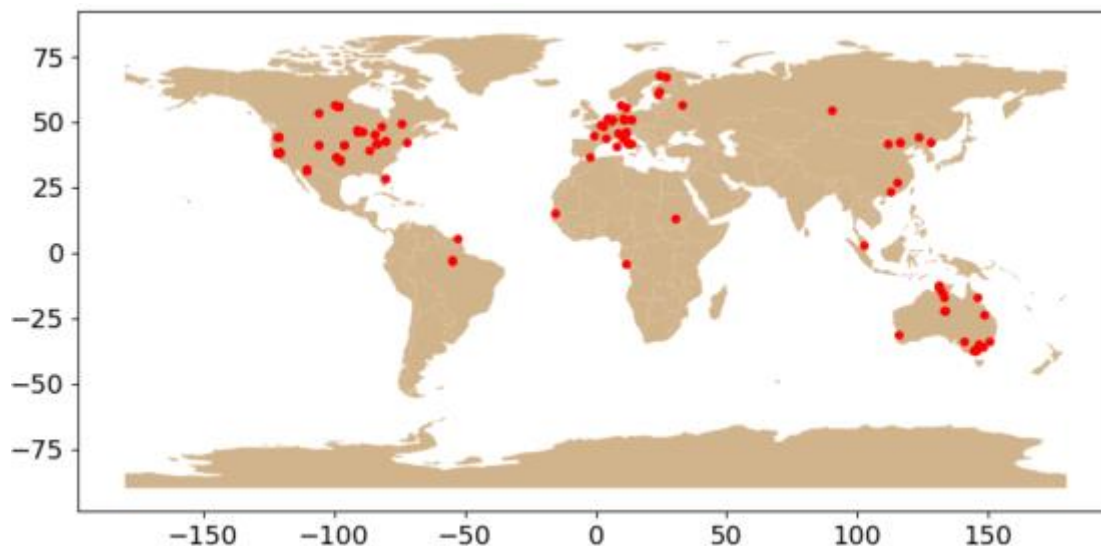
Figure 2. Global distribution of sites with some monthly measurements classified as wet surface evaporation (top
310   panel) and those with no wet surface values (bottom panel). For daily average data, many more sites had some days
of wet surface evaporation, so for daily averaging, the top panel would have more data point and the bottom panel
fewer. The 'naturalearth_lowres' basemap provided by geopandas (geopandas.org) is shown.

Using only wet-surface measurements, values of α_c, a_A, RH, and m were found that minimized RMS error between reference
315   and predicted values of α as described in Section 3. Optimal values of these parameters were also found for use in estimating
wet surface evaporation using the Priestley-Taylor equation (5). Results for estimating α under wet-surface conditions are
found in the top panel of Figure 3, and results for estimating wet surface evaporation itself are shown in the bottom panel as
well as in Table 2. Finally, optimal values of α_c, a_A, RH, and m were found which minimized RMS error when LE is calculated
using the CR formulation (18), where LE_{est} is found by taking y found with (18) and multiplying it by LE_p from (1). Results
320   using monthly data are shown in Figure 4, with further results (for daily averaging times) shown in Table 3.
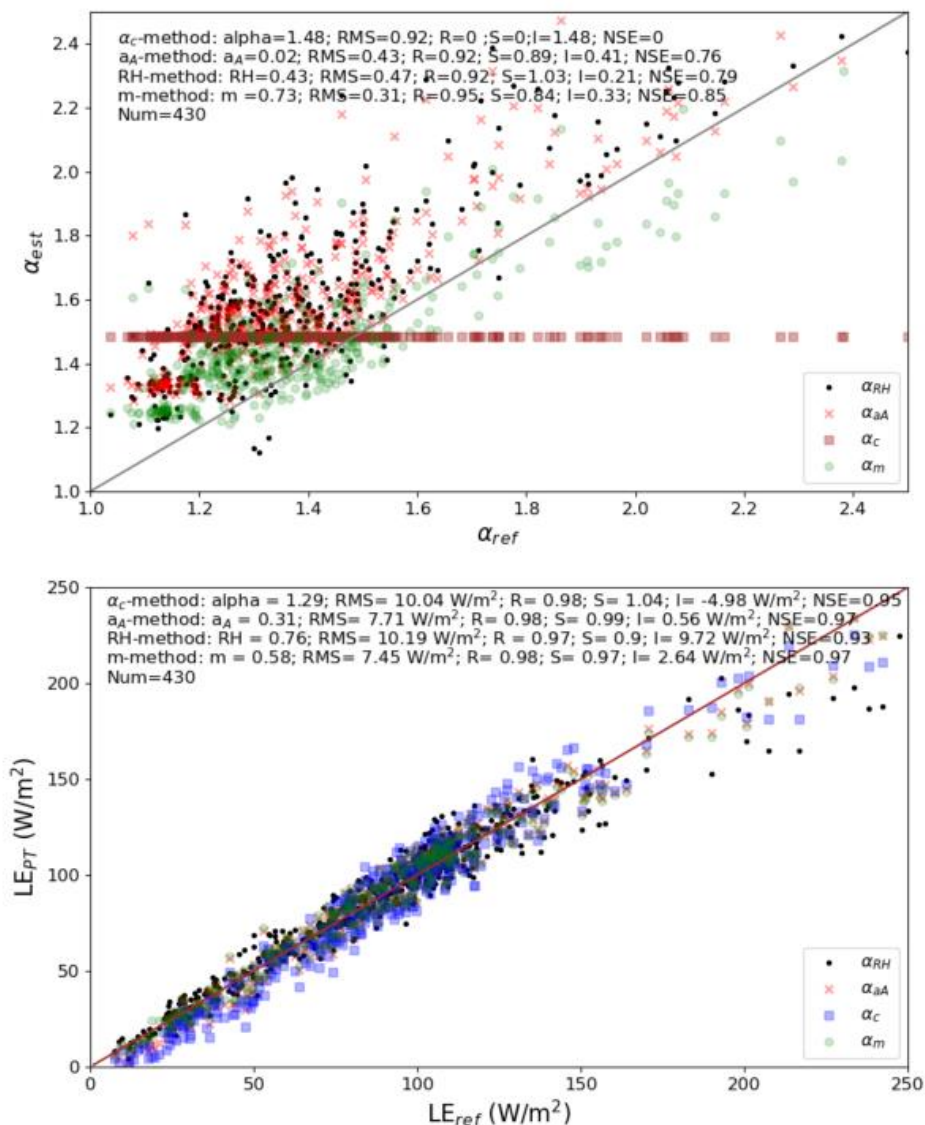
Figure 3. Results for monthly estimates of α and of nearly-wet-surface *LE*. Parameter values and statistics are included at the top of each graph. RMS is root mean square error, R is correlation coefficient, NSE is the Nash-Sutcliffe efficiency, and *S* and *I* are the coefficients in the linear regression equation.
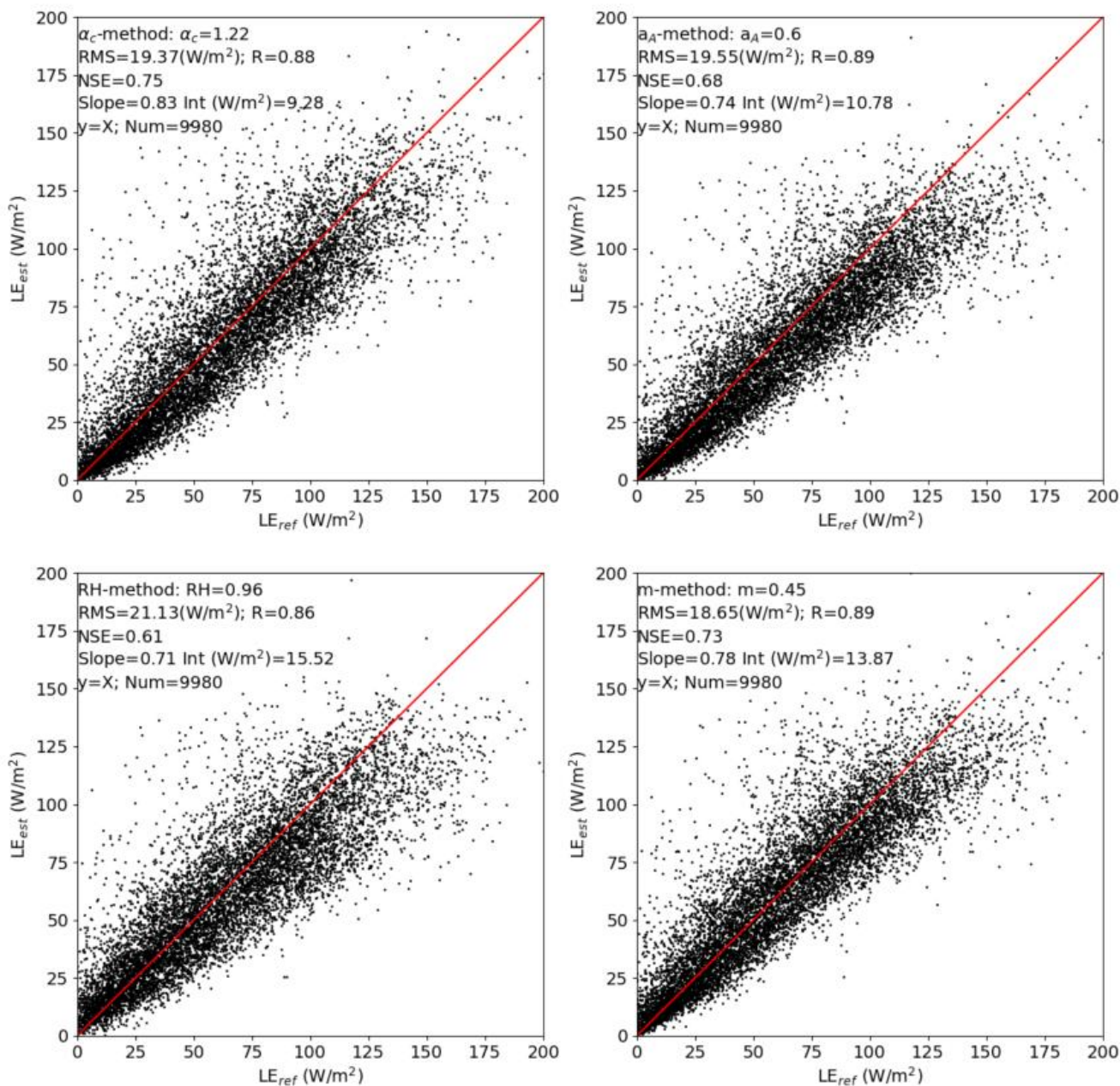
Figure 4. Results for monthly estimates of LE_{ref} using the CR. Parameter values and statistics are included at the top of each graph. RMS is root mean square error, R is correlation coefficient, and Slope and Int are the coefficients in the linear regression equation $y=Slope*x+Int$, where x is LE_{ref} and y is LE_{est}. Num is the number of data points included. All IGBP classes are in the dataset are included.

Table 1. Summary of results for monthly data (309 wet surface days; 9980 days total)

Method	Optimized variable	Parameter value	RMS error	R	S	I	NSE
α_c	α	1.48	0.92	0	0	1.48	0
α_A	α	0.02	0.43	0.92	0.89	0.41	0.76
RH	α	0.43	0.47	0.92	1.03	0.21	0.79
m	α	0.73	0.31	0.95	0.84	0.33	0.85
			W/m^2			W/m^2	
α_c	LE_w	1.29	10.04	0.98	1.04	-4.98	0.95
α_A	LE_w	0.31	7.71	0.98	0.99	0.56	0.97
RH	LE_w	0.76	10.19	0.97	0.9	9.72	0.93
m	LE_w	0.58	7.45	0.98	0.97	2.64	0.97
			W/m^2			W/m^2	
α_c	*LE*	1.22	19.37	0.88	0.83	9.28	0.75
α_A	*LE*	0.6	19.55	0.89	0.74	10.77	0.68
RH	*LE*	0.96	21.13	0.86	0.71	15.54	0.61
m	*LE*	0.45	18.65	0.89	0.78	13.86	0.73

335   Table 2. Summary of results for daily data (22998 wet surface days; 276020 days total)

Method	Optimized variable	Parameter value	RMS error	R	S	I	NSE
α_c	α	1.58	1.31	0	0	1.58	0
α_A	α	0.01	0.59	0.92	0.92	0.44	0.79
RH	α	0	0.93	0.75	0.65	0.84	0.34
m	α	0.71	0.42	0.95	0.87	0.3	0.87
			W/m²			W/m²	
α_c	LE_w	1.29	12.65	0.97	1.03	-5.27	0.94
α_A	LE_w	0.31	9.45	0.98	1	0.05	0.97
RH	LE_w	0.74	12.43	0.97	0.93	7.96	0.93
m	LE_w	0.58	9.01	0.98	0.97	1.94	0.97
			W/m²			W/m²	
α_c	LE	1.18	25.03	0.86	0.76	14.16	0.66
α_A	LE	0.6	24.89	0.86	0.71	15.46	0.61
RH	LE	0.97	26.67	0.84	0.66	18.69	0.51
m	LE	0.36	24.81	0.86	0.72	17.39	0.63

5 Discussion

5.1 General trends

340   For convenience, the use of α with a single global value will be called the "α_c-method" (corresponding to Hypothesis 1), with (8) it will be the "a_A-method" (Hypothesis 2), with (9) it will be the "RH-method" (Hypothesis 3), and with (11) it will be the "m-method" (Hypothesis 4). After discussing trends found in the results, the five hypotheses will be evaluated based on the results.

345   Figure 1 shows that LE_{ref} and LE_p (1) are very similar when the threshold for wet surfaces at a monthly time scale is taken to be $T=LE_{ref}/LE_p=0.90$. For daily data the same threshold provides good results, with low RMS error and linear regression close to the one-to-one line (statistics provided above in Section 4).

Figure 3 gives the results from the four methods in terms of prediction of α itself (top panel) and in wet surface evaporation
350   estimates from (5) (bottom panel). Results from the use of the four methods when used in the CR model $y=X$ are shown in Figure 4. Even when estimates of α differ considerably from the reference values (Figure 3, top panel), the methods still

provide good estimates of wet surface evaporation (LE_w—Figure 3 bottom panel) and actual evaporation (Figure 4). Table 2 provides similar data to Figures 3 and 4 (for monthly averaging), while Table 3 provides similar information for daily averaging. Because a large number of FLUXNET sites with a wide range of climates and land cover classes were included in

355   this study, the results from this study are likely to be relatively robust.

In Tables 2 and 3, note that the parameter values that optimize estimation of α can be quite different from the values needed to optimize estimates of wet surface evaporation (Figure 2 bottom panel) and also from values needed to optimize evaporation estimates under all moisture conditions using the CR (18). This is a result of the formulations being non-linear. However, it

360   means that parameter values (α_c, a_A, RH, and m) that provide the best estimate of α or of LE_w will not necessarily be optimal for use in the CR (18). Context is important.

There are three separate reasons why a particular estimate LE_{est} using the CR (18) might differ from the LE_{ref} values: First, α may not be estimated correctly; second, the LE_{PT} estimate LE_{est} may not adequately represent the hypothetical wet-surface

365   evaporation rate; and third, CR formulation may be inadequate.

Figures 3 and 4 and Tables 2 and 3 provide evidence that all four methods provide acceptable estimates of actual wet surface evaporation rates. But what about estimation of hypothetical wet surface evaporation rates? Szilagyi and Jozsa (2008) and Szilagyi and Scheppers (2014) have provided good evidence that a small wet patch within a drying region with wind speed

370   and available energy held constant should maintain a constant surface temperature. The use of (12) to get the temperature of an actually-saturated region is straightforward. Crago and Qualls (2021), Qualls and Crago (2020) and Szilagyi (2021) show graphically, using e versus T graphs, how air and ground-surface iso-enthalps can be determined, and they show that T_0 is simply the intersection of the ground-surface iso-enthalp with the saturation vapor-pressure curve.

375   Under drying surface conditions, since the wet surface temperature remains constant during drying (Szilagy and Scheppers, 2014), T_0 found with (12) under drying conditions should be the correct wet surface temperature, that is, the temperature at which (5) should be evaluated to estimate the hypothetical wet surface evaporation rate. During the regional drying process, Crago and Qualls (2021) showed that e_a slides down the air iso-enthalp as drying progresses, while T_0 is found just as it would be for a saturated surface, namely using (12). So, use of (12) to determine T_0 for either saturated or unsaturated surfaces seems

380   to have good support, and this T_0 value can be used to predict wet surface evaporation rates from (5) with (4). With respect to the best formulation for the CR, there is unfortunately no consensus regarding the best formulation (e.g. Crago et al. 2022, Han and Tian, 2018). However, with FLUXNET data from Australia, Crago et al. (2022) found that the $y=X$ formulation was the best overall for predicting latent heat fluxes under many conditions. Given the wide range of methods represented in Figures 3 and 4, it is actually striking how little variation there is among the various methods with respect to rms errors.

385

Comparison of the four methods associated with hypotheses 1-4 suggests that all the hypotheses can give good estimates in many cases. In section 5.2 we will compare the methods in the context of an examination of hypotheses 1 through 4 from the introduction of this paper.

5.2 Examination of the hypotheses

390 As discussed in section 1, the objective of this study is to evaluate different hypotheses or conceptualizations regarding α, by using them to estimate α itself, actual wet surface evaporation (5), and hypothetical wet-surface evaporation as a part of a CR model that predicts actual regional evaporation rates (18). As discussed in section 5.1, outcomes from these conceptualizations are used to evaluate the hypotheses stated in the introduction. Including a range of hypotheses in this process makes it more likely that the correct conceptualization will be included and identified as the best.

395

Hypothesis 1, based on the α_c-method, has been the default hypothesis in the majority of work with (5) and within CR formulations (e.g., Brutsaert, 1982, 2005, 2015; Crago et al., 2016, 2022, Han and Tian, 2018, 2020). Growing evidence that wet-surface, minimal-advection α actually has a fairly wide range of values (e.g., McNaughton and Spriggs, Lhomme, 1997 a,b, Raupach, 2000) might raise doubt regarding our ability to accurately estimate wet surface evaporation. Clearly,

400 unexplained variability is a real challenge, but the α_c estimate performs quite well in predicting actual wet surface evaporation and in the CR model (Figures 3 and 4, and Tables 2 and 3).

A possible explanation for this surprisingly good performance begins with work by Szilagyi et al. (2014) and Andreas et al. (2013), who showed that much of the variability of α is due to temperature, with α increasing with decreasing temperature.

405 Several formulations for α in terms of temperature are given in Figure 4, including α_A, α_m, α_{max} (defined in the Figure 5 caption), and a multi-term polynomial developed by Szilagyi et al. (2014) for α over saturated land surfaces. Because α is a function of temperature, it is likely that many of the large values of α_{ref} in Figure 3 (top panel) correspond to cold temperatures, which typically imply low available energy. Because available energy is small, relatively large errors in α result in only small absolute errors in wet surface evaporation using (5). Thus, the fact that the global constant value of α is too small for these low

410 temperature sites does not result in large absolute errors in wet surface evaporation rates. Nevertheless, this is clearly not the best-supported of the four hypotheses.
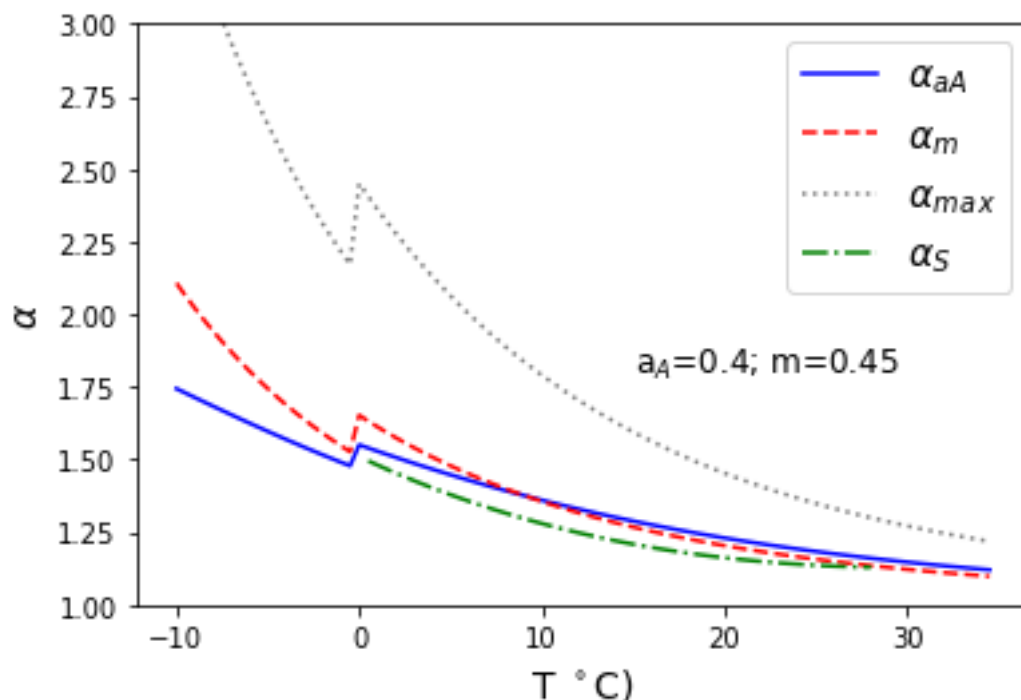
Figure 5. Variability of α from (8) and (9) with wet surface temperature. The value a_A=0.4 was chosen because it was recommended by Andreas (2013); the value of *m*=0.45 was chosen to approximately mimic the trends with the Andreas method. Here α_{max}=1+γ/Δ_{T0}, the maximum value of α suggested by Priestley and Taylor (1972). The green dash-dot line is α_S, based on the third-order polynomial suggested by Szilagyi et al., 2014, on the basis of their analysis of ERA-Interim data over saturated land surfaces.

Hypothesis 2, based on the a_A-method, assumes a constant ratio (a_A) of the Bowen ratio between equilibrium and minimal-advection conditions. The resulting equation for α (8) is able to account for much of the systematic variability of α_{ref} due to temperature variability because of the variable Δ_{T0} in (8). Figure 3 (upper panel) shows that a_A-estimates of α do increase as α_{ref} increases, but not as quickly as the reference values. While the trend is not matched perfectly, the a_A-method is clearly an improvement over the α_c-method in terms of predicting α_{ref}. The method also performs well at predicting actual wet surface evaporation and actual evaporation (Figures 1 through 6). With a clear definition and consistently-good performance, hypothesis 2 has considerable support. However, it is not obvious (based on physical principles) why a_A in (7) ought to be a constant. Overall, Hypothesis 2 does gain support from the data presented here.

Hypothesis 3, based on (9), also captures much of the variability of α_{ref}. Equation (9) is correct to within the accuracy of Penman's (1948) assumption regarding Δ_{T0}, provided that *RH* is the actual measured relative humidity. When measured *RH* is

430 replaced with the parameter *RH*, (9) provides an estimate for α_{ref}. Based on (1) combined with (5), (9) suggests that the optimal value of *RH* should ideally represent the relative humidity that characterizes wet surface evaporation with minimal advection. Note that in (9), α depends on *f(u)*, R_{n}-*G*, and temperature.

As seen in Tables 2 and 3, the *RH*-method does not rank highly for prediction of α, wet surface evaporation, or actual
435 evaporation. Hypothesis 3 makes a very intuitive claim regarding wet-surface minimal-advection evaporation, namely, that it is associated with a particular value of relative humidity. While this method is conceptually appealing and it performs relatively well with some subsets of the data (not shown), its performance in this study is not as good as that of hypotheses 2 and 4. Thus, this study does not provide much support for hypothesis 3.

440 Hypothesis 4 assumes that minimal advection has been achieved when α is a specified fraction (*m*) of the distance from $\alpha=1$ to the maximum physically-realistic value of $\alpha_{\text{max}}=1+\gamma/\Delta_{\text{T0}}$ (Priestley and Taylor, 1972). The idea of *m* being this fraction is clear and understandable, but it is not immediately obvious that it must be true on physical grounds. Overall, this method gives the lowest RMS error for estimating α, LE_{w}, and *LE* and it does this at both monthly and daily time scales. Furthermore, the other statistics included in Tables 2 and 3 are consistently favourable for this method, although not every statistic in Tables 2
445 and 3 is best for this model. The data examined here seem to provide considerable support for this method.

Note that another hypothesis was considered for inclusion, based on the α_{S} curve, developed by Szilagyi et al. (2014) for saturated land surfaces and included in Figure 5. The fact that α is a strong function of temperature is an important insight. However, the valid temperature range of their curve is more limited (from 0 to 28 °C) than the temperatures in the dataset, and
450 variability of α with temperature is already included in hypotheses 2, 3, and 4. Also, these hypotheses can be stated in terms of the parameters a_{A}, *RH*, and *m*, respectively, which have well-defined and physically-meaningful definitions. Therefore, no fifth hypothesis was evaluated.

6 Conclusions

Four hypotheses regarding the Priestley and Taylor (1972) parameter α were considered. Each of them has a different
455 assumption regarding the nature and variability of α. In the first hypothesis α is constant; in the second it represents a ratio of two Bowen ratios; in the third, it represents conditions at a given relative humidity value, and in the last, it can be seen as a midpoint between theoretical maximum and minimum values. Using FLUXNET data from a total of 171 stations, α, LE_{PT}, and actual evaporation values are compared to reference values in an attempt to determine which hypotheses best explain the data.

460 The second and fourth hypotheses generally produce the best results. In both of these, α is dependent on temperature, although the functional forms of the relationship are different. The third hypothesis has a very intuitive physical interpretation, but it

tends not to work as well as the α_A- and m-methods. But overall, the data in this study provide the most support for hypothesis 4, the m-method. According to this hypothesis, α for wet surfaces remains at a constant fraction (m) of the distance between the minimum of value of one and the maximum value of $1+\gamma/\Delta_{T0}$. Since Δ_{T0} is a function of the wet surface temperature T_0, so

465   is α_m.

Without a need for any additional data, the temperature-dependence of α can be included in evaporation equations. It seems appropriate to include this dependence in applications of the Priestley-Taylor (1972) equation, and in particular in the use of CR models to estimate actual evaporation over drying surfaces. It is striking that four distinct hypotheses for how to understand

470   the physical meaning of α can be stated clearly and that they have real implications regarding the nature and the numerical value of α.

Data Availability

475   All data were downloaded from the FLUXNET website (http://fluxnet.org). Data pre-processing by FLUXNET staff follows procedures described by Pastorello et al. (2020). Bucknell University is working with the first author to find an appropriate location to make the data and software available to the public. Links will be provided.

Author Contributions

480   R. Crago: Conception of study; acquisition and analysis of data; rough draft, edits

R. Qualls: Further development of concept; edits

J. Szilagyi: Further development of concepts; edits

Competing interests

485   The authors have no competing interests.

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