Assessment of the Priestley-Taylor Parameter Value from ERA-Interim Global Reanalysis Data

Jozsef Szilagyi [1,*], Marc B. Parlange [2], Gabriel G. Katul [3]

[1] Department of Hydraulic and Water Resources Engineering, Budapest University of Technology and Economics, Budapest, Hungary; also at School of Natural Resources, University of Nebraska-Lincoln, 3310 Holdrege St., Lincoln, NE, 68583, USA

[2] Department of Civil Engineering, University of British Columbia, Vancouver, Canada

[3] Nicholas School of Environment and the Earth Sciences, Duke University, Durham, North Carolina, USA

Peer Review History [1]

Abstract: *The Priestley-Taylor parameter α of wet surface evaporation is investigated using daily, 0.75-degree ERA-Interim reanalysis data for the winter hemispheres of 2000-2001, 2006-2007, and 2012-2013. Published ERA-Interim sensible and latent heat fluxes over sea and land yield two distinct best-fit curves for α as a function of air temperature (T_a). When the wet land surface temperature (T_{ws}) was estimated by an independent method, the two curves largely collapsed. Tropical land areas with low wind formed a subgroup of α distribution, yielding the lowest overall values of 1.06±0.03. The results for sea corroborate the widely accepted α value of 1.26±0.06 when T_a > 20 °C. At 0 °C the mean α value over sea is about 1.62±0.23. The α values for wet land surfaces with the independent T_{ws} estimates display about the same mean but with larger variations. Published values of α scatter around the overlapping α vs T_a curves.*

Keywords: *Evapotranspiration, land/atmosphere interactions, water/energy interactions, Priestley-Taylor parameter, wet surface temperature*

1. Introduction

Following the publication of the Priestley and Taylor (1972) equation describing wet environment evaporation under minimal horizontal advection of energy, many studies focused on relating the value of its empirical coefficient, α, to different environmental variables (Pereira, 2004). The coefficient α in the Priestley-Taylor equation (PTE):

$$\mathrm{LE} = \alpha \frac{\Delta}{\Delta + \gamma} \mathrm{Q_n} \tag{1}$$

is generally accepted to express the evaporation-enhancing effect of large-scale entrainment of drier free-tropospheric air resulting from the growing daytime convective boundary layer (CBL) (Brutsaert, 1982; deBruin, 1983; Culf, 1994; Lhomme, 1997; Heerwaarden et al., 2009). Here Q_n is the available energy at the wet surface equivalent to the sensible heat (H) and latent heat (LE) fluxes, Δ is the slope of the saturation vapor pressure curve at the air temperature (T_a), and γ (= $c_p P$ / (0.622L)) is the psychrometric constant, where c_p is the specific heat of air at constant pressure (P) and L is latent heat of vaporization for water. From observations over both sea and extended wet land surfaces, Priestley and Taylor (1972) reported that such large-scale entrainment typically enhanced evaporation by about 20-30% in comparison to what would result from saturated air, yielding a mean value of 1.26 for α. In subsequent studies, the value of α has been found to vary considerably on a

[1] *Paper JHER0206, submitted on 19/11/2014, accepted for publication after peer review and subsequent revisions on 15/12/2014*

* *Corresponding author may be contacted at szilagyi.jozsef@epito.bme.hu*

sub-daily (Yu, 1977; de Bruin and Keijman, 1979; Viswanadham et al., 1991; Parlange and Katul, 1992), daily (Davies and Allen, 1973), and seasonal basis (de Bruin and Keijman, 1979).

The limited number of experimental data and the sometimes conflicting results on the value of α motivated the present study of investigating its possible distribution based on data with a global coverage, such as the daily ERA-Interim reanalysis dataset (http://www.ecmwf.int/products/) at a 0.75° spatial resolution. The significance of the Priestley-Taylor equation (equation 1) at a temporal scale of a day (or longer) in hydrology, water resources and their related fields is important. It forms the backbone of numerous classical evaporation estimation methods such as the soil moisture (Davies and Allen, 1973; Spittlehouse and Black, 1982; Chen and Brutsaert, 1995) or complementary relationship based techniques (Brutsaert and Stricker, 1979; Morton et al., 1985; Parlange and Katul, 1992; Szilagyi et al., 2009) as well as remote-sensing enhanced approaches such as the two-source models (Anderson et al., 2008; Kustas and Anderson, 2009). In all these models PTE is employed with a preset α =1.26. Considering that α has a well-defined lower limit of unity (i.e., when the air is saturated and equilibrium profiles of T_a and specific humidity, q, exist) for extended wet surfaces, as well as an upper limit of 1 + $\gamma\Delta^{-1}$, a function of T_a (i.e., when air stratification is adiabatic, thus Q_n = LE), the present study focuses on defining the α-value distribution in relation to T_a as well. The results below will help future practical evaporation estimations of the above models by enabling prescription of the α value as a function of T_a, and thus improving their overall performance.

2. Estimation of the α parameter value from daily reanalysis data

Reanalysis data are considered as the best representation of reality because they combine measurements with modeling results by taking into account the errors in both of them. The European Centre of Medium-Range Weather Forecasts (ECMWF) has been producing reanalysis data since 1979. The latest such product, the ERA-Interim reanalysis dataset, is available free of charge near real time since 2009 at a spatial resolution of 0.75°. For the present study, daily and monthly 2 m T_a and dew point (T_d) temperature, surface P, 10 m wind velocity (u_{10}), net radiation (R_n), as well as ECMWF-estimated skin temperature (T_s), H, and LE fluxes were downloaded for the winter periods (i.e., the months of December, January, February for the northern hemisphere and June, July, August, for the southern one) of 2000-2001, 2006-2007, and 2012-2013. With the choice of the winter season the strong advection effect of the trade winds were meant to be minimized. The monthly values served only as a check of the ensuing daily analysis and yielded similar results. ECMWF-published skin temperature, T_s, is not identical to the radiometric skin temperature. T_s, by virtue of its derivation, should be conceived as an aerodynamic surface temperature.

The α value can be obtained by rearrangement of equation 1 as:

$$\alpha = \frac{(\Delta + \gamma)/\Delta}{Bo + 1} \tag{2}$$

where Bo (= H / LE), is the Bowen ratio. Equation 2 can also be written as (Priestley and Taylor, 1972):

$$\alpha = \frac{LE}{Q_n \Delta / (\Delta + \gamma)} = \frac{(\Delta_q + c_p / L) L d_z q}{\Delta_q (L d_z q + c_p d_z T_a)} = \frac{(\Delta + \gamma) d_z e}{\Delta (d_z e + \gamma d_z T_a)} \tag{3}$$

where Δ_q is the slope of the saturation specific humidity curve, e is vapor pressure and d_z denotes the vertical difference in the variable. For saturated surfaces Eichinger et al. (1996) gave an approximation of equation 3 as:

$$\alpha \approx \left[1 - \frac{\gamma (e^* - e)}{(\Delta + \gamma)(e_s^* - e)} \right]^{-1} \tag{4}$$

with saturation vapor pressure values starred and the subscript ‘s’ referring to the surface temperature. Equation 4 requires the same input as equation 3 and its overall performance is also similar, therefore only results from equation 3 are published below, by assuming saturated conditions at the surface.

The value of α was calculated separately for sea and land by equations 2 and 3 employing the ERA-Interim sea-land mask. The spatial extent of the 0.75° degree cells was considered large enough to be applicable with the PTE. T_s over land was estimated by ECMWF (2007) for obtaining the H and LE fluxes through a soil-moisture dependent resistance approach. The surface temperature values (T_{ws}) over land, to be used in equation 3 under assumed surface saturation conditions, have been estimated independently (Szilagyi, 2014) by relating the aerodynamic resistance of Monteith (1981) to Penman's (1948) Rome wind function and transforming u_{10} to the required 2 m value via $u_2 = u_{10}\ 0.2^{1/7}$ (Brutsaert, 1982).

Figure 1 displays the relative histograms of α, as a function of T_a for cells that yielded α values between unity and $1 + \gamma\Delta^{-1}$. The distribution of α from H, LE fluxes is much wider over land (1b) than sea (1a). Direct application of the ECMWF-estimated T_s values in equation 3, assuming surface saturation [in contrast to equation 2], yields a significantly different α distribution (1c), with higher overall α values.

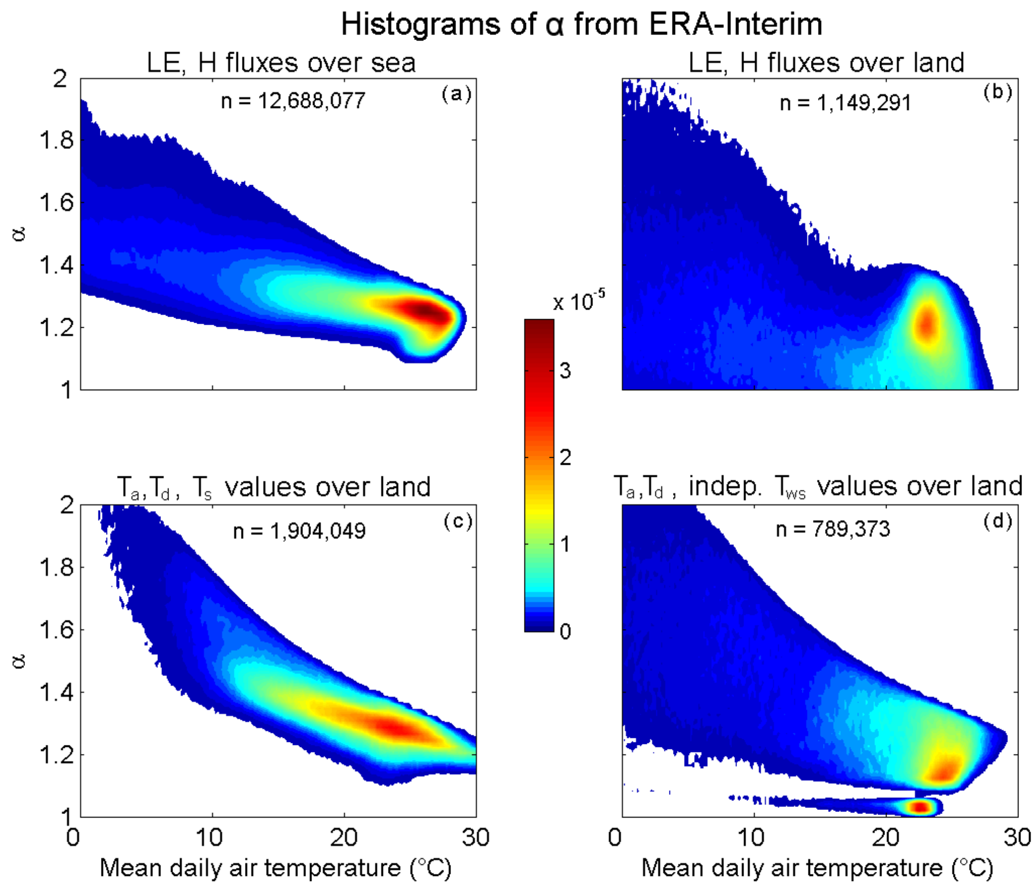

Figure 1 Relative histograms of the Priestley-Taylor α values calculated from mean daily ERA-Interim values of sensible- (H) and latent heat (LE) fluxes (1a,b), air (T_a), skin (T_s) as well as dew point (T_d) temperature values (1c). Wet surface temperature (T_{ws}) has been independently estimated (Szilagyi, 2014) in 1d. Bin-size is 0.02 °C by 0.02, n is the total number of α values found for the winter hemispheres of 2000-2001, 2006-2007, and 2012-2013 combined, within the $(1, 1 + \gamma\Delta^{-1})$ limits.

Assuming that the ECMWF-derived fluxes and the T_s values are correct, this discrepancy can only exist if the land surface is not always saturated when the resulting α value falls between the lower and upper bounds for saturated surfaces. With the independently obtained T_{ws} values; however, the resulting distribution (1d) is in between the former two, both in spread and location, with a new feature: the emergence of a distinct sub-group of very low α (< 1.08) values. The highest frequency of days with $\alpha < 1.08$ is predominantly found in the western part of the Amazon basin (reaching 79 out of a possible 92 days for the winter of 2000-2001) and in Indonesia (Figure 2), both near mountains, suggesting that large-scale advection is the weakest in these areas. Viswanadham et al. (1991) also reported a mean daily α value of 1.03 in the western part of the Amazon basin for the end of the austral winter season. Quite interestingly, these regions correspond to the wettest and calmest tropical regions of the world, with mean annual precipitation in excess of 2500 mm and mean wind velocities less than 2.7 ms^{-1} (source: climate-charts.com), providing strong support for the derived low α values. Note that over sea such low values cannot occur due to much stronger winds.

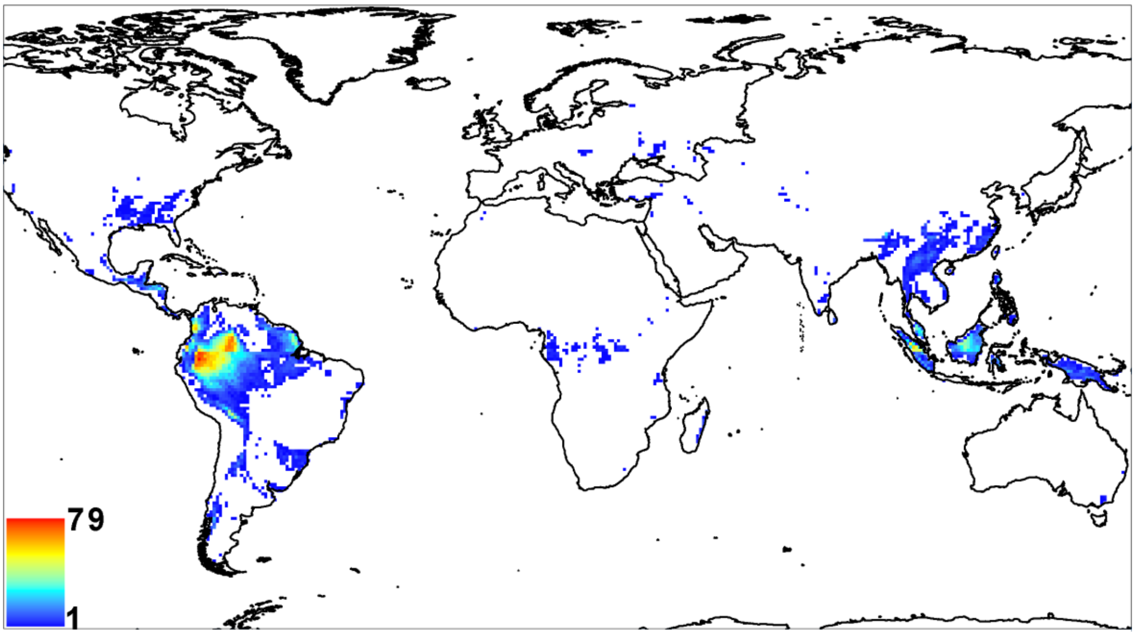

Figure 2 Spatial distribution of the number of winter days (2000-2001) when α over land fell within the interval of (1, 1.08) in Figure 1d. The highest values correspond to the most humid and least windy areas of the tropics having annual precipitation in excess of 2500 mm and mean wind velocities lower than 2.7 ms^{-1} (source: climate-charts.com).

Figure 3 displays the third-order polynomial curves (Table 1) fitted to 15 bin-means of α and to their plus/minus standard deviation (std) values (dashes). The value of α over sea decreases from a value of 1.62±0.23 at 0°C to a value of 1.22±0.03 at 30 °C. Between 20 and 30 °C, the typical mean daily summer temperature range for mid-latitudes when *LE* generally is the highest over land, α stays between 1.29±0.07 and 1.22±0.03, agreeing well with the original findings of Priestley and Taylor (1972).

Table 1 Parameters (with decreasing power) of the 3rd-order polynomials of Figure 3, fitted to 15 bin means of α values and to their plus/minus standard deviations

	($\cdot 10^{-6}$)	($\cdot 10^{-4}$)	($\cdot 10^{-2}$)	
LE, *H*, sea	-3.89, -0.89, -6.9	4.78, 5.95, 3.61	-2.54, -3.85, -1.2	1.64, 1.89, 1.39
LE, *H*, land	-4.84, -4.36, -5.31	7.07, 10.1, 3.99	-2.96, -4.85, -1.07	1.51, 1.86, 1.16
T_a, T_s, T_d, sea	1.57, -0.85, 4	2.55, 5.64, -0.53	-2.22, -3.66, -0.8	1.61, 1.86, 1.36
T_a, T_s, T_d, land	-0.7, -14.1, 12.7	7.62, 18.1, -2.91	-4.53, -7.44, -1.62	1.93, 2.25, 1.6
T_a, T_d, indep. T_{ws}, land	38.5, 20.8, 56.1	-10.8, -1.39, -20.3	-1.65, -3.98, 0.67	1.69, 2.03, 1.36
T_a, T_d, indep. T_{ws}, land, $\alpha > 1.08$	26.2, 16.9, 35.5	-6.29, 0.28, -12.8	-2.03, -4.15, 0.08	1.71, 2.03, 1.38

For land, equation 2 with ECMWF fluxes yields an α vs T_a curve distinctly lower than that for sea, while equation 3 with T_s values and under the assumption of surface saturation, yields another, markedly higher curve, especially when $T_a < 15$ °C. On the other hand, when the currently-estimated T_{ws} values are employed, the land and sea curves largely overlap. The overlap improves with the exclusion of the extremely low α value sub-group in Figure 1d from the fitting. In agreement with Priestley and Taylor (1972) who mixed sea and land measurements, the Bowen ratio, and thus the α value, regulated by entrainment of free-tropospheric air at the top of the CBL, should not in general differ between sea and wet land surfaces under largely similar environmental conditions, since at the top of the CBL the influence of the land surface is less significant. However, when *Bo* and α are indeed markedly different, then the environmental conditions themselves are significantly different, as was found for the wind in the α-value subgroup of 1d.

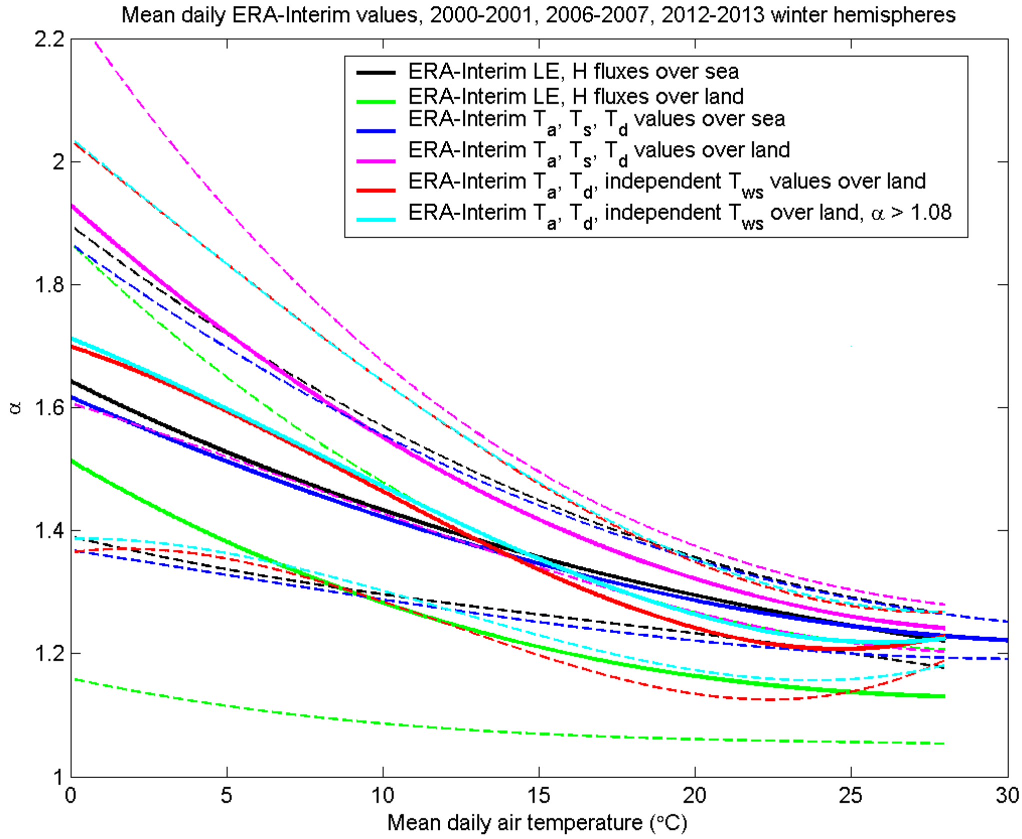

Figure 3 Third-order polynomials fitted to 15 bin means (at $T_a = 1, 3, \ldots$ °C) of ERA-Interim α values (with the corresponding standard deviation values denoted by dashes) found for the winter hemispheres of 2000-2001, 2006-2007, and 2012-2013 combined, within the (1, 1 + $\gamma\Delta^{-1}$) limits.

The overlap of the sea and land α vs T_a curves is a strong indication of the saturation of the land surface when the α value, resulting from equation 3 by assuming such saturation, falls between the limits, derivable for wet surfaces. Szilagyi and Schepers (2014) demonstrated that T_{ws} is invariant to drying of the environment under largely unchanged net radiation and wind conditions. Therefore, the estimated T_{ws} values could possibly come from drying conditions of the vegetated surface. But then it would be extremely fortuitous to obtain α values from equation 3 that largely coincide with the sea values from such drying land conditions (to be reflected in the measured 2 m T_a and T_d values) with the simultaneous 'false' assumption of a saturated surface. It is much more likely that the surface is indeed saturated whenever the derived α value (by equation 3) falls between unity and $1 + \gamma\Delta^{-1}$ through the application of the corresponding T_{ws} value.

Figure 4 displays published α values when the corresponding T_a values were available as well. With one single exception, the values fit well within the corresponding plus/minus std regions, and they are above the ERA-Interim *H*, *LE* derived α vs T_a curve for land, in support of the existence of a single α curve for both sea and land, although with larger variance for the latter.

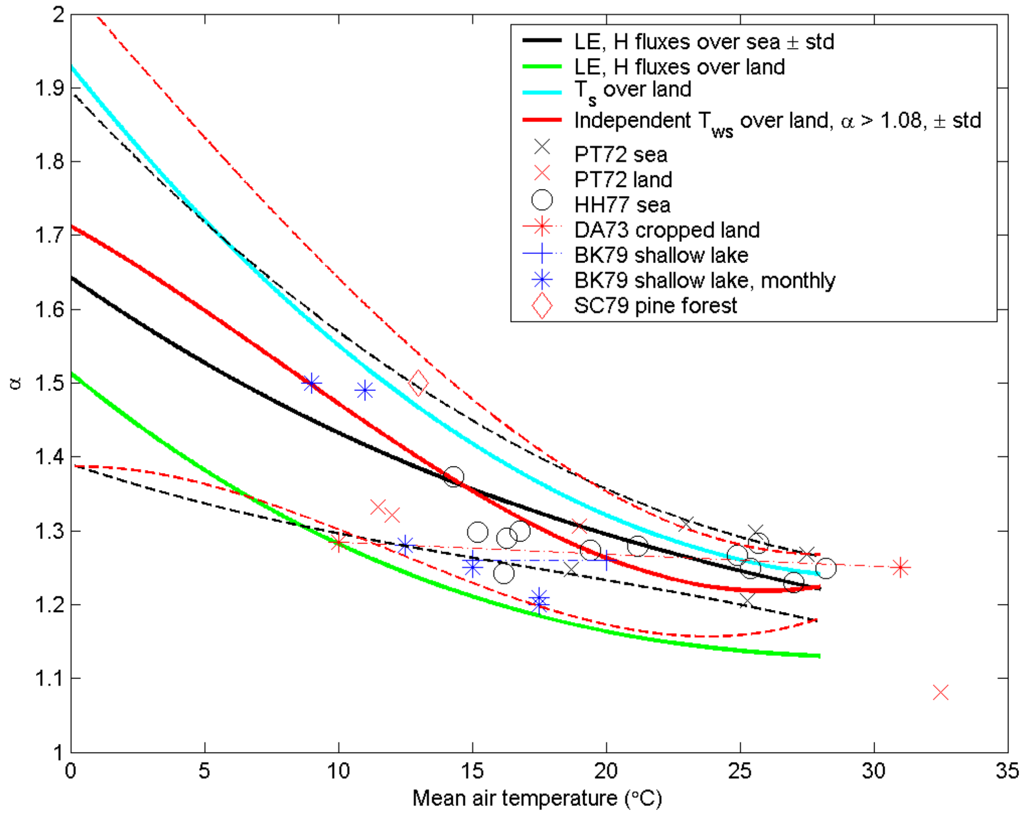

Figure 4 Subset of Figure 2, combined with reported values of α as a function of mean daily (or monthly) air temperature. Measurements over sea are in black, over land in red, and over a shallow lake in blue. The lines between the symbols denote reported intervals of α values as a function of T_a. See the List of References for the relevant publications.

3. Summary

Using daily ERA-Interim reanalysis data the value of the Priestley-Taylor parameter α with the corresponding interval of standard deviation, has been obtained as a function of T_a. Via the application of independently obtained wet surface temperature values, T_{ws}, the results support the existence of a single curve [hypothesized by Priestley and Taylor (1972)] for sea and extensive wet land surfaces, contrary to what is obtainable from ECMWF-derived *LE*, *H* fluxes or directly from T_s values of the same source, by simultaneously assuming saturation at the land surface.

As expected, variability of the derived α is larger for land than for sea (both increasing with decreasing temperatures), due to a higher degree of inhomogeneity in surface properties determined by topography, soil, and vegetation characteristics. At about 0 °C the average value of α is around 1.6-1.7, while over 20 °C it is found between 1.2 and 1.3, in agreement with the original, Priestley and Taylor (1972) derived average value of 1.26. In extreme environmental conditions, such as the most humid and least windy tropical land areas in the western part of the Amazon basin (as well as in Borneo and Sumatra), the α value may frequently reach as low a value as 1.03, close to its theoretical lower limit of unity.

Most of the published α values fall above or below the two distinct α vs T_a curves for land obtainable by daily ECMWF *LE*, *H* or T_s, respectively, while they do scatter around the sea α vs T_a curve and the largely overlapping land curve, the latter obtained by independently derived T_{ws} values.

4. Acknowledgements

This work has been supported by the Agricultural Research Division of the University of Nebraska-Lincoln. The data used for this study are available from http://old.ecmwf.int/products/.

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