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Modelling evapotranspiration in an alpine grassland ecosystem on Qinghai-Tibetan plateau

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Abstract:

Thus far, measurements and estimations of actual evapotranspiration (ET) from high-altitude grassland ecosystems in remote areas like the Qinghai-Tibetan plateau are still insufficient. To address these issues, a comparison between the results of the eddy covariance (EC) measurements and the estimates, considering the Katerji and Perrier (KP), the Todorovic (TD) and the Priestley–Taylor (PT) models, was carried out over an alpine grassland (38°03'1.7'' N, 100° 27' 26'' E; 3032 m a.s.l.) during the growing seasons in 2008 and 2009. The results indicated that the KP model after a particularly simple calibration gave the most effective ET values in different time scales, the PT model slightly underestimate ET at night and the TD model significantly overestimated ET at noon. In addition, the canopy resistance calculated by the TD model was completely different from that calculated using the inverted EC-measured data and the KP model, which may be due to some unrealistic assumptions made by the TD model. The KP parameters were $a = 0.17$ and $b = 1.50$ for the alpine grassland and appeared to be interannually stable. However, the PT parameter showed some interannual variations ($\alpha = 0.83$ and 0.74 for 2008 and 2009, respectively). Therefore, the KP model was preferred to estimate the actual ET at both hourly and daily time scales. The PT model, being the simplest approach and field condition dependent, was recommended when available weather data were rare. On the contrary, the TD model always overestimated the actual ET and should be avoided in case of the alpine grassland ecosystems.

KEY WORDS alpine grassland; evapotranspiration; canopy resistance; Penman–Monteith equation

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INTRODUCTION

Accurate estimates of evapotranspiration (ET) are essential for water balance studies, agricultural irrigation, water resources planning and management, and hydrologic modelling of stationary and changing climate conditions (Xu and Chen, 2005). However, ET is the most difficult to estimate among all the components of the hydrological cycle owning to complex interactions between the components of the land-plant-atmosphere system (Singh and Xu, 1997; Kelliher *et al*., 1995; Li *et al*., 2007), and uncertainty in ET from non-agricultural vegetation is particularly apparent (Sumner, 2001).

There exist a multitude of models to estimate ET. Among them, the Penman–Monteith (PM) combination equation and the Priestley–Taylor (PT) method were most commonly used (Pauwels and Samson, 2006; Shi *et al*., 2008). However, the application of the PM equation is constrained by the need to determine the canopy resistance r_c (Katerji *et al*., 2011). Up to now, the two approaches frequently used to parameterize the r_c are the semi-empirical approach suggested by Katerji and Perrier (1983) (hereafter named the KP approach/model) and the mechanistic approach proposed by Todorovic (1999) (the TD approach/model). Recently, a series of studies has been carried out to compare the suitability of semi-empirical and mechanistic approaches in estimating ET for different land surface such as irrigated grass, crops, natural prairies and forests (Lecina *et al*., 2003; Steduto *et al*., 2003; Pauwels and Samson, 2006; Shi *et al*., 2008; Katerji *et al*., 2011). However, different conclusions about the performances of the two approaches were obtained for different land surfaces (Katerji *et al*., 2011). Thus, the comparing studies in a wide vegetated surface under various climatic conditions are still need. The PT model (Priestley and Taylor, 1972) is a simplification of the PM equation and has successfully simulated ET in grassland, crop and forest ecosystems (Shi *et al*., 2008). However, a wide variation of the empirical parameter (α) in PT model has been reported (Nichols *et al*., 2004). Therefore, the sensitivities of α to environmental factors and the performances of the PT model in ET estimates in different ecosystems should be further studied.

The alpine grasslands, which are characterized by low temperature and plentiful sunlight owning their high elevation, are widely distributed in the Qinghai-Tibetan Plateau (Piao *et al*., 2006). The plateau has experienced substantial warming in recent decades (Liu and Chen, 2000), and this warming is expected to continue in the 21st century (IPCC, 2007). Therefore, accurate estimates of ET in the alpine grasslands on the Qinghai-Tibetan

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Plateau can provide insights into not only the hydrological cycle in the alpine ecosystem, but also the impacts of climate change on the water balance in the highest plateau of the world. Unfortunately, it still remains a blank in estimating actual ET in the alpine grasslands, and systematic investigations of the performances of the PM and PT models are even fewer or non-existent.

In the present study, the performance of the PM model after r_c parameterization using the KP and TD approaches and PT model in ET estimates from the alpine grassland on Qinghai-Tibetan Plateau were systematically assessed. This is done on the basis of comparison of modelled ET values with EC measurements during two main growing periods of the alpine grassland in 2008 (from 6 June to 30 September) and 2009 (from 1 May to 31 August). Also, the site-specific parameters of KP and PT models will be compared with other ecosystems. Finally, the observed divergences between measured and calculated ET will be analyzed.

MATERIALS AND METHODS

Study site

The study site is located at Arou freeze/thaw observation station (lat. 38° 03' 1.7 '' N, long. 100° 27' 26'' E) in the Qilian Mountains of the Qinghai-Tibetan plateau, China (Figure 1). The elevation is 3032 m above sea level. The annual average temperature and precipitation for 1990–2000 were −0.2 °C and 411.3 mm (Niu *et al*., 2008), respectively. The soil is classified as subalpine meadow soil with an average thickness of about 1 m (Chang *et al*., 2009). The soil organic matter is high (ca. 14.6%).

The plant community was dominated by *Kobresia humilis* and was occasionally accompanied by *Stipa grandi*, *Leontopodium* and *Potentillal*. During the peak growing seasons, the vegetation reaches a height of 20–30 cm, and the canopy cover was more than 85%. The grassland turns green at the end of May and becomes senescence in early or middle October, depending on the climate of a given year.

Measurements

The site was set up and instrumented in June 2008 as part of the Watershed Allied Telemetry Experimental Research project (see details in Li *et al*., 2009). Net ecosystem water vapour and carbon dioxide gas exchange was measured at the height 2.2 m using the eddy covariance (EC) system, which consists of a 3D sonic anemometer (CSAT-3, Campbell Scientific Inc. Logan, UT, USA) and an open-path CO_2/H_2O gas analyzer (Li-7500, LiCor Inc., USA). The signals were recorded at a rate of 10 Hz by a datalogger (Campbell Scientific Inc. Logan, UT, USA) and then block-averaged over 30-min intervals. Post-processing calculations, using the TK2software package (Mauder and Foken, 2004), included the WPL density fluctuation correction, spectral loss correction, planar fit coordinate rotation, sonic virtual temperature conversion and spike detection. Following the procedure in the LI-COR Instruction Manual (Li-COR Inc., 2000), the CO_2/H_2O analyzer system was calibrated every year at the beginning of the growing season. Zero points were established using dry N_2 gas, the CO_2 span was calibrated using a standard gas bottle of CO_2 (303.3 607.7 and 1000 ppmv standard CO_2 gases) and the water vapour using a dew-point generator (Li-610; Li-COR Inc., NE, USA).

Continuous complementary measurements also included standard climatological components and soil temperature and moisture. Rainfall was measuring using a tipping bucket rain gauge (TE525MM, Campbell Scientific Instruments Inc.). Air temperature and relative humidity (HMP45C, Vaisala Inc., Helsinki, Finland) were measured at heights of 2 and 10 m above the ground. Wind speed and direction (034B, Met One Instruments, Inc. USA) were measured at the height of 10 m. Downward and upward solar and longwave radiation (PSP, The EPPLEY Laboratory Inc., USA) and photosynthetic photon flux density (LI-190SA, LI-COR Inc.) were measured at height of 1.5 m. Soil temperature (Campbell-107, Campbell Scientific Instruments Inc.) and moisture (CS616, Campbell Scientific Instruments Inc.) were measured at 0.1, 0.2, 0.4, 0.8, 1.2 and 1.6 m depths. Soil heat fluxes were measured at the depths of 0.05 and

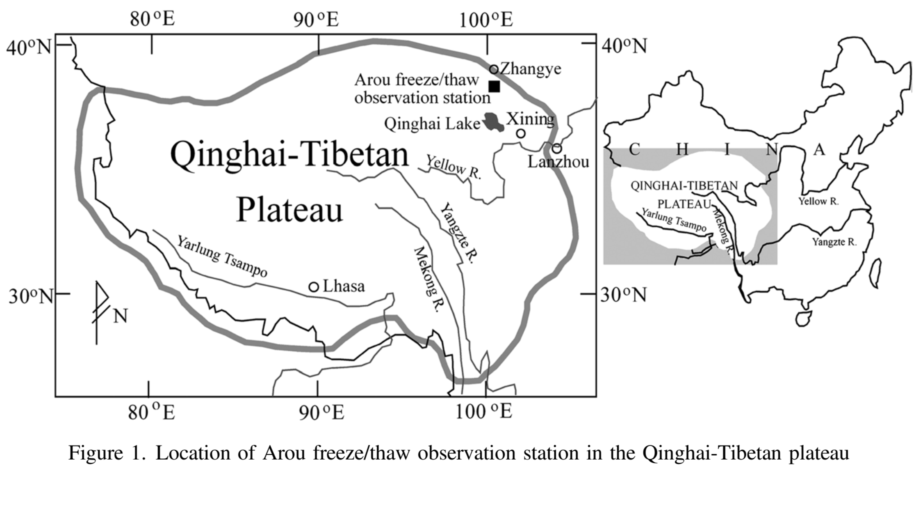

Figure 1. Location of Arou freeze/thaw observation station in the Qinghai-Tibetan plateau

0.15 m (HFT3, Campbell Scientific Instruments Inc.). These data were logged every 30 min by a digital micrologger (CR23X, Campbell Scientific Inc.) equipped with an analog multiplexer (AM416). Leaf area index (LAI) was measured by harvesting the vegetation approximately every 2 weeks during the growing season, and the gaps were linearly interpolated to daily interval.

Description of PM equation

The estimation of the actual ET from a vegetative surface, at hourly time scale, can be made on the basis of the PM model (Monteith, 1965). In this model, the latent heat flux is:

$$\lambda E = \frac{\Delta(R_n - G) + \rho_a C_p D_a / r_a}{\Delta + \gamma(1 + r_c/r_a)} \tag{1}$$

where λ is the latent heat of evaporation (J kg^{-1}), E is actual ET (kg m^{-2} s^{-1}), R_n is the net radiation (W m^{-2}), G is the soil heat flux(W m^{-2}), ρ_a is the air density (kg m^{-3}), C_p is the specific heat capacity of dry air (1013 J kg^{-1} K^{-1}), γ is the psychrometric constant (kPa K^{-1}), D_a (kPa) is the air water vapour pressure deficit at the reference height (2 m), r_a (s m^{-1}) is the aerodynamic resistance and r_c (s m^{-1}) is the canopy resistance.

The aerodynamic resistance r_a is usually computed with the following equation, assuming neutral stability conditions (Perrier, 1975; Brutsaert, 1982):

$$r_a = \frac{\ln\left(\frac{z-d}{h_c-d}\right)\ln\left(\frac{z-d}{z_0}\right)}{k^2 u_z} \tag{2}$$

where h_c is the mean vegetation height (m), z is the height of wind speed measurements (m), d is the zero plane displacement (m) estimated as $d = 0.67h_c$, z_0, the roughness length for momentum transfer (m), is estimated by $z_0 = 0.123h_c$, k is the von Karman's constant ($k = 0.41$) and u_z is wind speed at the reference height (m s^{-1}). In this study, the daily ET estimations was obtained by summing up the hourly values simulated by Equation (1) based on hourly averaged meteorological variables (Katerji and Rana, 2006; Rana and Katerji, 2008).

The KP model

By applying Buckingham π-theorem, Katerji and Perrier (1983) derived the following linear model for canopy resistance (r_c):

$$\frac{r_c}{r_a} = a\frac{r^*}{r_a} + b \tag{3}$$

where a and b are empirical calibration coefficients (dimensionless). r^* is the critical resistance (s m^{-1}) and it only depends on weather variables as follows (Pereira *et al.*, 1999):

$$r^* = \frac{\Delta + \gamma}{\Delta}\frac{\rho_a C_p D_a}{\gamma(R_n - G)} \tag{4}$$

By combining Equations (1), (3) and (4), the latent heat flux can be written as:

$$\lambda E = \frac{1 + \frac{\gamma}{\Delta+\gamma}\frac{r^*}{r_a}}{1 + \frac{\gamma}{\Delta+\gamma}\left(a\frac{r^*}{r_a} + b\right)}\frac{\Delta}{\Delta + \gamma}(R_n - G) \tag{5}$$

The advantage of the KP model is that it takes into account the set of climatic factors affecting r_c. However, the parameters of a and b must be calibrated previously. Here, the model was calibrated using the 9 days of hourly observations acquired between 20 and 28 July 2008 during the middle development stage, then it was validated a posterior during the years 2008 and 2009 (Lecina *et al.*, 2003; Rana and Katerji, 2008). This procedure has two aims: (1) to illustrate the interannual stability of the coefficients a and b for the alpine grassland; (2) to separate the model calibration period from the model validation period. For the calibration data set, the values of r_c were obtained by inverting Equation (1) using hourly EC-measured latent heat flux (λE_{EC}):

$$r_c = \frac{\rho_a C_p D_a + r_a\Delta(R_n - G)}{\gamma\lambda E_{EC}} - r_a\left(1 + \frac{\Delta}{\gamma}\right) \tag{6}$$

Equations (2) and (3) were used to get the hourly aerodynamic and critical resistance values. Thus, a simple linear regression between r_c/r_a and r^*/r_a was fitted to obtain values of parameters of a and b. In this study, the ET estimated with Equation (5) and r_c in Equation (3) was labelled as λE_{KP}, and r_{cKP}, and canopy resistance calculated using Equation (6) was labelled as r_{cEC}.

The TD model

A full discussion of the theory and assumptions of the TD model can be found in Todorovic (1999). Here, we simply present the equations used to get the canopy resistance (r_c) values. In this model, the canopy resistance is calculated as follows:

$$a^*\left(\frac{r_c}{r_i}\right)^2 + b^*\left(\frac{r_c}{r_i}\right) + c^* = 0 \tag{7}$$

where r_i is the climatological resistance(s m^{-1}) and is written as:

$$r_i = \frac{\rho_a C_p D_a}{\gamma(R_n - G)} \tag{8}$$

a^*, b^* and c^* (all three in kPa) are defined by

$$a^* = \frac{\Delta + \gamma(r_i/r_a)}{\Delta + \gamma}\left(\frac{r_i}{r_a}\right)D_a \tag{9}$$

$$b^* = -\gamma\left(\frac{r_i}{r_a}\right)\frac{\gamma}{\Delta}\frac{D_a}{\Delta+\gamma} \quad (10)$$

$$c^* = -(\Delta+\gamma)\frac{\gamma}{\Delta}\frac{D_a}{\Delta+\gamma} \quad (11)$$

Solving for Equation (7) which has only one positive solution, the hourly variable r_c can be obtained. In contrast to the Katerji and Perrier (1983) model, the main advantage of the Todorovic (1999) model is its application without specific calibration. Here, the ET estimated with Equation (1) and r_c in Equation (7) was labelled as λE_{TD} and r_{cTD}.

The Priestley–Taylor (PT) model

Owing to the frequent unavailability of some micro-meteorological variables needed for the PM model, Priestly and Taylor (1972) proposed a simplified version of the PM model to calculate actual ET:

$$\lambda E = \alpha\frac{\Delta}{\Delta+\gamma}(R_n - G) \quad (12)$$

where α is the Priestley–Taylor parameter (dimensionless), to compensate for the fact that the atmosphere does not always attain saturation. To apply the PT model for estimating actual ET, the values of α were determined by inverting PT Equation (12) using the hourly calibration data sets. The actual ET estimated with Equation (12) was labelled as λE_{PT}.

Statistical analysis

Comparisons between measured and estimated ET values were performed by simple error analysis and linear regression ($y = b_0 + b_1 x$), where measured values were used as the dependent variable y and the estimated ones were used as the independent variable x, b_0 is the intercept and b_1 the slope. For each method, the root mean square error (RMSE), systematic mean square error (MSEs) and index of agreement (IA) were calculated by using the following formular as described by Willmott (1982):

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - x_i)^2} \quad (13)$$

$$\mathrm{MSEs} = \frac{1}{n}\sum_{i=1}^{n}(\hat{y}_i - x_i)^2 \quad (14)$$

$$\mathrm{IA} = 1 - \frac{\sum_{i=1}^{n}(y_i - x_i)^2}{\sum_{i=1}^{n}[|y_i - \bar{x}| + |x_i - \bar{x}|]^2} \quad (15)$$

where y_i is the ith observed value, x_i is the ith estimated value, $\hat{y}_i$ is the ith predicted value through the linear regression and $\bar{x}$ is the mean of the estimated values.

RESULTS AND DISCUSSION

Meteorological and biological factors

Detailed information on the seasonality of key environmental variables is essential to assess seasonal variation in the actual ET. The seasonal change in daily averaged air temperature (T_a; °C), net solar radiation (R_n; MJ m^{-2} day^{-1}), precipitation (mm), soil water content (SWC; %) at the depth of 5 cm and LAI (m^2 m^{-2}) was illustrated in Figure 2. The daily averaged air temperature is about 8.8 °C, varying from 1.89 to 14.3 °C during the study period (Figure 2). Also, the ecosystem experienced a large temperature swing over the course of a day, usually more than 15 °C (data not shown). The daily net radiation was about 10 MJ m^{-2} day^{-1}, varying from 1.5 to 18 MJ m^{-2} day^{-1} (Figure 2). The annual precipitation was 449.4 mm and 401.2 mm for 2008 and 2009, respectively, and was not significant from the normal years. Due to the highly continental climate, rainfall during the growing seasons (from May to October) contributed 92% and 96% of the total precipitation in 2008 and 2009, respectively. Within this high-precipitation period, 2–7 consecutive dry days occasionally followed rainy days (Figure 2). During these short dry intervals, the SWC decreased gradually from 0.45 m^3 m^{-3} to values close to 0.3 m^3 m^{-3} (Figure 2), which suggests that there is no significant soil water stress.

The LAI increased rapidly from ~1 m^2 m^{-2} in early June to 3 m^2 m^{-2} in middle June and reached a maximum of ~4 m^2 m^{-2} in middle July. After the end of August, the LAI decreased rapidly from about 3 m^2 m^{-2} to 1 m^2 m^{-2} (Figure 2).

Calibration of the KP and PT models

The KP model was calibrated using 9 days of hourly data representative of all climatic conditions. The parameters a and b were determined from the relation r_c/r_a as a function of r^*/r_a (see Equation (3)). The linear regression fit resulted in $a = 0.17$ and $b = 1.50$ (coefficient of determination $R^2 = 0.60$; Table I). The value of a for the alpine grassland was very close to that for Mediterranean grass ($a = 0.16$; Katerji *et al*., 2011) and tall fescue ($a = 0.18$; Steduto *et al*., 2003). Also, our values of a and b were not significantly different from that for well-irrigated Mediterranean grass ($a = 0.11$ and $b = 0.90$) suggested by Rana *et al.* (1994) based on daily mean climatic variables. Although the parameters a and b are species dependent and site specific, our values fell within the range from previous studies. For example, the minimum value of a (at hourly scale) was 0.16 reported by Katerji *et al.* (2011) for the Mediterranean grass, and the maximum a value was 0.95 for soyabean (Katerji and Rana, 2006). The minimum value of b (at hourly scale) was −0.58 proposed by Alves and Pereira (2000) for an irrigated iceberg lettuce crop during the mid-growing season, and the maximum b value was 1.55 for Mediterranean grass (Katerji and Rana, 2006).

Great variations of the hourly PT parameter α were also found in our studies (discussed below). The hourly mean values of PT parameter α were 0.83 and 0.74 for 2008

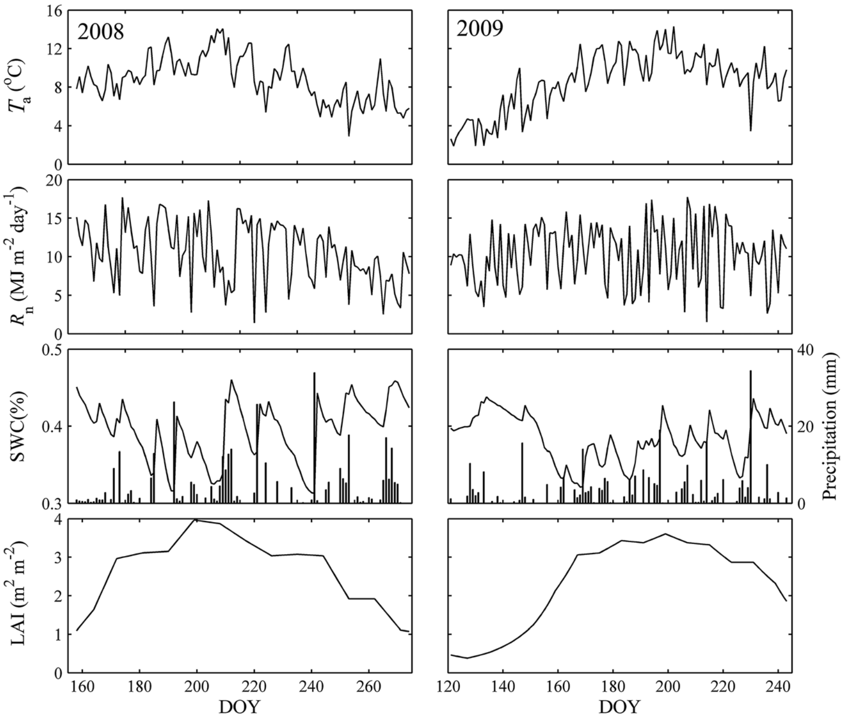

Figure 2. Seasonal variation in daily mean air temperature (T_a; °C), net solar radiation (R_n; W m^{-2}), precipitation (mm), soil water content (SWC; m^3 m^{-3}) at the depth of 5 cm and leaf are index (LAI; m^2 m^{-2})

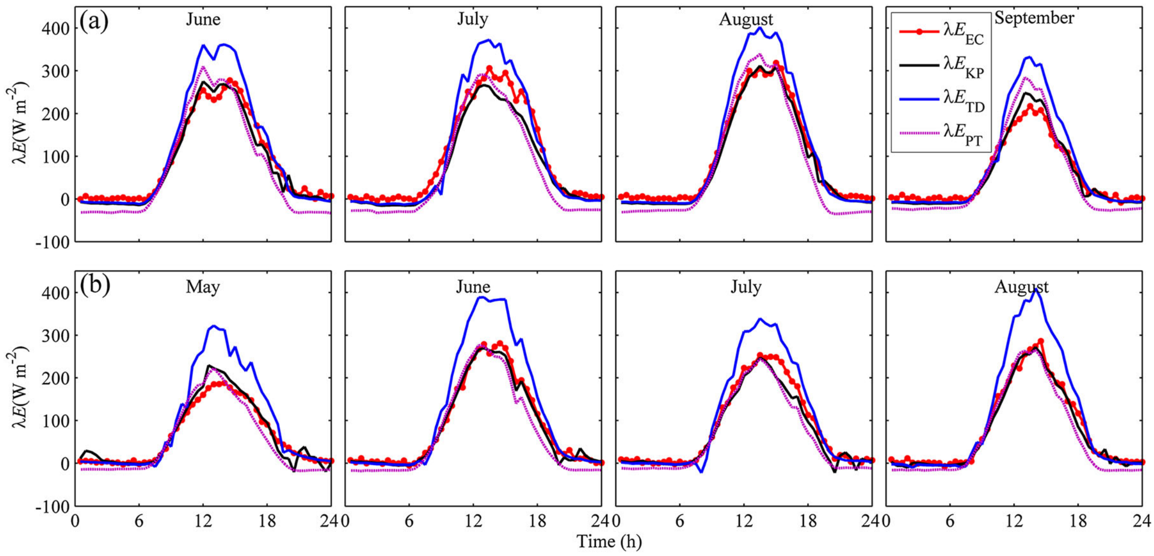

Figure 3. Diurnal cycles of EC-measured and KP-, TD- and PT-estimated evapotranspiration on a typical day during each month in different years (a) in 2008 and (b) in 2009

and 2009, respectively. Using micrometeorological observations over ocean surfaces and saturated land surfaces following rainfall, Priestley and Taylor (1972) recommended a best estimate of $\alpha = 1.26$. However, recent studies reported different values of the PT parameter α, with high value of 1.57 under strongly advective conditions (Jury and Tanner, 1975) and low values of 0.72 under unsaturated surface or Spruce forest (Shuttleworth and Calder, 1979), which is likely due to the effects of different vegetation types, soil moisture conditions and strength of advection (Fisher *et al.*, 2005).

Dynamics of hourly ET fluxes

The diurnal courses of mean hourly latent heat fluxes determined with the EC (λE_{EC}), KP (λE_{KP}), TD (λE_{TD}) and PT (λE_{PT}) methods for each month during the studies periods were illustrated in Figure 3. A similar diurnal evolution of λE was given by the four methods. The latent heat flux increased rapidly form sunrise and reached its maximum value at about 13:00. In the afternoon, it fluctuated around the maximum value until 15:00 p.m. After that, it decreased rapidly until sunset (Figure 3). Generally, during the morning (before 10:00 a.m) and in the

Table I. A comparison of parameters a and b in the KP model of the alpine grassland with the results of other studies

Species	a	b	R^2	References
Alpine grass[a]	0.17	1.50	0.60	The present study
Grass[a]	0.16	0.00	0.59	Katerji *et al.* (2011)
Tall fescue (*Festuca arundinacea* L.)[a]	0.18	0.92	0.91	Steduto *et al.* (2003)
Grass[b]	0.11	0.90	0.87	Rana *et al.* (1994)
Grass[a]	0.51	0.42	0.96	Pauwels and Samson (2006)
Grass[a]	0.40	0.39	0.73	Lecina *et al.* (2003)
Grass[a]	0.38	0.34	0.78	Lecina *et al.* (2003)
Soyabean[a]	0.95	1.55	0.69	Katerji and Rana (2006)
Iceberg lettuce[a]	0.73	−0.58	0.97	Alves and Pereira (2000)
Sweet sorghum[a]	0.84	1.00	0.92	Katerji and Rana (2006)
Vineyard[a]	0.91	0.45	0.78	Rana and Katerji (2008)
Citrus orchard[a]	0.23	0.00	0.60	Rana *et al.* (2005)
Forest[a]	0.55	1.31	0.61	Shi *et al.* (2011)

[a] Parameters were calculated using hourly data; [b] parameters were calculated using daily data.

afternoon (after 15:00), there were no significant differences between estimates by the three models and the EC measurement. In the noon (from 12:00 to 14:00 p.m), the maxima of TD estimates were 86–136 W m^{-2} higher than the maxima of the EC values, whereas the KP and PT estimates were closer to the EC measurements (Figure 3). At night time, the estimates by the PT model were significantly lower than EC measurements (Figure 3).

Figure 4 shows the comparison between the hourly values of λE measured by the EC system and those calculated by models (using the KP, TD and PT methods). All coefficients of determination were high, above 0.86, as well as all indices of agreement, above 0.93 (Table II). However, the KP method had a slope (0.92 and 0.91 for 2008 and 209, respectively) much closer to one than the PT (0.81 and 0.88 for 2008 and 2009, respectively) and TD (0.73 and 0.67 for 2008 and 2009, respectively); also, the RMSE of estimates for KP was about 15% lower than that for PT method, and it was about 64% lower than that for TD method (Table II). Additionally, the average values of hourly latent heat fluxes estimated by the KP method (83.2 and 86.2 W m^{-2} for 2008 and 2009, respectively) were closest to the EC measurements (89.7 and 82.2 W m^{-2} for 2008 and 2009, respectively) (Table II), whereas the PT method was 15–20% lower and the TD method was 20–40% higher than the EC average. Thus, the overestimation of λE by the TD model was significant for the apline grassland ecosystem. Katerji *et al.* (2011) reported that the TD model overestimated λE for annual cultivated crops (soyabean, sweet sorghum) by up to 30–50%, and recommend to avoid the use of TD model in case of these vegetations; Shi *et al.* (2008) found a significant overestimation of TD ET by about 58% for a temperate mixed forest, which was attributed to the effect of vapour water deficit of the air. However, some studies evaluated that the TD model performed well for ET estimations for several grassland (Lecina *et al.*, 2003; Steduto *et al.*, 2003) and cropped surface (Todorovic, 1999).

Here, the great number of experimental points allows us to classify the errors between estimated and measured actual λE as a function of r_a calculated by Equation (2) and the range of air vapour deficit (D_a) (Figure 5). It was noticed that for the values of r_a in the range 0–200 s m^{-1}, the absolute errors between the TD estimated and measured actual λE ($\lambda E_{TD} - \lambda E_{EC}$) mainly ranged from 0 to positive if D_a was greater than 1.5 kPa (Figure 5). Hence, the TD model would evidently overestimate actual λE at high D_a (especially more than 1.5 kPa) and low r_a

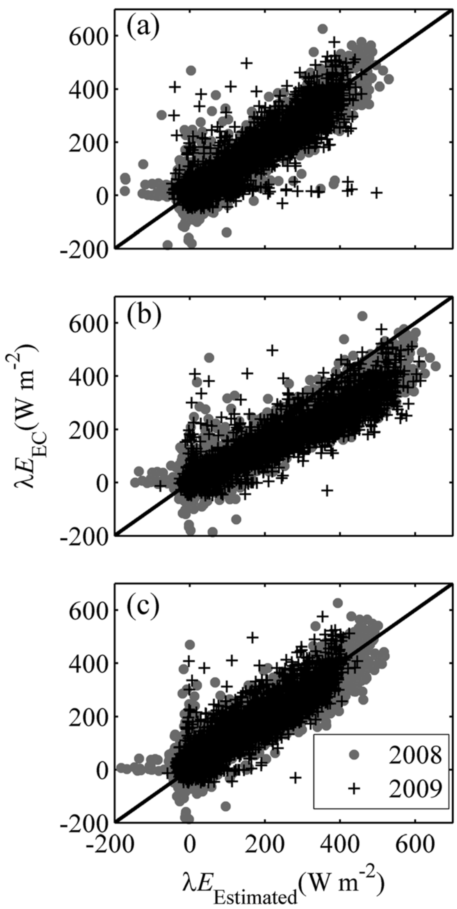

Figure 4. Regression between modelled and measured hourly evapotranspiration values by three different methods: (a) Katerji-Perrier model; (b) Todorovic model; (c) Priestley-Taylor model. The line represents 1:1 relation

Table II. Statistical analysis of hourly evapotranspiration estimations

Study period	Linear regression	n	R^2	b_0	b_1	RMSE	MSEs	IA	Average EC	Average models
2008	KP	5087	0.90	13.05	0.92	40.44	51.18	0.97	89.66	83.16
	TD	5097	0.91	10.70	0.73	65.70	65.70	0.96	89.66	108.26
	PT	5099	0.90	31.26	0.81	52.41	50.38	0.96	89.66	72.14
2009	KP	5271	0.86	4.17	0.91	42.71	128.85	0.96	82.21	86.22
	TD	5271	0.89	14.75	0.67	70.77	260.45	0.93	82.21	115.66
	PT	5271	0.87	20.61	0.88	43.28	183.55	0.96	82.21	69.77

n, sample sizes; R^2, coefficient of determination; b_0, intercept of regression; b_1, regression slope; RMSE, the root mean square error; MSEs, systematic mean square error; IA, index of agreement.

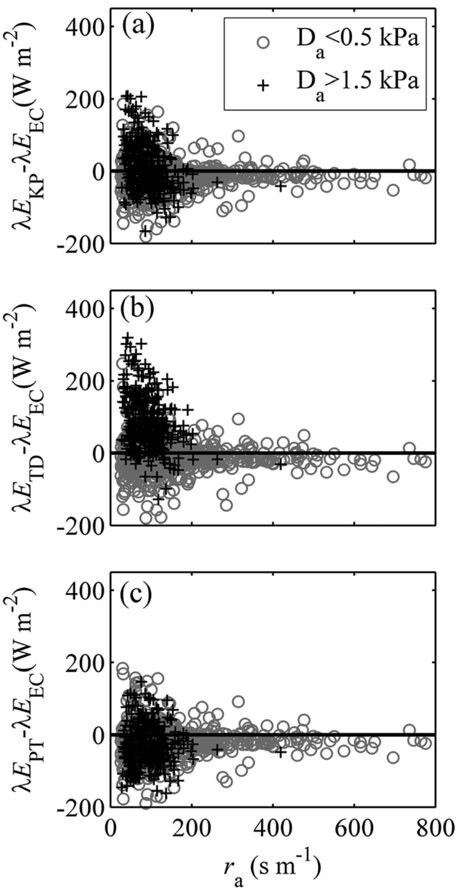

Figure 5. The gap between hourly calculated and measured actual evapotranspiration λE, by different models: (a) Katerji-Perrier model; (b) Todorovic model; (c) Priestley-Taylor model, as function of the aerodynamic resistance (r_a) and the range of air vapour pressure deficit (D_a)

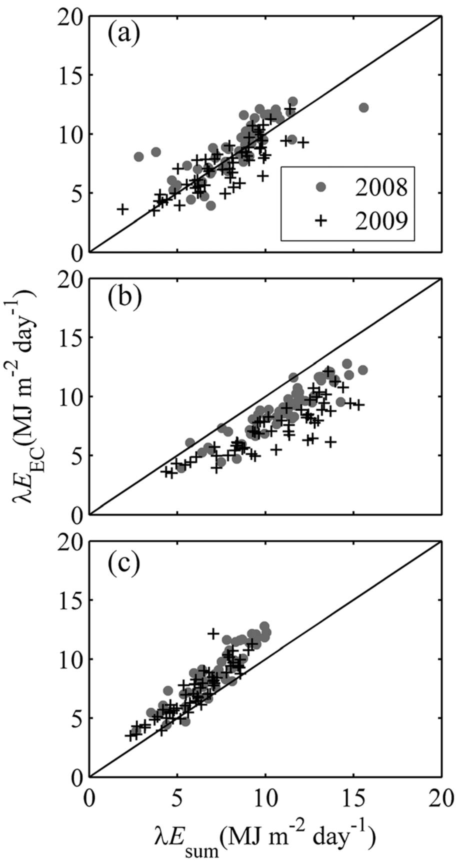

Figure 6. Regression between measured and modelled daily ET values by three different methods by summing up hourly estimates (a) Katerji-Perrier model ; (b) Todorovic model; (c) Priestley–Taylor model

(0–200 s m^{-1}). On the contrary, the divergences between the measured and estimated λE by the KP and PT models were randomly distributed and seemed not to be influenced by D_a (Figure 5). Furthermore, it can be noticed that the errors on the estimations of λE by the three models tended to decrease when r_a was greater than 200 s m^{-1} (Figure 5).

Estimation of daily ET fluxes

The relationship between the EC-measured (λE_{EC}) and modelled daily ET fluxes computed by summing up hourly estimates (λE_{sum}) were illustrated in Figure 6, and the corresponding statistical analysis was listed in Table III. Results indicated that the KP model was superior to both the PT and the TD models on daily scale during the study periods. For example, the KP model has the slope much closer to one (varying from 0.92 to 1.09 with a mean value of 1.01) than the TD model (varying from 0.64 to 0.86 with a mean value of 0.75) and the PT model (varying from 1.11 to 1.15 with a mean value of 1.13) (Table III). Furthermore, the RMSE of the estimates for the KP model was about 50% lower than for the TD model, and it was about 20% lower than for PT model. As for the average daily ET, the KP estimations (9.68 and 8.70 MJ m^{-2} day^{-1} for 2008 and 2009, respectively) was also closer to the EC measurements (10.32 and 8.43

Table III. Statistical analysis of daily evapotranspiration estimations

Study period	Linear regression	n	R^2	b_0	b_1	RMSE	MSEs	IA	Average EC	Average Models
2008	KP_{sum}	57	0.85	−3.72	1.09	1.81	2.97	0.86	10.32	9.68
	TD_{sum}	57	0.84	−5.59	0.86	2.58	5.81	0.81	10.32	12.66
	PT_{sum}	57	0.84	7.22	1.15	2.23	3.96	0.81	10.32	8.36
2009	KP_{sum}	55	0.73	6.35	0.92	1.34	1.98	0.92	8.43	8.70
	TD_{sum}	55	0.72	6.70	0.64	3.82	14.72	0.71	8.43	11.95
	PT_{sum}	55	0.83	6.28	1.11	1.78	9.12	0.86	8.43	6.96

n, sample sizes; R^2, coefficient of determination; b_0, intercept of regression; b_1, regression slope; RMSE, the root mean square error; MSEs, systematic mean square error; IA, index of agreement. Average EC, average value of latent heat fluxes measured by EC; average models, average value of latent heat fluxes computed by different models.

MJ m^{-2} day^{-1} for 2008 and 2009, respectively) than the TD estimations (12.66 and 11.95 MJ m^{-2} day^{-1} for 2008 and 2009, respectively) and PT estimations (8.36 and 6.96 MJ m^{-2} day^{-1}). Therefore, it can be concluded that the KP model estimated daily ET without bias; the PT model slightly underestimated daily ET; and the TD model evidently overestimated daily ET for the average of overall data in both years (Figure 6). Similar results were also reported in previous studies for a wide range of cultivated crops and natural ecosystems: soyabean (Katerji and Rana, 2006; Katerji *et al*., 2011), sweet sorghum (Katerji and Rana, 2006; Katerji *et al*., 2011), vineyard (Rana and Katerji, 2008; Katerji *et al*., 2011), grass (Pauwels and Samson, 2006; Katerji *et al*., 2011), temperate mixed forest (Shi *et al*., 2008).

In addition, the KP model was calibrated only using a small number of observations (9 days of data in middle July 2008), then it was used for validating the model in the remaining part of 2008 and 2009. The good relation of KP-EC daily ET during the two years (Figure 6a) confirms the interannual stability of the calibration. Thus, the requirements of *in situ* calibration of the parameters in the KP model were not a strong constraint for its applicability (Katerji *et al*., 2011).

Variations of r_{cEC}, r_{cKP}, r_{cTD} and α

The mean diurnal course of the hourly values of r_{cEC}, r_{cKP} and r_{cTD} for each month during the study period was presented in Figure 7. In general, the evolution of r_{cEC} and r_{cKP} showed a similar trend during the day (Figure 7). It slightly increased from sunrise to reach the maximum values around 11:00–12:00 a.m. After that, it decreased slightly until sunset (Figure 7). The interception for higher r_{cEC} and r_{cKP} values at noon may be that the excessive solar radiation at noon caused a corresponding inhibition of photosynthesis, which led to a closure of the stomata (Alves *et al*., 2008). On the contrary, the diurnal course of the mean hourly values of r_{cTD} was completely different from that of r_{cEC} and r_{cKP}: it decreased from sunrise to reach minimum value around 9:00–11:00 a.m. and varied very little until sunset in the afternoon (Figure 7). Additionally, the mean hourly values of r_{cTD} in the present study for the alpine grass was 40–80 s m^{-1} (Figure 7), whereas the mean values of the hourly r_{cEC} and r_{cKP} were about 120–240 s m^{-1}. The overestimations

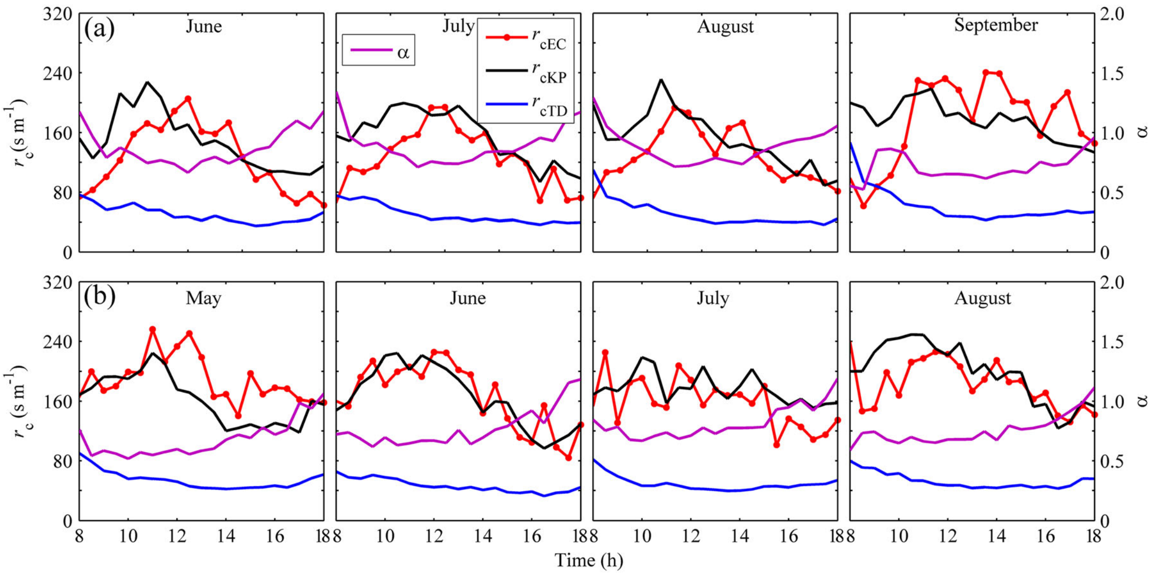

Figure 7. Diurnal variation of PT parameter α and canopy resistance calculated by inverting EC measured data (r_{cEC}), the Katerji-Perrier method (r_{cKP}) and the Todorovic method (r_{cTD}) for different years: (a) 2008 and (b) 2009

of ET by the TD model in present study assured us that the r_{cTD} seemed to be unreliable. The possible causes may be contributed to the several unrealistic assumptions made by the TD model. First, the TD model assumes the resistances to diffusion of water vapour and heat to be equal. However, the former depends on many factors while the latter mainly depends on the wind speed (see the analysis by Katerji *et al.*, 2011); Second, the TD model assumes the canopy resistant to be dependent mainly on air vapour pressure deficit, without explicitly taking into account other climatic variables (i.e. net radiation and aerodynamic resistance) (Katerji *et al.*, 2011) and any *in site* parameters (i.e., soil and water deficit) (Pauwels and Samson, 2006; Katerji *et al.*, 2011). Thus, the physiological control on the transpirational process exerted by plant through stomatal opening and closing was completely neglected in the TD model. A similar result was obtained by Pauwels and Samson (2006) on a wet sloping grassland prairie using monthly average meteorological data. Interestingly, we found the canopy resistance (r_{cEC}, calculated using the Equation (6) based on EC measured data) of the alpine grassland was higher than that of the low-elevation grassland reported in literature ranging from 30 to 70 s m^{-1} (Lecina *et al.*, 2003) and that recommend by the FAO (70 s m^{-1}; see Allen *et al.*, 1998). Thus, using published values without site-specific calibrations would result in overestimations in ET by PM model for the alpine grassland.

A great diurnal variation of the PT parameter α was also observed in our study, and the distributions of α generally demonstrated a conflicting tendency to r_{cEC} (Figure 7). According to the literature, the variation of the PT parameter α was considered to be related SWC (Flint and Childs, 1991; Fisher *et al.*, 2005), air water vapour pressure deficit (Shi *et al.*, 2008) and green foliage area (Burba and Verma, 2005). In our studies, the PT parameter tended to decrease as r_a increased (Figure 8a). However, the effects of SWC and air water vapour pressure deficit on α were weak (Figure 8b), partly due to the non-significant soil water stress for the alpine grass ecosystems. After simple calibration, the ET estimated by the PT model were not significant different from measured values during the study periods (Figures 2 and 4). Thus, the PT model performed well despite its relative simplicity.

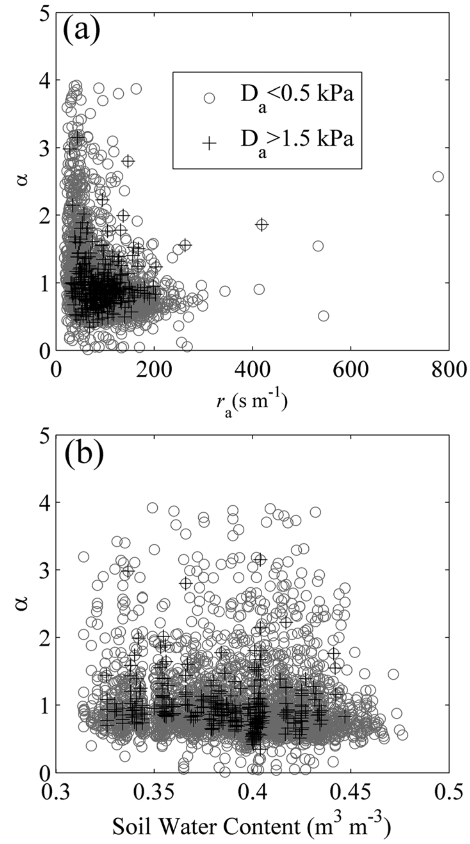

Figure 8. Hourly values of PT parameter α as function of (a) the aerodynamic resistance (r_a) and the range of air vapour pressure deficit (D_a), and (b) soil water content

CONCLUSIONS

The objective of this paper was to compare three commonly used models to estimate ET with the EC-measured data for an alpine grassland on the Qinghai-Tibetan plateau. These ET models are: the KP, the TD and the Priestley–Taylor (PT). Evaluating performances of these models on both hourly and daily time scales, the most promising and superior model suitable for the alpine grassland ecosystem has been proposed. Various statistical measures such as the coefficient of determination (R^2), the RMSE, MSEs and IA formed the deciding criteria for selecting the best model. The following specific conclusions are drawn from the analyses:

1. On the hourly time scale, the performance evaluation of the three methods suggested that the most superior and effective method for the alpine grassland was the KP model, followed by the PT and TD models. The diurnal courses of estimated and measured latent heat fluxes (λE) showed bell curves. However, the TD model significantly overestimated λE at noon due to high value of the air water vapour pressure deficit (more than 1.5 kPa), whereas the PT model slightly underestimated λE at night.
2. For the case of daily ET estimates using summed-up hourly estimates, the KP method gave the most effective values. The TD and PT methods overestimated and underestimated ET, respectively. The good performances of the KP model after a simple calibration procedure confirmed the interannual stability of the coefficients and suggested the requirements of a specific calibration were not a strong constraint for its applications.
3. The canopy resistance calculated using the inverted EC-measured data (r_{cEC}) and the KP method (r_{cKP}) showed similar diurnal trends with maximum values at around 12:00 a.m partly due to excessive-solar-radiation-caused stomatal closure at noon. On the contrary, the canopy resistance calculated using the TD method (r_{cTD}) remained relatively constant during the

diurnal courses and was significantly lower than that of r_{cEC} and r_{cKP}. Thus, TD model seemed to be unreliable for the alpine grassland ecosystems.

4. The parameters in the PT model (α) showed significant temporal variations and were different from those proposed for other vegetations. After specific calibrations, the PT models seemed to be robust and reliable. In our study, no obvious relationship between α and SWC were found, which may be due to the non-significant soil water stress for the alpine grass ecosystems.

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