温带阔叶红松林生态系统潜热通量模拟
——气孔导度组合模型在 Shuttleworth-Wallace 双源模型中的应用

黄 辉[1,2], 于贵瑞[1,*], 伏玉玲[1], 张雷明[1], 任传友[3], 韩士杰[4]

(1. 中国科学院地理科学与资源研究所, 北京 100101; 2. 中国科学院研究生院, 北京 100049;
3. 沈阳农业大学, 沈阳 100161; 4. 中国科学院沈阳应用生态研究所, 沈阳 110016)

摘要: 叶片水平的气孔导度组合模型已被成功扩展到冠层水平,并被应用于冬小麦生态系统潜热通量的模拟研究,但该研究仅基于 1a 的数据,有必要研究模型在更长时间尺度和其它生态系统类型的适用性。以长白山阔叶红松林(CBS)为研究对象,将组合模型进一步应用于 Shuttleworth-Wallace 双源模型,模拟了 CBS 3a 生长季内的潜热通量,利用涡度相关系统观测的潜热通量数据对模型进行验证,并对比了双源模型与单源模型的模拟结果。结果显示,双源模型较单源模型能取得更高的模拟精度,生长季不同时期的潜热通量模拟值和实测值的日变化较一致。对双源模型模拟值和实测潜热通量的相关分析显示,二者直线回归斜率和 R^2 分别为 0.96 和 0.72。对长白山阔叶红松林生态系统的蒸散和植被蒸腾的季节和年际变异分析发现,影响冠层蒸散和植被蒸腾季节动态的主要因素是饱和差和辐射,而影响它们年际动态的主要因素则是饱和差和温度。

关键词: 气孔导度; 组合模型; 双源模型; 涡度相关; 蒸散
文章编号: 1000-0933(2008)07-3212-09 **中图分类号**: Q948 **文献标识码**: A

Simulation of latent heat flux over a temperate mixed forest: application of a combination model to Shuttleworth-Wallace model

HUANG Hui[1,2], YU Gui-Rui[1,*], FU Yu-Ling[1], ZHANG Lei-Ming[1], REN Chuan-You[3], HAN Shi-Jie[4]

1 *Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing* 100101, *China*
2 *Graduate University of Chinese Academy of Sciences, Beijing* 100049, *China*
3 *Shenyang Agricultural University, Shenyang* 100161, *China*
4 *Institute of Applied Ecology, Chinese Academy of Sciences, Shenyang* 110016, *China*

***Acta Ecologica Sinica*, 2008, 28(7): 3212 ~ 3220.**

Abstract: A leaf-scale combination model has been successfully scaled up to canopy level and coupled with single source model (SSM) to estimate canopy-scale latent heat flux (λE) of winter wheat based on one year data. It is necessary to study the applicability of the combination model at longer time scale and for other ecosystems. In this study the combination model was used as the stomatal conductance sub-model in Shuttleworth-Wallace (S-W) model, which is a widely used dual source model (DSM). We applied the S-W model to estimate diurnal patterns of λE over a temperate mixed forest at Changbaishan (CBS) in Northeast China. Measured λE data from the eddy covariance (EC) system were used for model validation. Diurnal variation of estimated λE is in good agreement with that of measured λE. Simulated results of SSM and

基金项目: 中国科学院知识创新工程重要方向资助项目(KZCX2-YW-432); 国家自然科学基金重大资助项目(30590381)
收稿日期: 2008-01-28; 修订日期: 2008-04-22
作者简介: 黄辉(1980 ~), 女, 湖南郴州人, 博士生, 主要从事生态系统过程机理及模拟研究. E-mail: huangh.05b@igsnrr.ac.cn
* 通讯作者 Corresponding author. E-mail: yugr@igsnrr.ac.cn
Foundation item: The project was financially supported by Knowledge Innovation Project of Chinese Academy of Sciences (No. KZCX2-YW-432); National Natural Science Foundation of China (No. 30590381)
Received date: 2008-01-28; **Accepted date**: 2008-04-22
Biography: HUANG Hui, Ph. D. candidate, mainly engaged in mechanism and simulation of ecosystem process. E-mail: huangh.05b@igsnrr.ac.cn

S-W model were compared and the S-W model exhibits better simulation than SSM. The slope and R^2 of the line regression between the S-W model simulated and observed λE are 0.96 and 0.72 ($n = 8519$), respectively. The results show that dominant factors controlling the variation in ecosystem evapotranspiration (ET) and vegetation transpiration (T_r) at CBS are different at seasonal and inter-annual time scales. Vapor press deficit (D) and photosynthetically active radiation (Q_p) are the dominant factors for the seasonal variation of ET and T_r, while the differences in D and temperature determine their inter-annual variation.

Key Words: stomatal conductance; combination model; dual source model; eddy covariance; evapotranspiration

Stomatal behavior is an important physiological process occurring within leaves but linking regional and global climate systems to ecosystem water, carbon and nutrient cycles. Predicting the effects of global climate change on biogeochemical cycles thus requires understanding of stomatal response to these influences and the consequent changes in evapotranspiration from diverse ecosystems[1]. Accurate estimation of ecosystem evapotranspiration is important in studying the vegetation-atmosphere interaction.

Monteith[2] assumed the canopy as a big leaf′ and proposed a single source model (Penman-Monteith equation) for estimating evapotranspiration. In a similar way, Shuttleworth and Wallace[3] developed a dual source model (S-W model) by considering substrate surface evaporation. S-W model can simulate vegetation transpiration and substrate evaporation separately and has been widely used since it was presented[4-6]. Stomatal resistance (reciprocal of stomatal conductance) is the only physical item that has a direct association with vegetation in five resistances of S-W model. Simulation of stomatal conductance has been a subject of interest because it plays an important role not only in predicting ecosystem water, carbon and nutrient cycles, but in coupling land surface and atmosphere models[7].

Jarvis[8] supposed that the environmental variables be independent in determining stomatal conductance and proposed a multiplication model (Jarvis-type model). A semi-empirical model (B-B model) proposed by Ball *et al.*[9] and modified by Leuning[10,11] summarized the relation between stomatal conductance and CO_2 assimilation rate. The two models have been widely used as sub-models of evapotranspiration. But the estimation precision of Jarvis-type model decreases when the model is used at the long-time scale [12], and the B-B model is inconvenient in application because it requires many parameters for estimating photosynthesis. Yu *et al.*[12] proposed a combination model for estimating stomatal conductance over a long term as a refinement of Jarvis-type model. The combination model is a product of the potential stomatal conductance (*PSC*) and the relative degree of stomatal opening (*RDO*). It was scaled up to the canopy level and coupled with single source model (SSM) for estimating latent heat flux over a winter wheat cropland based on one year data[13]. A major challenge at current is to study the applicability of the combination model at longer time scale and for other ecosystems.

Temperate mixed forest is an important part of the typical forest ecosystem in Northeast China transect[14,15], which is very sensitive to climate change[16]. The eddy covariance flux observation over this forest has been made since 2002, as a part of ChinaFLUX. Simulation of evapotranspiration at this site can help us study the interactions between water and carbon cycles in the forest ecosystem. The objectives of this work are to introduce the stomatal conductance combination model into S-W model based on three years observed flux data; to simulate the diurnal patterns of latent heat flux; and to analyze the major factors driving the seasonal and inter-annual variations of ecosystem evapotranspiration at Changbaishan (CBS).

1 Model description

1.1 Energy balance above canopy and substrate surface

The sum of sensible heat (H) and latent heat (λE) fluxes above the canopy is available energy (A), and is given by[3,17]:

$$A = \lambda E + H = R_n - S - G - P \tag{1}$$

where R_n is the incoming net radiation, S and P are physical and biochemical energy storage terms, respectively, and G is the soil heat flux. Energy balance equations above the canopy and the substrate surface are:

$$R_{nc} = \lambda E_c + H_c + S \tag{2}$$

$$R_{ns} = \lambda E_s + H_s - G \tag{3}$$

Where the subscripts '$_c$' and '$_s$' represent canopy and substrate surface, respectively. P is usually ignored in the energy balance equation. S is usually ignored for vegetation of short height, but needs to be considered for forest. It is given by[18]:

$$S = S_a + S_\lambda \tag{4}$$

$$S_a = \frac{\partial}{\partial t}\int_0^{hc} \rho C_p (1 + 0.84\bar{q}) T_b d_z \tag{5}$$

$$S_\lambda = \frac{\partial}{\partial t}\int_0^{h} \rho \lambda q_b T_b d_z \tag{6}$$

where S_a and S_λ are sensible and latent heat flux storage in the atmosphere and canopy, respectively, h is canopy height (h = 26 m), q_b and T_b are the mean air humidity and temperature within the canopy, and ρ is the air density.

R_n decreases exponentially within canopy and the radiation reaching the soil surface (R_{ns}) can be calculated using the Beer's law relationship of the form:

$$R_{ns} = R_n \exp(-CL) \tag{7}$$

where L is leaf area index, and C is the extinction coefficient (C = 0.7)[3].

1.2 Evapotranspiration

Surface λE is the sum of vegetation transpiration (λE_c) and soil evaporation (λE_s):

$$\lambda E = \lambda E_s + \lambda E_c \tag{8}$$

Eq. (8) could be expressed as the form:

$$\lambda E = C_c PM_c + C_s PM_s \tag{9}$$

where PM_c and PM_s are potential transpiration from entire vegetation cover and potential soil evaporation from bare soil, respectively, and are given by:

$$PM_c = \frac{\Delta A + \{\rho C_p D - \Delta r_a^c A_s\}/(r_a^a + r_a^c)}{\Delta + \gamma\{1 + r_s^c/(r_a^a + r_a^c)\}} \tag{10}$$

$$PM_s = \frac{\Delta A + \{\rho C_p D - \Delta r_a^s (A - A_s)\}/(r_a^a + r_a^s)}{\Delta + \gamma\{1 + r_s^s/(r_a^a + r_a^s)\}} \tag{11}$$

where Δ is the slope of saturation vapor pressure versus temperature, C_p is specific heat at constant pressure (C_p = 1005 J kg^{-1} K^{-1})[19], D is vapor pressure deficit at reference height, γ is psychrometric constant (γ = 0.067 kPa K^{-1})[20], r_a^a is aerodynamic resistance between canopy source height and reference level, r_a^c is canopy boundary layer resistance, r_a^s is aerodynamic resistance between the substrate and canopy source height, r_s^s is bulk canopy stomatal resistance (reciprocal of stomatal conductance), and r_s^s is soil surface resistance (r_s^s = 500 s m^{-1})[3].

C_c and C_s are resistance coefficients and are given by the following expressions:

$$C_c = \{1 + R_c R_a / R_s (R_c + R_a)\}^{-1} \tag{12}$$

$$C_s = \{1 + R_s R_a / R_c (R_s + R_a)\}^{-1} \tag{13}$$

where R_a, R_c and R_s are calculated as:

$$R_a = (\Delta + \gamma) r_a^a \tag{14}$$

$$R_c = (\Delta + \gamma) r_a^c + \gamma r_s^c \tag{15}$$

$$R_s = (\Delta + \gamma) r_a^s + \gamma r_s^s \tag{16}$$

1.3 Resistances

1.3.1 Stomatal resistance

The multiplicative model presented by Jarvis[8] has been widely used for estimating stomatal conductance. By considering the environmental stress to stomata at different time scales, Yu *et al.* [12] developed the Jarvis-type model into a combination model. It is the product of *PSC* and *RDO*, and was scaled up to the canopy level[13]:

$$r_s^c = (g_{sw})^{-1} = (PSC \times RDO)^{-1} = \{(g_{s,\max}) \times (g_s/g_{s,\max})\}^{-1} \tag{17}$$

or:

$$r_s^c = (g_{sw})^{-1} = (PSC \times RDO)^{-1} = \{(g_{s,\mathrm{mean}}) \times (g_s/g_{s,\mathrm{mean}})\}^{-1} \tag{18}$$

Where g_{sw} is stomatal conductance for water vapor (m s^{-1}) and the subscripts 'max' or 'mean' denote daily maximum and average values, respectively.

PSC and *RDO* are functions of air temperature (T) and photosynthetic photon flux density (Q_p). *PSC* depends on the daily averages of T and Q_p, and *RDO* depends on the relative varation of environmental variables during daytime:

$$g_{sw} = (a_1 + a_2 T_{\mathrm{mean}} + a_3 T_{\mathrm{mean}}^2)(b_1 + b_2 Q_{\mathrm{pmean}})(c_1 + c_2 T/T_{\mathrm{mean}} + c_3 T/T_{\mathrm{mean}}^2)$$
$$(d_1 + d_2 Q_p/Q_{\mathrm{pmean}} + d_3 Q_p/Q_{\mathrm{pmean}}^2) \tag{19}$$

Where a_1—d_3 are multivariate regression coefficients.

1.3.2 Eddy diffusion resistance

r_a^a, r_a^c and r_a^s can be expressed as fractions of the overall aerodynamic resistance (r_a) for momentum transfer in the soil-vegetation system[21]:

$$r_a^a = \frac{u_r - u_h}{u_r} r_a \tag{20}$$

$$r_a^c = \frac{u_h}{\sigma_a u_r} r_a \tag{21}$$

$$r_a^s = \frac{u_h}{(1 - \sigma_a) u_r} r_a \tag{22}$$

where u_r is the wind speed at the reference height, and r_a is calculated as[17]:

$$r_a = \frac{1}{k^2 u_r}\left[\ln \frac{Z_r - d}{Z_0}\right]^2 \tag{23}$$

where Z_r is the reference height (Z_r = 40 m), d and Z_0 are zero plane displacement ($d = 0.78h$) and roughness length ($Z_0 = 0.075h$), and k is the von Karman's constant (k = 0.4)[22]。

σ_a is the momentum partition coefficient which depends on leaf area index (L)[23]:

$$\sigma_a = 1 - \left(\frac{0.5}{0.5 + L}\right)\exp\left(-\frac{L^2}{8}\right) \tag{24}$$

2 Materials and methods

2.1 Site description

The study site locates in a mature broad-leaved and Korean pine mixed forest (CBS, 42°24′N, 128°6′E, 738 m above sea level) on the northern slope of the Changbai Mountain in Jilin Province, China. This area belongs to the temperate continental climate zone influenced by Asia monsoon, with a mean annual temperature of 3.6 ℃.

The prevailing wind direction is southwest. The precipitation mainly occurs in summer with mean annual total precipitation of 695 mm. The observation site is flat with upland dark brown forest soil. The forest is about 180 year-old with an average crown height of 26 m. Detailed description of CBS site can refer to Guan *et al.* [24] and Wang *et al* [15].

2.2 Experiments and data processing

An open-path eddy covariance system and a routine meteorological measurement system were installed on a 62 m high tower at CBS site. The fluxes of CO_2, water vapor and heat, and meteorological variables above and within the canopy were measured simultaneously. Half-hourly averaged values were used in this study. More details of the measurement procedures at CBS site can be found in Yu *et al.* [25] and Ren *et al.* [26].

L was measured with LAI-2000 (Licor Inc.) every two weeks during the growing season. To get continuous variation of L, we estimated L by using the measured Q_p blow and above the canopy [27,28]. The R^2 between estimated and observed L is 0.92.

The data were processed by the following procedures: (i) three-dimensional rotation of the coordinate was applied to the wind components to remove the effect of instrument tilt or irregularity on the airflow [29,30]; (ii) the flux data were corrected for the variation of air density caused by the transfer of heat and water vapor [31]; (iii) remove the spikes data induced by rainfall, water condensation or system failure; (iv) mean daily variation (MDV) method was used to fill the water and heat flux data gaps[32].

2.3 Model parameterization

Calculation from inverted Penman-Monteith equation and non-linear least square method were used for fitting the parameters of stomatal conductance model (Eq. 19). Data of 14 days (sunny and rainless) in August 2003 were chosen for model parameterization. Values of regression coefficients used in Eq. (19) are shown in Table 1.

Table 1 Values of regression coefficients used in combination model

Model	Coefficient	Remark
PSC	a_1 7.1344; a_2 −0.3959; a_3 0.0062; b_1 11.5722; b_2 −0.0090;	Eq. (19)
RDO	c_1 −0.7940; c_2 1.6696; c_3 −0.7452; d_1 −0.4927; d_2 4.4476; d_3 −0.7716	Eq. (19)

3 Results and discussion

3.1 Seasonal variations of environmental factors and leaf area index

The CBS site is dominated by the temperate continental climate that is characterized with monsoon, and precipitation in same phase with temperature. The mean annual air temperature at the site in the year 2003, 2004 and 2005 were 4.7, 4.9, and 3.4 ℃, respectively. Compared to long-term records, it was warmer in 2003 and 2004. Precipitation in springtime (April) was abundant and the soil moisture increased evidently (Fig. 1). The leaf area index increased rapidly in May and maintained a relatively high value throughout the growing season. Precipitation from June to August accounted for 67.8% of the annual total during the three years (Fig. 1).

3.2 Comparison of measured and simulated evapotranspiration by SSM and S-W model

Table 2 shows the correlation between simulated evapotranspiration with SSM and S-W models and measured data with EC technique during the active growing season. The model description of SSM can be found in Huang *et al.* [13]. By considering the soil evaporation, the S-W model shows obvious improvement in estimating evapotranspiration as compared with SSM.

3.3 Comparison of diurnal patterns of measured and simulated λE with the S-W model

Fig. 2 shows the diurnal variation of λE from EC measurements and S-W model simulation during the growing

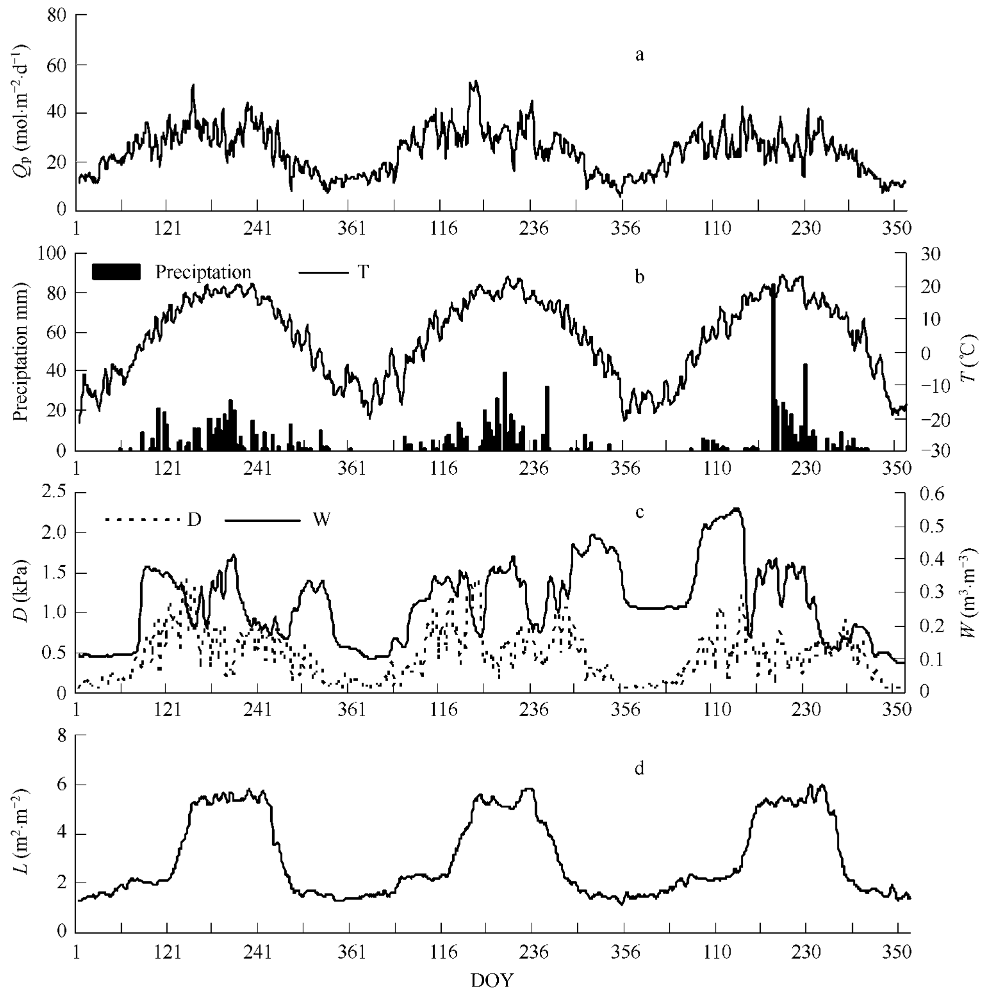

Fig. 1　Seasonal variations of environmental factors and leaf area index during 2003 —2005 at CBS

(a) Photosynthetically active radiation (Q_p); (b) Air temperature (T) and precipitation; (c) Vapor pressure deficit (D) and volumetric soil water content (W); (d) leaf area index (L); Q_p and precipitation are daily sum values; D, W and T are daily average values; Lines denote 5-days running average curves

season in 2003, 2004 and 2005. As shown in Table 2, there is a good agreement in diurnal variation between measured and simulated λE by coupling the stomatal conductance combination model with S-W model. Diurnal variations of λE usually follow normal distribution on sunny days, with the peak evapotranspiration appearing at midday. Evapotranspiration is evidently restrained on rainy days, like DOY (day of year) 158 in 2003, 193 and 201 in 2004, and 237 in 2005. The reason is that precipitation helped improve the atmosphere humidity and depressed the leaf to air vapor pressure deficit, which reduced vegetation transpiration. The canopy evapotranspiration decreased accordingly.

Table 2　Correlation between simulated (y) and measured (x) evapotranspiration with EC technique during the active growing season with half-hour resolution (n = 8519) (SSM: single source model; S-W: Shuttleworth-Wallace model)

Simulation period	Model	Function	R	P
Jun. — Aug. in 2003 — 2005	SSM	$y = 0.78x$	0.81 **	$P < 0.001$
	S-W	$y = 0.96x$	0.85 **	$P < 0.001$

* * Correlation is significant at the 0.001 level

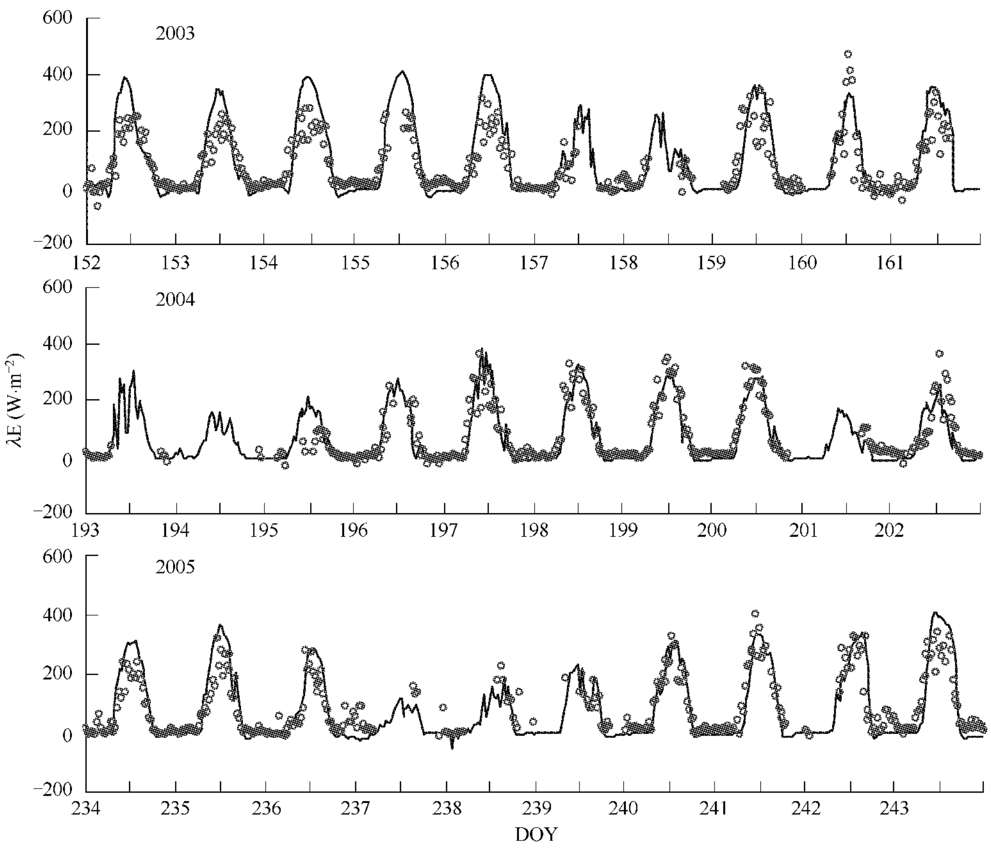

Fig. 2 Diurnal variations of simulated (solid line) and measured (dots) latent heat flux (λE)

3.4 Environmental controls on seasonal and inter-annual variations of evapotranspiration

Figure 3 shows the effects of D and Q_p on S-W model simulated daily ET and transpiration (T_r) during the growing season in 2003 — 2005 at CBS. The ET increased with D and Q_p, and the tendency for T_r was similar to that of ET. Table 3 gives the mean values of T and D, maximum L, mean daily ET, and T_r during the growing season. As shown in Table 3, the simulated ET was highly consistent with the measured ET. The vegetation coverage is high during the growing season at CBS and the vegetation transpiration accounted for the most proportion of evapotranspiration, which is higher than 95% in each year. The dominant factors for transpiration are also those for evapotranspiration. The seasonal dynamics of ET and T_r are affected mainly by D and Q_p (Fig. 3), and the dominant factors for inter-annual difference of ET and T_r are D and T (Table 3). Ecosystem evapotranspiration and vegetation transpiration were higher during warmer and drier years (like 2003 and 2004), and were lower in cool and moist year (like 2005).

Table 3 Values of mean air temperature (T, ℃), mean vapor pressure deficit (D, kPa), maximum leaf area index (L_{max}, $m^2\ m^{-2}$), and mean daily evapotranspiration (ET, $kg\ m^{-2}d^{-1}$) and transpiration (T_r, $kg\ m^{-2}d^{-1}$) during the growing season of 2003 — 2005 at CBS

Year(DOY)	T	D	L_{max}	ET^a	ET^b	T_r^b	RMSE^c
2003(121-273)	16.20	0.67	6.12	2.83	2.83	2.79	0.82
2004(122-274)	16.25	0.65	5.93	2.59	2.70	2.61	0.68
2005(121-273)	15.83	0.50	6.20	2.50	2.48	2.42	0.74

a Observed data by EC technique; *b* Model simulated values; *c* Root mean square error between simulated and observed daily ET

4 Conclusions

In this study a stomatal conductance combination model was used as stomatal conductance sub-model in

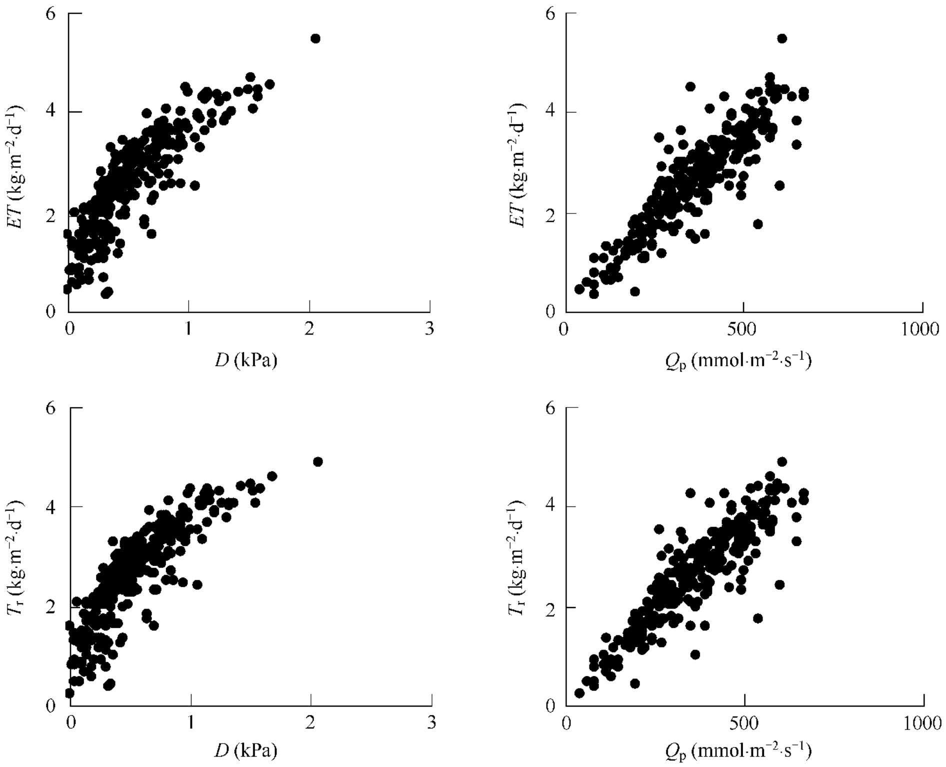

Fig. 3　Effects of D and Q_p on daily ET and T_r during the growing season of 2003 — 2005 at CBS

(D: vapor press deficit; Q_p: Photosynthetic photon flux density; ET: Evapotranspiration; T_r: Vegetation transpiration)

Shuttleworth-Wallace model and was applied to simulate latent heat flux over a temperate mixed forest in Changbaishan. There is a good agreement in diurnal variation between simulated latent heat flux with S-W model and that measured with eddy covariance technique. As a dual source model, the S-W model simulates canopy evapotranspiration and vegetation transpiration simultaneously. It shows great improvement in comparison with the single source model. The ecosystem evapotranspiration at CBS shows obvious seasonal and inter-annual dynamics. The seasonal variation of evapotranspiration is mainly affected by vapor pressure deficit and photosynthetically active radiation, and the dominant factors for the inter-annual variation in evapotranspiration are vapor pressure deficit and temperature.

Acknowledgements

We are grateful to Prof. Li Sheng Gong and Dr. Wang Qiu Feng of Institute of Geographic Sciences and Natural Resources Research for their valuable comments in thesis writing and modification. We thank Dr. Hu Zhong Min of Institute of Geographic Sciences and Natural Resources Research for very helpful discussions concerning the Shuttleworth-Wallace model. Thanks also go to colleagues of Institute of Applied Ecology for providing flux and meteorological data.

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