A Common Stomatal Parameter Set Used to Simulate the Energy and Water Balance over Boreal and Temperate Forests

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Abstract

A parameter set expressing the potential response used to simulate evapotranspiration was inferred from pooled data of leaf-level stomatal conductance in the Far East. We used Jarvis-type parameterization, which consists of restriction terms of light, air dryness, temperature, and soil water. Two parameter sets, pooled common (PC) and within-site (WS)

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sets, were determined using stomatal conductance data of eight species at nine sites. Seasonal changes of energy and water fluxes observed at four tower sites are well reproduced by a land surface model, despite using a different set of parameters. The results suggest that energy and water fluxes can be simulated using only one common parameter set with no parameter tuning, at least for forests in a wide region of the Far East.

   We discuss why similar fluxes were simulated using PC and WS parameters despite the clear differences between these two parameter sets. Sensitivity experiments showed that the effects of maximum stomatal conductance and soil water content mutually cancel each other in Yakutsk and that an optimum temperature effect was added.

1. Introduction

   Forests are an important land surface component for climate and water cycles. In particular, boreal forests, which extend widely over northern Eurasia, from 45° to 70°N, constitute one-third of the total global forest area. Although we often imagine boreal forests as uniform, climate conditions differ greatly in such areas (Baldocchi et al. 2000). For example, annually averaged temperature ranges from − 10°C to 7°C, and annual precipitation is 200–600 mm. Consequently, the vegetation response and characteristics of the energy/water cycle most likely depend on location. However, it remains unclear whether the physiological characteristics themselves change or whether the changes are merely superficial responses.

   The energy and water balance over a forest is simulated using parameterization in land surface models. The evolution of the land surface model is described in detail in a review by Pitman (2003). Determination of the vegetation parameters in the model is difficult. Sellers et al. (1996b) estimated the time and space variation of canopy structure parameters, such as the leaf area index and the greenness fraction, using a satellite dataset. For stomatal conductance, which determines transpiration, these parameters were considered to depend on the tree species and climate conditions. However, these parameters are sometimes determined merely by the plant type (C_3 or C_4) because of the difficulty of setting parameters for individual tree species (e.g., Cox et al. 1999). Therefore, it would be advantageous to use a parameter set that is independent of plant type and climate.

   Yamazaki et al. (2004) evaluated forests and a grassland area in eastern Siberia using a one-dimensional land surface model. They showed that when both plant and leaf areas are given, the outline of seasonal water and heat balance can be simulated with the model using the same stomatal parameters for forests and grassland sites. Matsumoto et al. (2008a)

suggested the concept of common potential responses of surface conductance, which is a vegetation-scale parameter used in the Penman-Monteith equation (e.g., Monteith, 1981), to environments in five mature forests in three regions of the Far East. These authors showed that energy and water exchanges can be expressed using a single common parameter set determined on the basis of all data from the five forests (pooled data among all sites) as well as each parameter set determined using only within-site data. Park et al. (2008) examined the tempo-spatial characteristics of energy budget and evapotranspiration in eastern Siberia using the model of Yamazaki et al. (2004).

   The purpose of this study is to propose a new stomatal parameter set that can be used in land surface models for various forests not only in boreal regions but also in temperate regions. This study determines stomatal parameters on the basis of "leaf-level" within-site physiological measurements for eight species at nine sites in the Far East. Most land surface models that consider physical processes while separating leaf layers and the forest floor (soil layers) need leaf-level stomatal conductance (not vegetation-scale surface conductance, as studied in Matsumoto et al. (2008a)). Here, two types of parameter sets are determined: within-site (WS) parameter sets for each site using only within-site data and pooled common (PC) parameter sets using all pooled data.

   A Jarvis-type model will be used for stomatal conductance; Jarvis (1976) empirically expressed stomatal conductance as a function of environmental variables. During and after the 1990s, semi-empirical models, termed Ball-Berry type models, which incorporate carbon exchange and photosynthesis (Farquhar et al. 1980; Ball et al. 1987), were often used in land surface models (Collatz et al. 1991; Sellers et al. 1996a; Cox et al. 1999). However, in such models, equations related to photosynthesis must be solved simultaneously. Consequently, it is difficult to directly discuss the relationship between stomatal conductance and the environment, e.g., light intensity, temperature,

and dryness. Moreover, we specifically examine energy and water exchanges separately from carbon exchange. Therefore, we choose a Jarvis-type model that can easily analyze elements that restrict transpiration. Energy and water fluxes are simulated to validate the stomatal parameters using a land surface model for boreal and temperate forests, where input meteorological data and fluxes are observed and can be used for validation.

2. Model

2.1 Outline of the land surface model

The land surface model used in the present study is described in Yamazaki (2001) and Yamazaki et al. (2004) with the addition of a snow interception process (Yamazaki et al. 2007). The evapotranspiration factor in Yamazaki et al. (2004) is replaced by stomatal conductance, which is described later. This model is composed of three submodels: those of vegetation, snow cover, and soil. The entire model can calculate energy and water fluxes above and within the forest. Input data given over the forest as a whole are wind speed, air temperature, specific humidity, precipitation, solar shortwave radiation, and downward longwave radiation.

- Vegetation submodel

  In the vegetation submodel, the canopy is divided into a "crown space" and a "trunk space" (without leaves); the crown space is further subdivided into two layers (we term the vegetation submodel as the "two-layer model," abbreviated to "2LM"). The heat balance equations are solved as leaf-temperatures are unknowns. The submodel predicts the radiative, sensible, and latent heat fluxes among the atmosphere and the two crown layers. The heat storage and intercepted water on the leaves are also calculated.

- Snow-cover submodel

  The snow-cover submodel employs simple assumptions regarding both the structure and physical process of snow. The number of snow layers depends on snow depth, and the thickness of each layer is 0.02 m. To apply this model to intensely cold regions, the snow-cover submodel can incorporate depth hoar using an effective temperature gradient and can calculate snow temperature, density, and water content profiles.

- Soil submodel

  In the soil submodel, the soil (0–10 m) is divided into layers, the thickness of each of which is 0.1 m, except for the top layer, which is 0.02 m. To calculate soil temperature, we consider a heat

conduction equation. The heat of fusion in frozen soil is considered using a method in which the heat capacity is regarded as larger within a small temperature range near the melting point. Liquid water movement is also considered in this submodel. The equation is characterized by ground surface resistance including the effect of understory vegetation. Kelliher et al. (1997), Ohta et al. (2001), and Iida et al. (2009) reported that understory evapotranspiration reached 35−52% of the total evapotranspiration in larch forests in eastern Siberia, and Yamazaki et al. (2004) simulated understory evapotranspiration using this model.

The water used for transpiration is withdrawn from the top three soil layers (0–22 cm). However, if the layers are drier than the wilting point, water is pulled out from the lower layers.

2.2 Conductance expression

Each sensible/latent heat flux is assumed to be directly related to differences of temperature and specific humidity. For example, sensible heat flux from the canopy to the atmosphere is assumed proportional to the temperature difference between the top upper layer and the atmosphere over the canopy. The proportional coefficient is calculated considering atmospheric stability as well as roughness length and zero-plane displacement, which are functions of canopy density and height.

The transpiration generated in canopy layer i, E_{Ci}, is calculated as

$$E_{Ci} = \rho_a (\mathrm{PAI}' - \mathrm{PAI}'_{min}) \frac{\delta_i}{\delta} g_s (q_{sat}(T_{Ci}) - q_i), \qquad (1)$$

where ρ_a is the air density (kg m^{-3}); PAI' represents the effective plant area index; PAI'$_{min}$ is the effective plant area index excluding leaves; δ and δ_i show the thickness of crown space and each canopy layer (m), respectively; g_s is the stomatal conductance (m s^{-1}); T_{Ci} and q_i signify the canopy temperature (°C) and specific humidity (kg kg^{-1}), respectively, in each canopy layer; and q_{sat} represents the saturation-specific humidity.

The 2LM employs a Jarvis-type stomatal conductance model (Jarvis, 1976), which describes the relationship between stomatal conductance, g_s, and several variables. The Jarvis model is simple; it does not express photosynthesis processes and has the limitation that environmental variables do not provide feedback to each other. However, this model does provide the benefit of enabling the analysis of environmental elements that restrict transpiration. Considering four restricting terms, the stomatal

Table 1.   List of leaf-level gas exchange measurements. The botanical names of trees that grow in Japan are cited from Kitamura and Murata (1979).

genera	site	year	date	species (Botanical name)
Betula	Yakutsk (YKS)	2007	Jun 20, 24, 29, Jul 1, 4, 5	*Betula platyphylla* Sukatchev.
	Esso (ESO)	2003	Aug 8, 10, 15, 16	*Betula platyphylla* Sukatchev.
	Moshiri (MOS)	2004	Jul 24, 29, Aug 7, 14	*Betula ermanii* Cham.
	Sapporo (SAP)	2006	Jul 22, Oct 4, 5	*Betula platyphylla* Sukatchev var. *japonica*
	Aokigahara (AOK)	2006	Jul 27, 29 Aug 1, 3, 5	*Betula grossa* Siev. et Zucc.
Quercus	Seto (SET)	2003	Jun 5, 27	*Quercus serrata* Murray
	Yamashiro (YAM)	2006	Sep 20–22, 24, 25	*Quercus serrata* Murray
Larix	Yakutsk (YKS)	2005	Jun 20, 27, Jul 4, 13	*Larix cajanderi* Mayr.
	Esso (ESO)	2003	Aug 8, 10, 15, 16	*Larix cajanderi* Mayr.
	Sapporo (SAP)	2006	Aug 11, 27, Sep 9	*Larix kaempferi* (Lamb.) Carriere
Pinus	Fujiyoshida (FUJ)	2006	Aug 25, 29, 31 Sep 2, 3	*Pinus densiflora* Siev. et Zucc.
	Okayama (OKA)	2006	Aug 8, Sep 15, 22	*Pinus densiflora* Siev. et Zucc.

conductance g_s is described as follows:

$$g_s = g_{smax} \cdot f_1(\text{PPFD}) \cdot f_2(\text{VPD}) \cdot f_3(T_{leaf}) \cdot f_4(\theta) \qquad (2)$$

$$f_1(\text{PPFD}) = \frac{\text{PPFD}}{\text{PPFD} + \dfrac{1}{a}} \qquad (3)$$

$$f_2(\text{VPD}) = \frac{1}{1 + \left(\dfrac{\text{VPD}}{D_{50}}\right)^b} \qquad (4)$$

$$f_3(T_{leaf}) = \left(\frac{T_{leaf} - T_{min}}{T_o - T_{min}}\right) \cdot \left(\frac{T_{max} - T_{leaf}}{T_{max} - T_o}\right)^{\left(\frac{T_{max} - T_o}{T_o - T_{min}}\right)} \qquad (5)$$

$$f_4(\theta) = 1 - \exp\left[k\left(\theta_{min} - \theta\right)\right] \qquad (6)$$

In Equations (2)–(6), g_{smax} is the maximum stomatal conductance (observed maximum value, m s^{-1}); f_1, f_2, f_3 and f_4 are functions ranging from 0 to 1; PPFD is the photosynthetic photon flux density (μmol m^{-2} s^{-1}); VPD is the vapor pressure deficit (kPa); T_{leaf} is the leaf temperature (°C); θ is the volumetric soil water content (%); a is the slope of the function f_1 (PPFD) at PPFD = 0, b is the curvature; D_{50} is the value of VPD when g_s = 0.5 g_{smax}; T_o is the optimum temperature (°C); T_{min} and T_{max} are the minimum and maximum temperatures, respectively, for active transpiration (if $T_{leaf} < T_{min}$ or $T_{leaf} > T_{max}$, f_3 is set to 0)(°C); θ_{min} is the minimum soil water content; and k is a parameter. In fact, θ is averaged between the soil surface and a depth of approximately 0.5 m; the depth varies by site because the measurement depth is not the same at all sites.

3.   Data

3.1   Measurement of stomatal conductance

We measured stomatal conductance using a portable open-flow gas exchange system (LI-6400; Li-Cor Inc., USA) at nine sites for four genera; these cover the eight species listed in Table 1 and shown in Fig. 1. Stomatal conductance was measured in intact canopy leaves under natural conditions. The measurement interval was 1–2 h from predawn to sunset. Air and leaf temperatures (T_{air} and T_{leaf}), relative air humidity, and PPFD at the leaves were logged simultaneously during the stomatal conductance measurements.

3.2   Parameter Determination

Parameter values were fitted simultaneously by a nonlinear least squares technique using the equation solver in Excel (Microsoft Corp.) to minimize the root mean square error (RMSE) between the measured and estimated values using Eqs. (2)–(6) for g_s. However, if the estimated value obtained with the function of certain environment variables is greater than the measured value (meaning that the function is not an envelope curve of the measurements), then the estimated stomatal conductance is always smaller than the measured conductance. Therefore, to determine the parameters, we impose the constraint that each of Eqs. (3)–(6) envelop the plotted data. Moreover, to avoid difficulty in determining the parameters, T_{min} is limited to $0°C < T_{min} <$ observed minimum temperature; T_{max} is limited to observed maximum temperature $< T_{max} < 50°C$. In addition, θ_{min} is fixed at 5%, although this parameter might depend on soil type.

First, we determined the WS parameters for each site using only the data measured within each site and
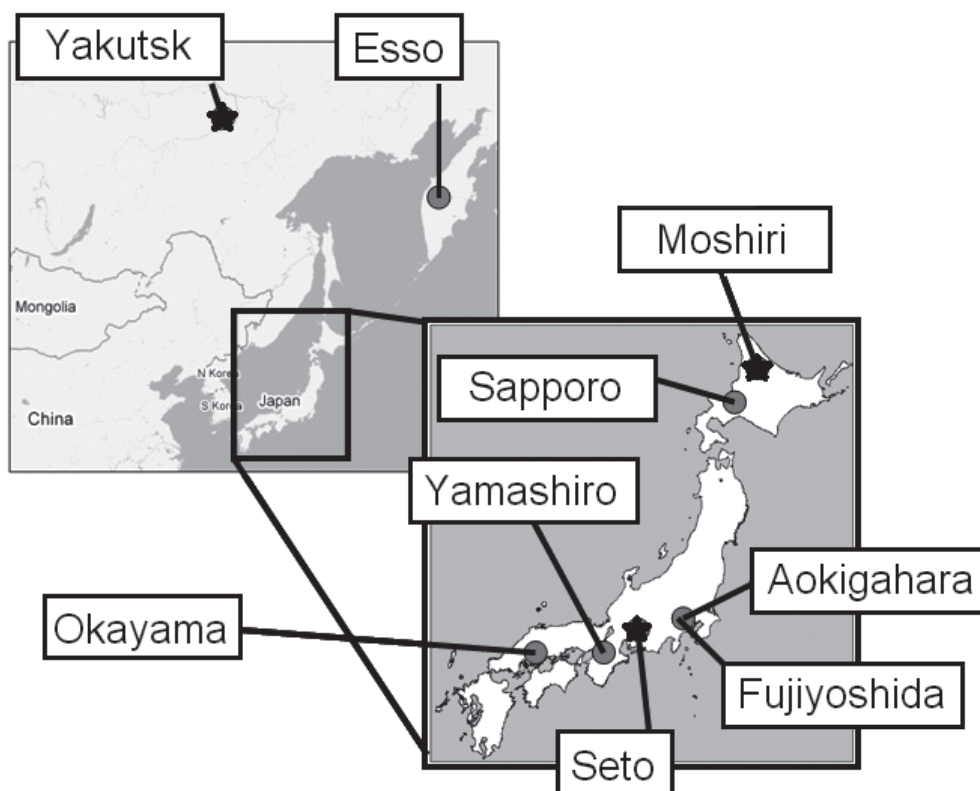
Fig. 1.   Location map of stomatal conductance measurements. The stars show the regions where meteorological data and energy fluxes were also measured.

Table 2.   Characteristics of the sites used to validate the model.

Site, Year	Latitude, Longitude	Main species	Canopy height (m)	Tower height (m)	PAI'$_{min}$	PAI'$_{max}$
Yakutsk Larch (YL), 2004	62°15'N, 129°37'E	*Larix cajanderi*	18	32	0.8	1.2
Moshiri Birch (MB), 2005	44°23'N, 142°19'E	*Betula ermannii*	11.5	20	0.5	1.4
Moshiri Mixed (MM), 2005	44°19'N, 142°16'E	*Betula platyphylla, Phellodendron amurense, Quercus crispula*	25	30	0.7	2.0
Seto Mixed (SM), 2003	35°15'N, 137°04'E	*Quercus serrata, Evodiopanax innovas, Ilex pedunculosa*	8	18	1.7	3.5

for each species. In principle, it is expected that the model simulates the energy and water balance reasonably for certain sites and species based on the parameters of the site. However, these WS parameters do not apply to other sites and species. Therefore, we determined a set of PC parameters by using pooled measurement data for all sites.

3.3   Measurement of fluxes and forcing data

We measured meteorological and hydrological data including energy fluxes at four towers in three regions, which are marked by stars in Fig. 1 (no flux data are available for the other regions). Table 2 shows the location, vegetation species, canopy and tower heights, and plant area index at each site. In Yakutsk, Russia, we adapted the model to a larch forest (YL) that
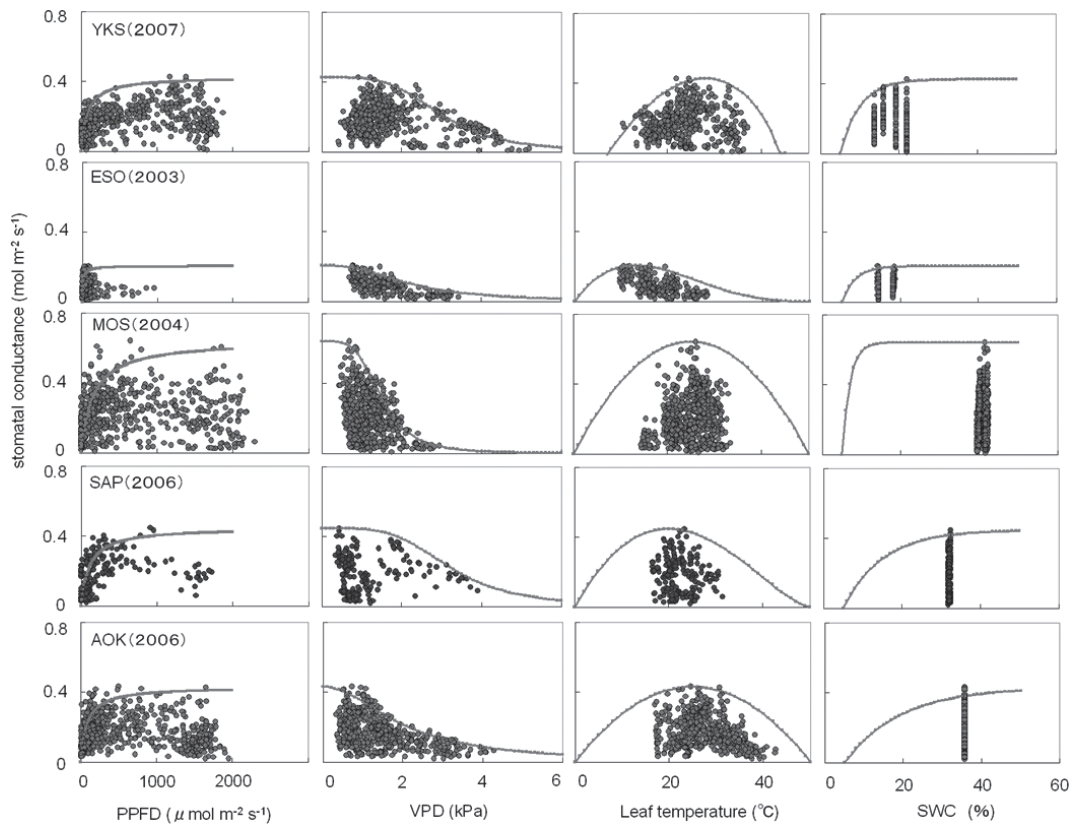
Fig. 2. Observed stomatal conductance and fitting curves for various environmental conditions (Betula, within-site analysis). Refer to Table 1 for site abbreviations.

experiences continuous permafrost (Ohta et al. 2001). Daily mean air temperatures are less than $-40°C$ in midwinter but reach approximately $25°C$ in summer; annual precipitation is 237 mm in Yakutsk. In Moshiri, Japan, we have two towers: one is in a birch forest (MB) and the other is in a mixed forest of evergreen conifers and deciduous broadleaf trees (MM). Moshiri is in a region that experiences heavy snow (the snow depth reaches 2–3 m), and the annual mean air temperature and precipitation are approximately $4°C$ and 1900 mm, respectively. In Seto, Japan, one tower is located in a mixed forest of deciduous and evergreen broadleaf trees (SM). The annual air temperature and precipitation in this region are approximately $15°C$ and 1600 mm, respectively. More detailed descriptions of the site and observation methods can be found in Matsumoto et al. (2008b). We used meteorological data obtained above the forest as input data to activate the model. We then used measured energy fluxes to validate the model.

For model simulation, we require the plant area index, PAI, and the leaf area index, LAI. Because we did not measure the PAI and LAI directly, the seasonal changes in PAI were obtained from the measured ratio of solar radiation on the forest floor to solar radiation above the forest. LAI is calculated as $PAI-PAI_{min}$, where PAI_{min} is the stem and branch area per unit ground area. For the YL and MB sites, PAI_{min} is obtainable as PAI in winter because the forest is deciduous. However, it is difficult to determine PAI_{min} at the MM and SM sites because leaves remain on the trees in winter in these mixed forests. Therefore, we assumed PAI_{min} for the MM and SM sites from the ratio of PAI_{min} to PAI_{max} at other sites.

Simulated energy fluxes are validated by comparing the Bowen ratio (sensible heat flux/latent heat flux) as well as the observed sensible and latent heat fluxes. The reason for using the Bowen ratio is that the net radiation is larger than the sum of sensible and latent heat fluxes as indicated at most forest sites (e.g., Matsumoto et al. 2008b). A possible cause of this is the existence of systematic structures in the atmospheric
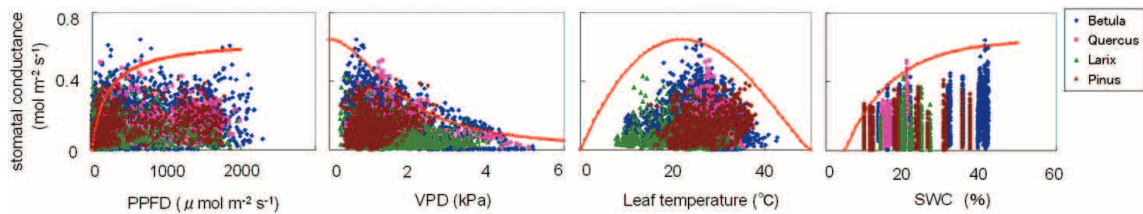
Fig. 3. Observed stomatal conductance and fitting curves for various environmental conditions (pooled from all site and species data).

Table 3. Stomatal parameters estimated from leaf-level gas exchange measurements.

genera	site (year)	g_{smax} mol m^{-2} s^{-1}	a (μmol m^{-2} s^{-1})$^{-1}$	T_o °C	D_{50} kPa	b	T_{min} °C	T_{max} °C	k
Betula	YKS (2007)	0.43	0.0117	28.0	3.00	4.00	7.4	43.6	0.200
	ESO (2003)	0.19	0.0897	13.0	2.20	2.50	0	50	0.297
	MOS (2004)	0.64	0.0062	25.0	1.50	4.00	0	50	0.500
	SAP (2006)	0.45	0.0089	20.0	3.22	4.00	0	50	0.100
	AOK (2006)	0.43	0.0116	25.0	2.00	2.00	0	50	0.070
Quercus	SET (2003)	0.52	0.0057	26.4	2.13	3.25	0	50	0.972
	YAM (2006)	0.29	0.0069	30.0	2.80	7.90	0	50	0.200
Larix	YKS (2005)	0.43	0.0069	15.0	2.00	1.80	0	50	0.150
	ESO (2004)	0.20	0.0133	15.0	2.20	2.50	0	50	0.200
	SAP (2006)	0.37	0.0565	25.0	2.00	2.00	0	50	0.100
Pinus	FUJ (2006)	0.35	0.0113	22.0	1.30	2.00	0	50	0.070
	OKA (2006)	0.41	0.0070	30.0	2.50	4.00	0	50	0.201
	All pooled	0.64	0.0050	22.0	1.80	2.00	0	50	0.080

boundary layer (e.g., Lee 1998). Moreover, the Bowen ratio is the most important index for evaluating the effect of the land surface on the atmosphere because it indicates the distribution of the incoming radiation flux.

4. Results

4.1 Parameter fitting

Figure 2 shows the observed stomatal conductance and fitting curves for each site containing Betula (WS: within-site analysis). The results show that the relationship between environmental variables and stomatal conductance differs depending on the site. Note that some plots exceed the value obtained from fitting curves in spite of the constraint to envelop the plotted data because of characteristics of the least squares method. For other genera, the relationship between environmental variables and stomatal conductance varies among sites and years (data not shown). In contrast, Fig. 3 shows the pooled data on the same graphs. The plots are distributed complementari-

ly. Therefore, we can determine a common parameter set by drawing a fitting envelope line for each environmental variable (pooled common analysis: PC). Each envelope is dominated by data collected at a few sites where the value of conductance is large. The plots representing sites with small conductance are restricted by other environmental variables.

Table 3 presents estimated stomatal parameters: the last line of the table is the PC parameter set. The remaining lines are WS parameter sets for each genus and site. The WS parameters except for T_{min} and T_{max} are widely distributed. The value of g_{smax} in PC is given as the maximum value measured over all sites. Because g_{smax} is measured in moles per square meter per second, we must divide these values in Table 2 by moles per unit volume of air (41.4 mol m^{-3}) to obtain the conductance in meters per second, as used in Eq. (1).

Figure 4 illustrates the reproducibility of the stomatal conductance using WS and PC parameter sets. The calculated stomatal conductance exhibits a large scatter with the PC parameter set for Pinus
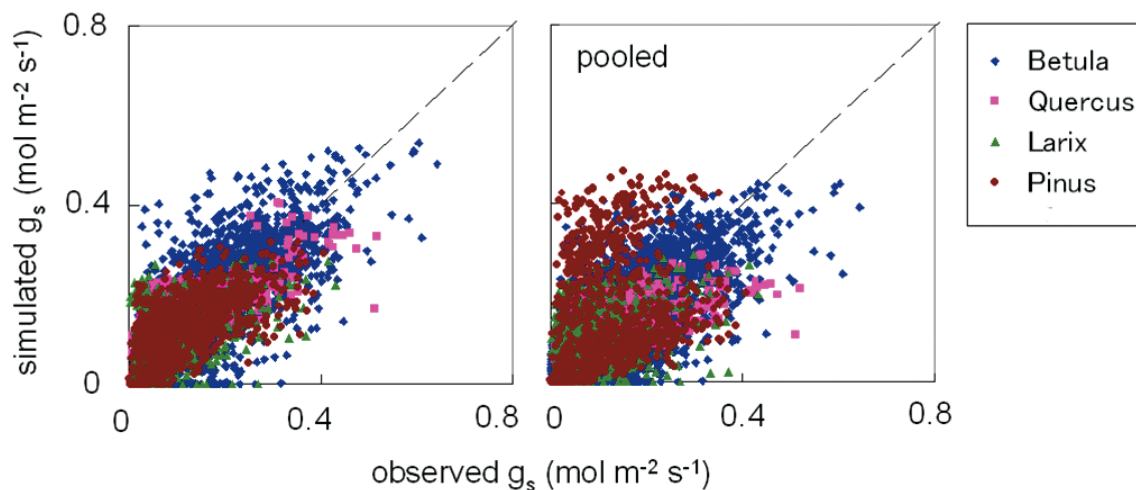
Fig. 4.   Reproducibility of stomatal conductance. Left: within-site analysis (WS), Right: pooled common analysis (PC).

Table 4.   Root mean square errors (RMSE) of estimated stomatal conductance (mol m^{-2} s^{-1}) and the ratio of the RMSE obtained using PC parameters to that obtained using the WS parameters.

genera	site (year)	WS	PC	PC/WS
Betula	YKS (2007)	0.0587	0.0713	1.215
	ESO (2003)	0.0280	0.0500	1.783
	MOS (2004)	0.0866	0.0897	1.036
	SAP (2006)	0.0775	0.0810	1.045
	AOK (2006)	0.0497	0.0585	1.178
Quercus	SET (2003)	0.0537	0.0694	1.293
	YAM (2006)	0.0601	0.0473	0.788
Larix	YKS (2005)	0.0423	0.0485	1.147
	ESO (2004)	0.0266	0.0320	1.204
	SAP (2006)	0.0906	0.1017	1.122
Pinus	FUJ (2006)	0.0597	0.1471	2.463
	OKA (2006)	0.0456	0.0700	1.536
	overall	0.0572	0.0724	1.265

forests. Table 4 presents the RMSE for the WS and PC parameter sets. The overall RMSEs are 0.0724 for the PC parameter and 0.0572 for the WS parameter. The RMSE of PC is greater than that of WS by 26.5%. Similar fluxes can be simulated when PC parameters are used, as shown in section 4.2. The ratios of the RMSE for the PC parameters to those of the WS parameters are between 1.0 and 1.3, except for FUJ2006, ESO2003, OKA2006, and YAM2006.

4.2   Simulation of seasonal variations in energy flux

The simulated fluxes at the Yakutsk larch site (YL) are presented in Fig. 5 (within-site: WS) and Fig. 6 (pooled common: PC). The lower panels show a comparison of the Bowen ratio calculated using observations and that obtained using model simulation. Both parameter sets, WS and PC, can simulate reasonable seasonal changes in energy fluxes. Snow disappears on 18 May in the simulation, and leaves open on trees between May 27 and June 13. The estimated daily mean errors (model-obs.) for sensible and latent heat fluxes in the foliating season (28 May to 6 August) are 5 W m^{-2} and -1 W m^{-2} for WS and 4 W m^{-2} and -1 W m^{-2} for PC, respectively. Obviously, the simulated sensible heat flux in the snow-covering period is larger than that observed. However, the sum of observed sensible heat and latent heat fluxes is 50–70 W m^{-2}, it is smaller than the observed mean net radiation of 103 W m^{-2} (7 April to 30 April). The latent heat flux increases over the forest because of foliation. Conversely, the sensible heat flux decreases, although most of the net radiation is transformed into sensible heat before the snow disappears. At the forest floor, latent heat is considerable (approximately half of that over the forest). However, the sensible heat flux is approximately zero.

Figures 7 and 8 depict the simulated fluxes and the Bowen ratio at the Moshiri birch site (MB). Snow disappears on June 19, foliation occurs on June 5–20, and defoliation occurs on October 8–23. The simulated Bowen ratio is reasonable in June and July but is overestimated in August and September, especially
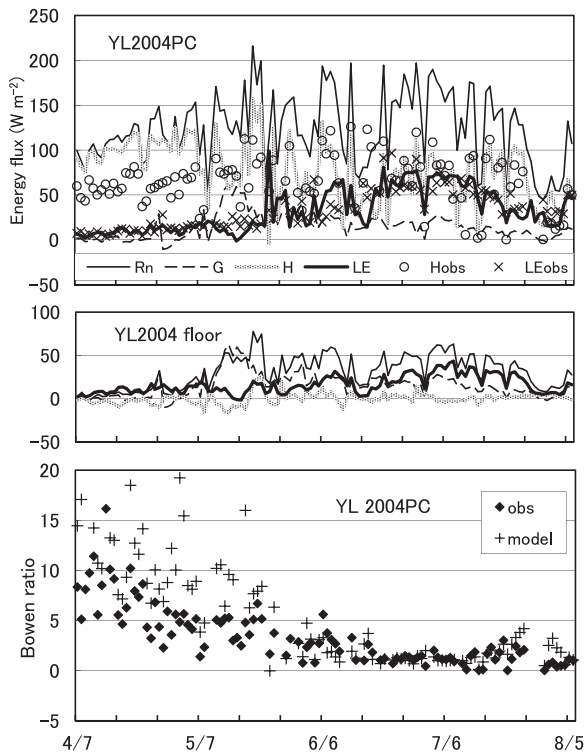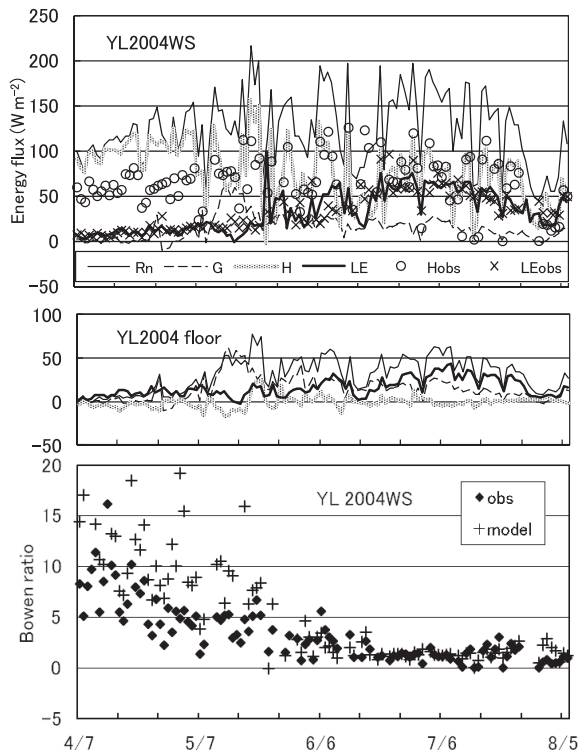
Fig. 5. Simulated fluxes and Bowen ratios at the Yakutsk larch site (YL) using WS parameters. Circles and crosses in the upper panel are observed sensible and latent heat fluxes over the forest, respectively. The middle panel indicates simulated fluxes at the forest floor.

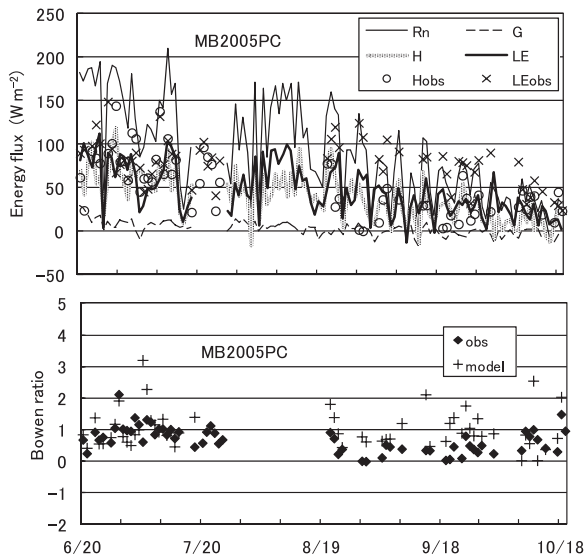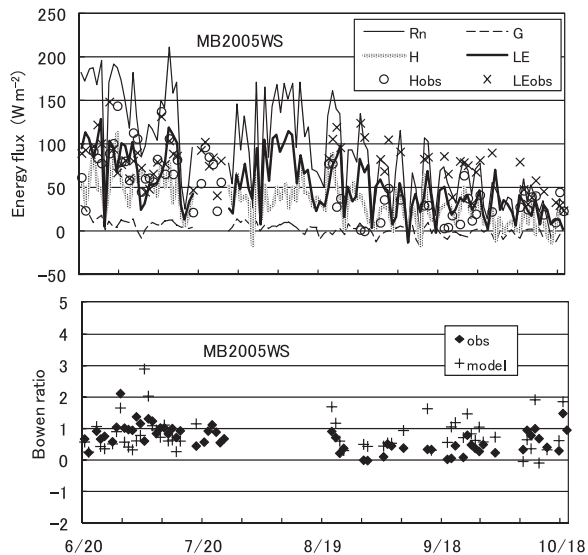Fig. 6. The same as Fig. 5, except for using PC parameters.

Fig. 7. Simulated fluxes and Bowen ratios at the Moshiri birch site (MB) using WS parameters.
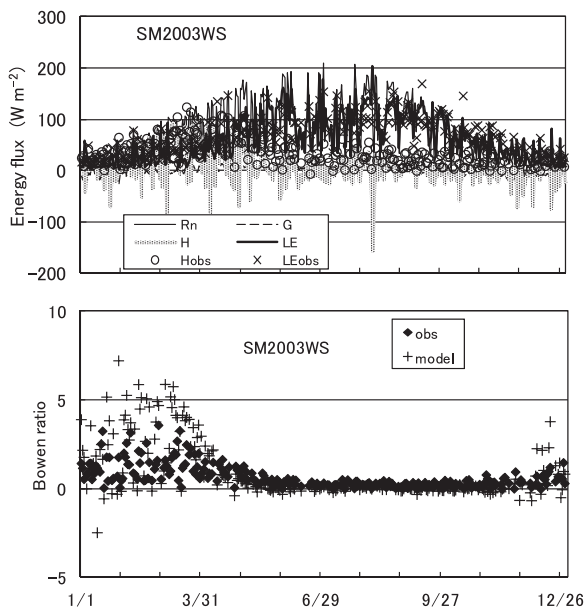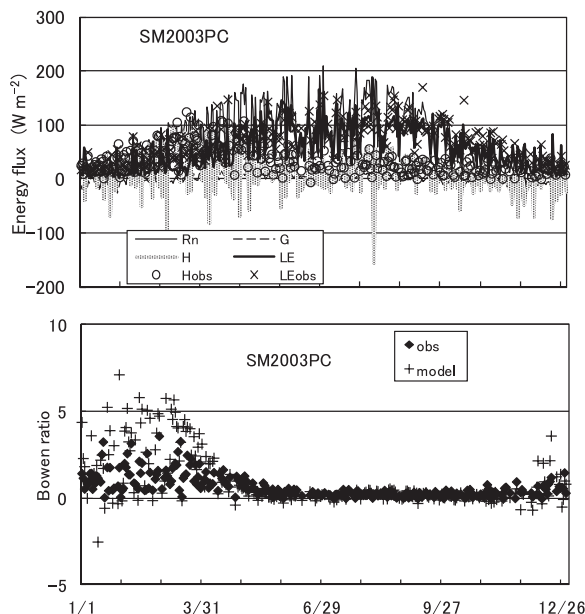
Fig. 8. The same as Fig. 7, except for using PC parameters.

Fig. 9.   Simulated fluxes and Bowen ratios at the Seto mixed forest site (SM) using WS parameters.

Fig. 10.   The same as Fig. 9, except for using PC parameters.

when using PC parameters (Fig. 8). The estimation errors for sensible and latent heat flux during the entire period are 7 W m^{-2} and -21 W m^{-2} for WS and 12 W m^{-2} and -28 W m^{-2} for PC, respectively. In June and July, the values are -14 W m^{-2} and -2 W m^{-2} for WS and -4 W m^{-2} and -12 W m^{-2} for PC, respectively. In August and September, the values are 22 W m^{-2} and -35 W m^{-2} for WS and 27 W m^{-2} and -39 W m^{-2} for PC, respectively. For the Moshiri mixed forest site (MM), we executed the simulation using the PC and WS parameters for the MB site because we were unable to obtain leaf-level gas exchange data except for birch in Moshiri, and we assumed a PAI$_{min}$ of 0.7 (figure omitted). The simulated Bowen ratio for 2005 is distributed between 0 and 2 and almost agrees with the observation, although the value is small when WS parameters are used. The estimation errors of sensible heat and latent heat flux during the entire period are -24 W m^{-2} and 9 W m^{-2} for WS and -15 W m^{-2} and -0.5 W m^{-2} for PC, respectively.

Figures 9 and 10 show the results for the Seto mixed forest site (SM). At this site, net radiation balances latent heat in summer; consequently, the Bowen ratio becomes less than 1. This situation is simulated using both WS and PC parameters. Many negative spikes are found in the simulated sensible heat flux. These days are rainy; thus, evaporation from intercepted rain is large; the main energy source of this evaporation is sensible heat from the air to canopy. The eddy covariance measurement system does not work in rainy days; thus, we have no data of sensible and latent heat fluxes for these days. The latent heat flux is overestimated (i.e., the Bowen ratio is small) in spring and summer, especially during April and May, when the WS parameter is used. The estimated fluxes are reasonable when the PC parameter is used, although the latent heat flux is slightly overestimated in May. The estimation errors for sensible heat and latent heat flux during the entire period are -14 W^{-2} and -2 W m^{-2} for WS and -8 W m^{-2} and -8 W m^{-2} for PC, respectively.

Consequently, outlines of seasonal flux changes are simulated using both WS and PC parameter sets for the four sites presenting various climate conditions and forest types. Energy and water fluxes can be simulated using only one parameter set, at least for forests throughout a wide region of the Far East. The PC parameter set is more general. Moreover, this finding suggests that the concept of common potential responses (Matsumoto et al. 2008a), which is proposed at the canopy scale, is reasonable in terms of the land surface model including leaf-level parameters.

Our results suggest that the characteristics of vegetation responses to the environment do not vary widely over a large scale, which might explain why many land surface models simulate the energy and
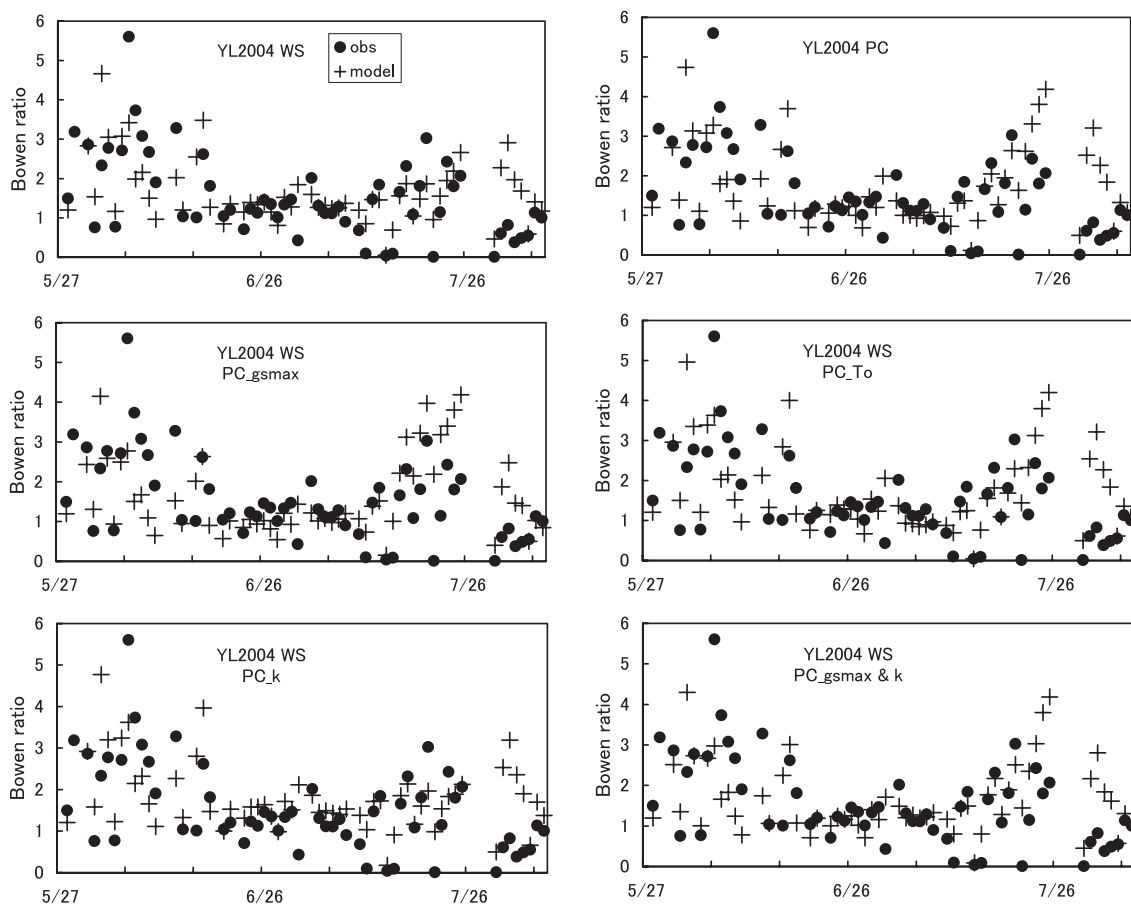
Fig. 11.   Sensitivity of the Bowen ratio to parameters (YL2004). Upper left panel: simulated using WS parameters. Upper right panel: simulated using PC parameters. Other panels: simulated using WS, but only certain parameter (s), which are indicated in each panel, are changed to PC parameter (s).

water balance reasonably, even though, as described in section 1, stomatal parameters are based simply on plant type.

5.   Discussion

Despite having different values, the WS and PC parameters are both useful to calculate the same flux. The reason for this will be discussed using sensitivity experiments with changed parameter values. At the YL site, significant differences were found in the parameters of g_{smax}, T_o, and k. We examined the Bowen ratio using the WS parameter set, but only a certain parameter of g_{smax}, T_o, and k is changed to the PC parameter from the WS parameter. Figure 11 shows the results of these sensitivity experiments. The upper left panel illustrates a simulation using all parameters of the WS set in YL, and the upper right panel shows a

simulation using all parameters of the PC set. The Bowen ratio obtained using the PC parameters is slightly smaller than that obtained using the WS parameters. The Bowen ratio becomes large at the end of July in the PC simulation because transpiration is significant during the early part of the season and the soil becomes dry. The Bowen ratio decreases until the beginning of July but increases at the end of July because of soil water shortage; at this time, only g_{smax} is changed from WS to PC (middle left panel of Fig. 11). In contrast, when only k is changed from WS to PC (lower left panel of Fig. 11), the Bowen ratio increases until the beginning of July. Almost the same Bowen ratio is calculated if both g_{smax} and k are changed from WS to PC (lower right panel of Fig. 11). Consequently, the effects of both g_{smax} and k offset each other. Because the value of g_{smax} is given as the maximum value for

considering data, the value of g_{smax} in WS is less than that in PC. This means that the restriction is weak in PC and the other restricting terms strongly work. In contrast, g_{smax} is a significant restricting factor in WS. The effect of the change in T_o is to decrease the Bowen ratio until the beginning of July; for this reason, the Bowen ratio decreases slightly when using PC parameters until the beginning of July. This explanation is valid only for YL and does not universally express that WS and PC parameter sets give similar fluxes. For PC parameter sets, what parameter, except for g_{smax}, is strongly related to restricting transpiration depends on climate and soil water conditions; further investigation will be performed in a future study.

As shown in Figs. 7 and 8, for the MB site, a smaller latent heat flux (a larger Bowen ratio) is simulated when the PC parameter set is used. The parameter k differs depending on whether WS or PC parameters are used for the simulation at the MB site. The Bowen ratio becomes similar to that obtained in the PC simulation when only k is changed from WS to PC. For the MB site, the WS parameter engenders a slightly larger Bowen ratio. There are several possible reasons for this. 1) Leaf-level stomatal conductance was measured under a narrow range of conditions at each site. For that reason, the PC parameter, which covers a wide range of environmental conditions, might be more general. 2) The absence of a tuning calculation for the determined parameters, which are independent of the land surface model, does not guarantee reproducibility even if the calculation is determined from WS data. Model estimated energy fluxes depend not only on stomatal conductance but also on other model components and parameters. In particular, uncertainties in PAI affect the estimation of heat balance. The simulation error of fluxes using the WS parameter is larger than that obtained using the PC parameter (e.g., YL2004 and MM2005), apparently for the same reason.

The parameter T_o was determined under limitations on T_{min} and T_{max} described in Section 3.2; thus, T_{min} and T_{max} were mostly fixed at $0°C$ and $50°C$. To discuss arbitrariness of T_o, we examined estimation errors for sensible and latent heat fluxes with change of T_o by $±5°C$ from WS and PC parameters. The differences of errors from WS and PS parameters were smaller than 5 $W\ m^{-2}$. This means that heat balance is not sensitive to the value of T_o, and we can estimate T_o roughly.

6. Concluding remarks

Seasonal flux changes were simulated based on leaf-scale stomatal parameters measured at each site

(within-site responses) in the Far East with no tuning for boreal and temperate forests. Almost identical results were obtained using a parameter set determined using all pooled data; the parameter set is apparently a potential response to environments. This pooled common parameter set is available for various climate and forest type regions of the Far East. The results support the concept of common potential responses from the viewpoint of the land surface model. This concept is applicable to other land surface models that can distinguish leaf from nonleaf (branch and stem) matter.

Finally, we describe objectives for future study. We will examine the applicability of the concept and the efficiency of common pooled parameters for other areas including tropical forests. When the applicability of this concept is proved, it can become the basis for expressing a forest (or vegetation) with one parameter set; this will be of great benefit to studies of climate and hydrology and to the future prediction of climate and water cycles. Although we chose the Jarvis-type conductance model, we expect that the concept can be extended to the Ball-Berry type model, which relates stomatal conductance to CO_2 exchange.

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