Inverse Analysis of the Effect of Soil Vertical Heterogeneity on Land Surface and Subsurface Processes

*** Kun Yang[1], Toshio Koike[1], Baisheng Ye[2]**
(1: University of Tokyo, 2: Chinese Academy of Science)
*** River Lab., Dept. of Civil Engineering, University of Tokyo, Hongo 7-3-1, Bunkyo-ku, Tokyo 113-8656, Japan.**
e-mail: yangk@hydra.t.u-tokyo.ac.jp

Abstract

Surface soil moisture and temperature have been widely addressed in land surface processes modeling and satellite remote sensing, because they play a key role in land surface energy and water budget. However, it is rather difficult for most of land surface models to reproduce the surface soil state in areas with high soil vertical heterogeneity, because these models use a single parameter-set to characterize soil hydraulic and thermal processes. This study develops a single-source land surface model to parameterize this heterogeneity. Its soil parameters are inversely estimated by minimizing a cost function that is objectively determined by the discrepancy between observed and model-predicted values of soil moisture and temperature. The approach is then used to investigate how the soil vertical heterogeneity affects subsurface processes and thus controls soil surface state and surface energy budget. By a synthetic numerical experiment and a Tibet field experiment, we indicate that (1) vertical heterogeneous soils cannot be effectively approximated by vertically homogenous soils in a land surface model no matter how the soil parameters are adjusted; (2) soil vertical heterogeneity obviously affects soil subsurface processes, and plays a very important role in controlling surface soil wetness and surface energy partition; (3) in particular, the existence of dense vegetation roots in topsoils may significantly reduce thermal conductivity, increase soil water potential, and enhance surface evaporation. We therefore conclude that it is indispensable to take the soil vertical heterogeneity into account in land surface models, although most of them still assume vertically uniform soil parameters.

Keyword: Inverse approach, soil parameter estimation, soil vertical heterogeneity, surface energy partition

1. Introduction

Soil structures are not only horizontally heterogeneous but also often vertically heterogeneous. The top layer of a soil can have a soil texture and amount of organic matters different from the deep layer. In this study, we intend to evaluate the effects of soil vertical heterogeneity in land surface processes, which can play an important role in some regions but have not been widely addressed in land surface models (LSMs). For this purpose, this study develops a LSM that can take soil vertical heterogeneity into consideration. Because some parameters are highly variable or sensitively change the input-state-output response, we use an inverse approach to estimate soil parameters in this LSM, so that the model can reproduce the observed soil state. While many early studies (Gupta et al., 1999; Bastidas, 1999) only use near-surface soil moisture and ground temperature, this study uses detailed measurements of soil moisture and temperature at several soil depths to estimate soil parameters and investigate soil vertical heterogeneity. The inverse approach consists of three main steps, comprised of (1) a land surface model to predict soil moisture and temperature profiles and surface fluxes, (2) a cost function to express the discrepancy between observed and model-predicted values of soil moisture and temperature (Section 3), and (3) an efficient scheme to search the global minimum of the cost function (Section 4). Then, the inverse approach is used to investigate the effect of soil vertical heterogeneity on soil wet ness, ground temperature, and surface energy partition (Section 5). Finally, we summarize the results (Section 6)

2. A Single-Source Land Surface Model

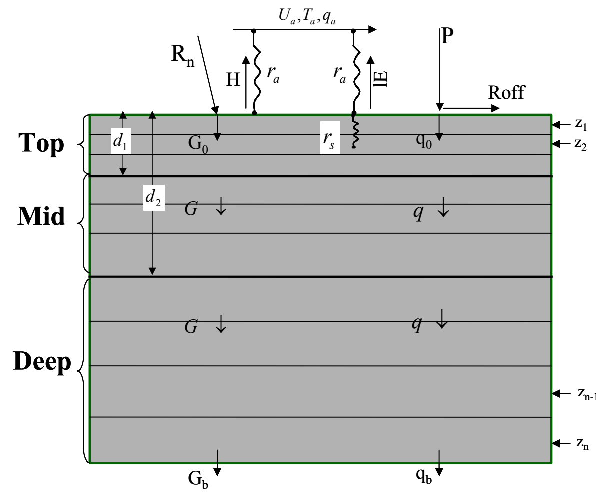

Fig. 1 Schematic of the single-source land surface model

Yang et al. (2004) suggested that single-source concept is applicable to bare soil surfaces or sparsely and shortly vegetated surfaces. The single-source model used in this study is simplified from a dual-source model (Sellers et al., 1996). The single-source model structure is shown in Fig. 1. It has three distinct features: (1) flux parameterizations for bare soils or shortly vegetated surfaces are improved based on the GAME-Tibet experiments (Yang et al., 2002); (2) soil subsurface water and heat flows are simulated by a multi-layer scheme; and (3) soil vertical heterogeneity is parameterized. The model consists of a bulk parameterization of surface turbulent fluxes, Richards' Law to calculate the soil water flow, and thermal diffusion equation to calculate the soil heat flow. Vertically heterogeneous soil column is approximated by two uniform domains (top soil domain, bottom soil domain) and a transitional domain between the two. Each domain consists of a number of layers, thinner in the top domain (~1 cm) and thicker in the bottom domain (~10 cm). The number of computational layers is adjustable.

3. Inverse model

Input data of the inverse model include forcing data to drive the LSM, and soil moisture and temperature profiles for calibrations. There are many parameters in the LSM. Surface albedo can be derived from measured downward and upward short-wave radiations; aerodynamic roughness length z_0 can be derived from wind profiles; the surface emissivity is specified as 0.97; the soil bulk density ρ_d is measurable by experiments; hydraulic conductivity is roughly estimated by an empirical formula. Therefore, we select the parameters in Table 1 for optimization.

Table 1 Optimized parameters of the land surface model.

Parameter	Symbol	Unit
Soil porosity	θ_s	$m^3\ m^{-3}$
Hydraulic parameters	ψ_s	m
	b	—
Thermal parameters	λ_m	$W\ m^{-1}\ K^{-1}$
	k_T	—
Boundary of transitional domain	d_1	m
	d_2	m

In this study, we simultaneously estimate soil hydraulic and thermal parameters. To establish a single-criterion for a multi-objective calibration, it is crucial to select weight numbers to maintain a trade-off between different measures in the cost function. In this study, we use the following objective function:

$$F = RMSE_T / RMSE_{T,\min} + RMSE_\theta / RMSE_{\theta,\min} \qquad (1)$$

where $RMSE_T$ and $RMSE_\theta$ represent the root mean square errors of soil temperature and soil water content, respectively. $RMSE_{T,min}$ and $RMSE_{\theta,min}$ are their minimum values.

The optimization includes two steps: step I, minimize $RMSE_T$ to obtain $RMSE_{T,min}$, and minimize $RMSE_\theta$ to obtain $RMSE_{\theta,min}$; step II, minimize the multi-objective function Eq. (1) using the same data set and the same LSM as model operator.

4. Optimization Algorithm

Optimizing parameters is a tough task in inverse problems of soil parameters because cost functions usually have multi-parameters and are highly nonlinear, non-derivable and even discontinuous. The parameter space usually contains multiple minima. To find the global minimum, this study adopts the Shuffled Complex Evolution method developed at The University of Arizona (SCE-UA) (Duan et al., 1992).

5. Case studies

The inverse approach described above is used to calibrate the land surface model to two different data sets. The first is a numerically generated data set (hereafter identical twin). The second is a real data set collected at the GAME-Tibet Anduo site. Both cases are used to clarify (1) how soil vertical heterogeneity can affect surface soil state and energy partition, and (2) whether vertically heterogeneous soils can be approximated by uniform soils with adjustable parameters. In addition, we show the capacity of the inverse approach in estimating parameters by the identical twin study, and address effects of vegetation roots on soil properties by the Tibet case study.

5.1 Identical twin

5.1.1 Data set. We assume that the total soil depth is 1.6 m and that this total depth is represented by three soil layers with thickness values of 0.10, 0.15, 1.35 meters (in other words, $d_1 = 0.1\,\mathrm{m}$, $d_2 = 0.25\,\mathrm{m}$). We also assume that the topsoil is a typical clay loam with a higher porosity and water potential and the bottom soil is a typical sandy loam with a lower porosity and water potential. The ground is a bare soil surface, which is wetted by two-day continuous precipitation every 10 days in the first month, and dried in other days. A diurnally varying wind speed, temperature, radiations, and a constant specific humidity are used to drive the model. The model is then integrated 60 days (hereafter forward run). Soil moistures at five depths and soil temperatures at nine depths are recorded hourly. These data are used as input data in the inverse estimation.

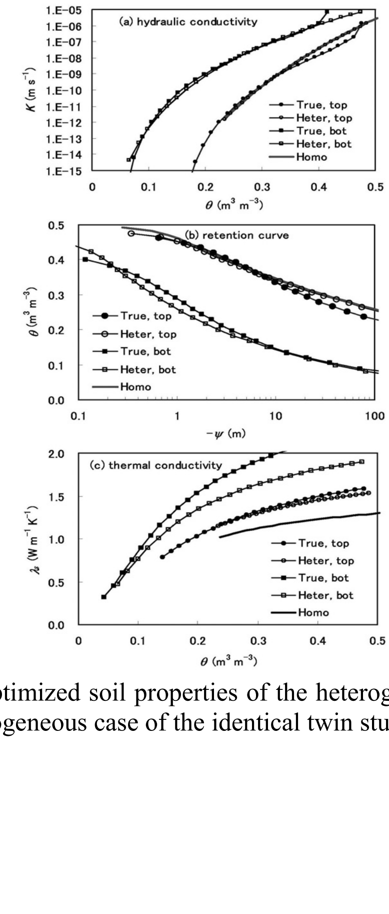

Fig. 2 Optimized soil properties of the heterogeneous case and homogeneous case of the identical twin study.

5.1.2 Parameter estimation and optimized output. We carry out two calibrations: one considers the heterogeneity and uses different parameter-sets to characterize top and bottom soils (hereafter heterogeneous case); the other uses a single uniform parameter-set to characterize the heterogeneous soil (hereafter homogenous case). For comparisons, results of the two cases are summarized in Fig. 2 - Fig. 4. Fig. 2 shows the estimated soil hydraulic and thermal properties; Fig. 3 and Fig. 4 present the scatter-plots showing the comparisons of simulated soil surface variable and energy partition between the "truth" run and the optimized run. The heterogeneous case reasonably optimizes soil hydraulic functions and thermal properties, while the homogenous case does not (Fig. 2). The heterogeneous case also output correct ground temperature, soil water content, sensible heat fluxes, and latent heat fluxes (Fig. 3) while the homogenous case does not (Fig. 4).

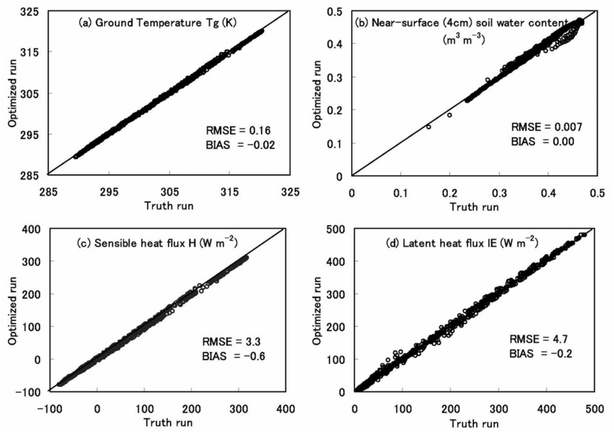

Fig. 3 Comparison of surface variables between the "true" and the optimized values for the heterogeneous case of the identical twin study

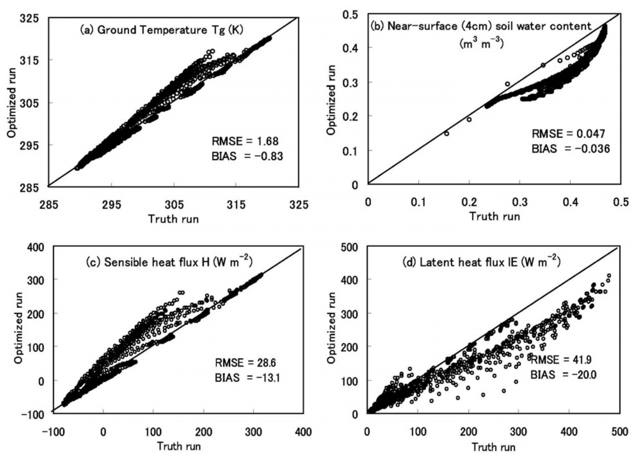

Fig. 4 Same as Figure 3, except for the homogeneous case

5.2 GAME-Tibet Anduo site

5.2.1 Description of site and data set. The GAME-Tibet Anduo site (Lat. 32.241° N, Lon. 91.635° E, Elev. 4700m) locates at the central Tibetan Plateau. This site is covered by sparse and short grasses in the summer, but vegetation roots share a large volume of the surface soil layer in all seasons and the bulk density of the soil is therefore much lower than the deeper soil. Intensive observations were carried out during May-Sepetember 1998, including 30-minute-recorded forcing data, hourly-recorded soil temperature and moisture profiles. Moreover, there are two sets of observed energy partitions measured by the eddy-correlation technique and by the Bowen ratio method. Note that the so-called eddy-correlation measured latent heat fluxes were derived from surface energy budget equation given eddy-correlation measured sensible heat fluxes (the latent heat fluxes were actually measured by the eddy-correlation, but the measurements are not trustable due to a sensor problem, see Yang et al. (2004) for more details). Additionally, five soil samples were tested to analyze soil properties

5.2.2 Parameter estimation and optimized output. Similar to the identical twin study, we have a heterogeneous case and a homogeneous case. In the estimations, the aerodynamic roughness length is a key parameter in determining energy partition, and its value is derived by Yang et al. (2003) using wind and temperature profiles. The results are summarized in Fig. 5 - Fig. 7. Fig. 5 shows the hydraulic and thermal functions. Fig. 6 - 7 present the scatter-plots of energy partition between the simulation and the observation. The most impressive result in Fig. 5 is that the top domain and the deep domain have completely different properties, indicating that the existence of dense vegetation roots within the topsoil significantly changes its properties. Particularly, the topsoil has a high porosity, low thermal conductivity, and high soil water potential. It also outputs reasonable surface soil moisture and ground temperature (not shown), and energy partition (Fig. 6), while the homogeneous gives lower surface wetness, higher ground temperature (not shown), lower latent heat fluxes, and higher sensible heat fluxes (Fig. 7).

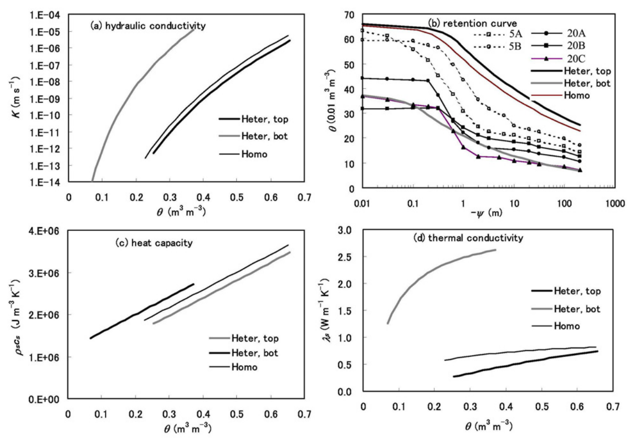

Fig. 5 Comparison of soil properties between optimization cases and experiments for the Anduo site. Retention curves in (b) were analyzed from five soil samples

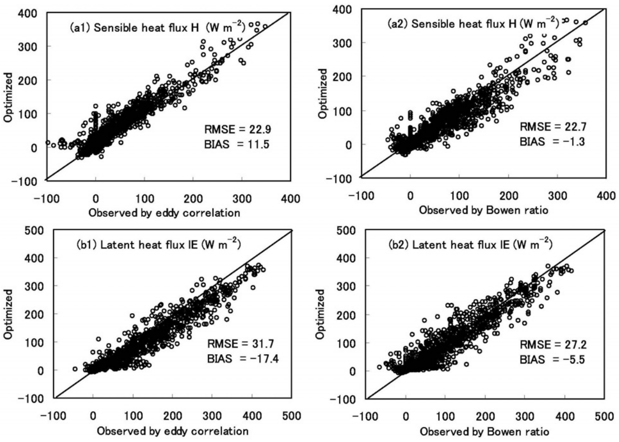

Fig. 6 Comparison of sensible heat flux and latent heat flux between the observations and the optimized values (from the inverse calibration) for the heterogeneous case of the Anduo site for the optimizing period.

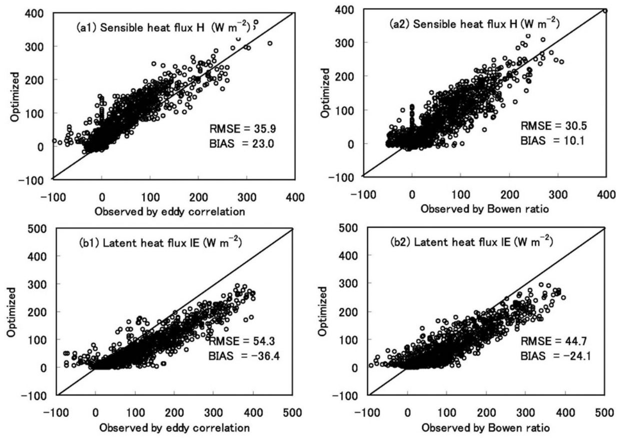

Fig. 7 Same as Fig. 6, except for the homogeneous case

6. Conclusions

This work develops an inverse system to evaluate the role of soil vertical heterogeneity in controlling surface soil wetness, ground temperature, and surface energy partition. It consists of a single-source land surface model to predict soil temperature and soil moisture, a cost function to calculate the discrepancy between observed and model-predicted values of soil moisture and temperature, and an efficient scheme SCE-UA to search the global minimum of the cost function. The estimated parameters can effectively characterize subsurface thermal and hydraulic processes.

We apply this system to a numerical synthetic data set and a GAME-Tibet data set. Both suggest that soil vertical heterogeneity plays a very important in determining surface soil wetness, ground temperature, and thus surface energy partition. Particularly, dense vegetation roots in the Tibetan Plateau can significantly change the properties of the topsoil, such as high porosity, high soil water potential, and low thermal conductivity. The high soil water potential may result in a wet soil surface, and thus enhance evaporation fluxes while reduce ground temperature and sensible heat fluxes. Therefore, the top domain, although shallow, is not only very important to sustain the plateau ecological system, but also control water and energy budget.

Moreover, we indicate that the subsurface and surface processes in vertically heterogeneous soils cannot be parameterized in the framework of a single uniform soil. Therefore, it seems to be difficult for most of current LSMs to account for the effects of the soil heterogeneity, since they use a single parameter-set to characterize soil properties. Fortunately, the Global Soil Data Task (2000) is making efforts to build a globally covered data set of soil parameters, which can provide soil information of both horizontal heterogeneity and vertical heterogeneity. Although there are still many uncertainties inside the data set due to high variability of soil texture, it provides a possibility to update current LSMs models by considering soil vertical heterogeneity.

References

Bastidas, L. A., H. V. Gupta, S. Sorroshian, W. J. Shuttleworth, and Z. L. Zhang, Sensitivity analyis of a land surface scheme using multicriteria methods. ***J. Geophys. Res.,*** **104** (D16), 19,481-19,490, 1999.

Duan, Q., S. Sorooshian, and V.K. Gupta, Effective and efficient global optimization for conceptual rainfall-runoff models. ***Water Resour. Res.*** **28**, 1015-1031, 1992.

Global Soil Data Task, Global Soil Data Products CD-ROM (IGBP-DIS), CD-ROM, International Geosphere-Biosphere Programme, Data and Information System, Potsdam, Germany. Available from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, U.S.A. [http://www.daac.ornl.gov], 2000.

Gupta, H. V., L. A. Bastidas, S. Sorroshian, W. J. Shuttleworth, and Z. L. Zhang, Parameter estimation of a land surface scheme using multicriteria methods. ***J. Geophys. Res.,*** **104** (D16), 19,491-19,503, 1999.

Sellers, P. J., D. A. Randall, G. J. Collatz, J. A. Berry, C. B. Field, D. A. Dazlich, C. Zhang, G. D. Collelo, and L. Bounoua, A revised land surface parameterization (SiB2) for atmospheric GCMs, Part I: Model formulation. ***J. Climate,*** **9,** 676-705, 1996.

Yang, K., T. Koike, H. Fujii, K. Tamagawa, and N. Hirose, Improvement of surface flux parametrizations with a turbulence-related length. ***Q. J. R. Meteor. Soc,*** **128**, 2073–2087, 2002.

Yang, K., T. Koike, and D. Yang, Surface flux parameterization in the Tibetan Plateau. ***Boundary-Layer Meteorol.,*** **106**, 245-262, 2003.

Yang, K., T. Koike, H. Ishikawa, and Y. Mao, Analysis of the Surface Energy Budget at a site of GAME/Tibet using a Single-Source Model. ***J. Met. Soc. Jap.,*** **82**, 131-153,2004.