Applicability of HYDRUS to predict soil moisture and temperature in vadose zone of arable land under monsoonal climate region, Tokyo

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Abstract
In order to project effects of future climate change on the vadose zone, performance of HYDRUS ver 4.09 model, which had been mostly applied to dry regions (e.g. Saito *et al.* 2006), was tested for a monsoonal climate. We conducted analysis of simultaneous liquid water, vapor and heat transport across the border between atmosphere and vadose zone, and prediction of annual change in soil moisture and temperature of arable land in Tokyo. Besides, we monitored soil temperature and soil moisture and made a dataset for model validation. In the simulation, soil hydraulic and thermal parameters were obtained by laboratory experiments. Meteorological data being open to the public had been used for input data for boundary condition. The simulation in general represented the monitored data well. The HYDRUS model could be considered appropriate proper and reasonable for the future use in the monsoonal climate region.

Key Words
Simultaneous heat and water transport, vadose zone, numerical simulation, climate change

Introduction

Prediction of effects of climate change on the vadose zone is a new application of numerical analysis of simultaneous heat and water movement between atmosphere and vadose zone. As well it is important since vadose zone is a foundation of ecosystem and agriculture. Changes in elements of climate such as air temperature, rainfall, and concentration of CO_2 would influence soil physical conditions such as moisture and temperature. Effects of climate change on soil have been discussed for many aspects. Nadden and Watts (2000) predicted the amount and distribution of available water resources in the United Kingdom with a fusion of Global Climate Model (GCM) and Land Surface Model (LSM) by focusing on the phenomena of soil surface and atmosphere. On the other hand, Huang (2006) showed soil temperature and downward heat flux in deep bore-holes all over the world has been rising for about 100 years. However, physical processes of water and heat transport in the vadose zone, and the boundary between atmosphere and soil related to climate change has not been discussed.

Though some models have already been proposed for simulating water and heat transport in the vadose zone, the models are not ready to simulate changes in heat and water conditions in response to future climate change such as temperature rise and variation of precipitation characteristics. One of the problems is a lack of comprehensive soil parameters and datasets corresponding to variety of climate and land use types for input and validation. For example, HYDRUS 1-D is a software system for simulating 1-dimensional heat, water and solute transport in unsaturated, partially and fully saturated porous media (Simunek *et al.* 2008). Its ver. 4.09 can consider surface energy balance as a boundary condition for bare soils (Saito *et al.* 2006). However, the model performance was mainly tested for dry regions and validation of energy balance was insufficient The purpose of this study is to test HYDRUS model performance for arable land in a monsoonal climate in order to predict impacts of future climate change on soil moisture and soil temperature in the vadose zone.

Methods

Field Monitoring

The field monitoring and soil sampling has been done at the Field Production Science Center in Graduate School of Agricultural and Life Sciences of the University of Tokyo (hereafter called Tanashi Farm) in Tanashi, Nishi-Tokyo City, western suburb of Tokyo (N 35°44′13″, E 139°32′30″). Monitoring period was from September 2008 to August 2009. The soil of 0 to 40cm under the surface was Kuroboku andisol, and below it to 100cm, Tachikawa loam andisol was distributed. A 10 m square area was prepared as the experimental site and kept bare through the experiment. There, albedo was observed using pyranometer (ML-020VL, EKO), and data of solar radiation, precipitation, air temperature, wind speed and relative humidity was obtained from weather station of Tanashi farm and AMeDAS (Automated Meteorological Data Acquisition System), belonging to Japan Meteorological Agency, near to the farm.

Near the surface, heat flux plate (CHF-HFP01, Hukseflux Thermal Sensors) was laid for measuring soil surface heat flux. For monitoring soil moisture and soil temperature, TDR sensors (self-made) and copper-constantan thermocouples were inserted at depths of 3, 5, 7, 10, 20, 30, 50, 80cm. All sensors were connected to CR10X data logger (Campbell Sci.) and data was collected every 20 minutes for a year.

Determination of Soil Physical Properties

Water retention curves of the soils were measured in the laboratory by hanging water column method and pressure plate method. Then inverse analysis with evaporation method (Simunek *et al.* 1998) was applied to determine the soil hydraulic parameters for Durner Model (1984) [1].

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} = w_1\left(1 + |\alpha h|^{n_1}\right)^{-m_1} + w_2\left(1 + |\alpha_2 h|^{n_2}\right)^{-m_2}$$

$$K(S_e) = K_s\left(w_1 S_{e1} + w_2 S_{e2}\right)^l \times \frac{\left(w_1\alpha\left[1-(1-S_{e1}^{1/m})^m\right] + w_2\alpha_2\left[1-(1-S_{e2}^{1/m2})^{m2}\right]\right)^2}{\left(w_1\alpha + w_2\alpha_2\right)} \quad [1]$$

where K_s is saturated hydraulic conductivity [m/s], S_e is effective saturation [-], and l, m=(1-1/n) and n are empirical parameters [-].Using the observed data of evaporation experiment, θ_r, θ_s, α, n, K_s, l ,w_2 , α_2 and n_2 in Durner model were estimated by inverse analysis by using HYDRUS 1-D.

Soil thermal conductivity λ at several different soil moisture contents was measured using KD2 heat probe (Decagon Devices) for both Kuroboku and Tachikawa loam. Then Chung and Horton (1987) model, eq. [2], was fitted to determine soil thermal parameters. Volumetric heat capacity of each sample was determined by weighed average corresponding to volumetric fraction of solid, air and water with eq. [3]

$$\lambda(\theta) = b_1 + b_2\theta + b_3\theta^{0.5} \quad [2]$$

$$C_p(\theta) = C_n\theta_n + C_o\theta_o + C_w\theta_w + C_a \approx 1.92\theta_n + 2.51\theta_o + 4.18\theta_w \quad [3]$$

where C is volumetric heat capacity, θ is volumetric fraction, n, o, w, and a show solid phase, organic matter, liquid water and air phase respectively.

Simulation of Water and Heat Transport in the Field

After determination of parameters, simulation of water and heat transport in vadose zone in the field from DOY1 (1st January, 2008) to DOY609 (31st August, 2009) was conducted by using HYDRUS. Depth of calculation profile was fixed as 100 cm, consisted of two layers according to field observation.

Boundary conditions for water and heat movement and input data needed for estimation are shown in Table 1. Because the exact initial soil moisture and thermal conditions and their sensitivity have not been known, preliminary calculation for preparing initial conditions was conducted. In the preliminary calculation, pressure head distribution of whole calculated profile -100cmH_2O, and temperature profile was after the observed data on December 31st, 2008. With these I.C.s , one year numerical simulation with B.C.s representing climate data of the experimental site had been done. Results of the preliminary calculation were employed as I.C.s for exact numerical simulation. Then model validation was done by comparing with the monitored and simulated values.

Table 1. Boundary Conditions and Input Data.

	Boundary	Condition	Input Data
Water	Upper	Precipitation intensity [cm/day]	Rainfall intensity
		Evaporation rate [cm/day]	Air temp. and R.H.
	Lower	Free drainage	
Heat	Upper	Surface heat flux [MJ m^2/day]	Solar radiation, air temp., wind speed, sunshine hour,
		Sensible heeat flux of precipitation [MJ m^2/day]	Rainfall intensity & Air temp.
	Lower	Zero gradient	

Results and Discussion

Fitting curves and measured soil water retention curves, unsaturated hydraulic conductivity and the relationship between volumetric water content and thermal conductivity for Kuroboku and Tachikawa loam are shown in Figure 1 from (a) to (c). Predicted solar radiation R_s and surface heat flux G were compared with observed ones as shown in Figure 2. Positive values indicate an incoming flux to the land surface (downward) while negative values imply outgoing flux from the land surface (upward). Both simulated surface heat flux and solar radiation described the dynamics of monitored values well. The meteorological model which employed HYDRUS is reasonable and proper for not only predicting soil surface radiation, but also producing thermal B.C. for soil surface.

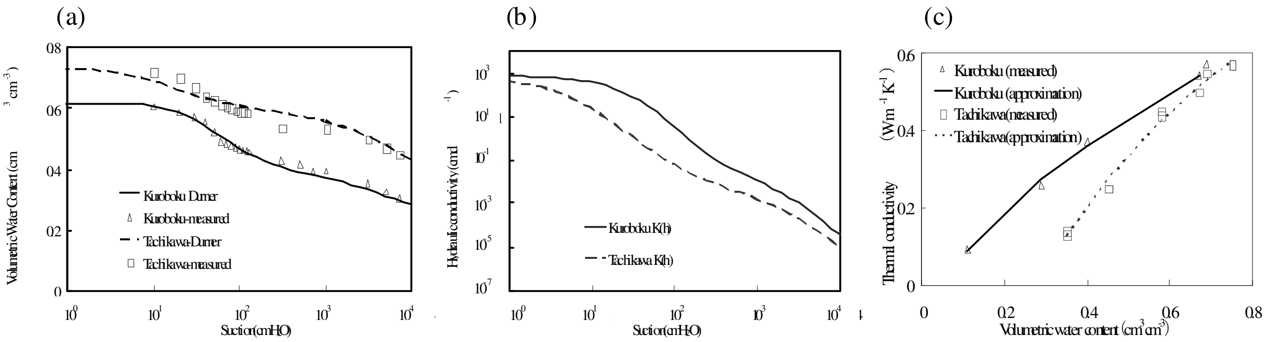

Figure 1. Simulated soil physical properties (a) water retention curves for Kuroboku and Tachikawa loam andisol, (b) unsaturated hydrolic conductivity (c) relation ship between soil moisture and soil thermal conductivity.

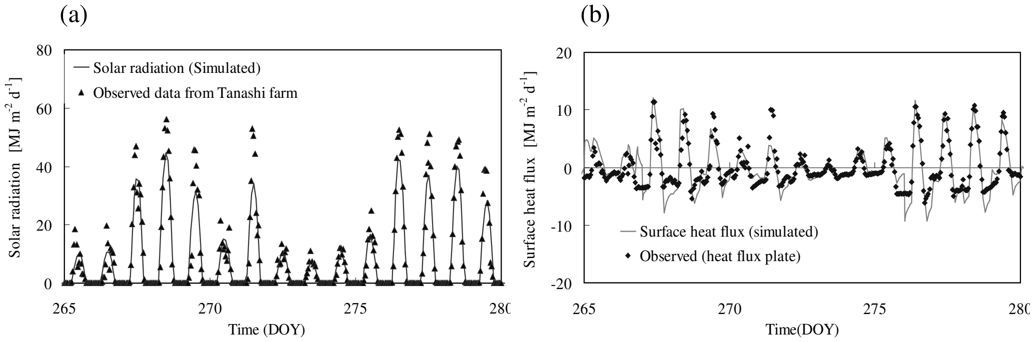

Figure 2. Validation of meteorological model (a) Surface heat flux (b) Solar radiation.

Figure 3 shows the soil temperature change at the depth of 3cm from (a) fall to winter, and (b) spring to summer. Simulated results described the observed temperature well especially in spring to summer. However, from fall to winter, simulated results tended to be underestimated soil temperature. It may be caused by lack of term describing latent heat and changes in heat capacity due to soil freezing in heat flow equation. Where soil frost is observed, it is better to consider the change in the amount of latent energy stored in the ice (Hansson *et al.* 2004)

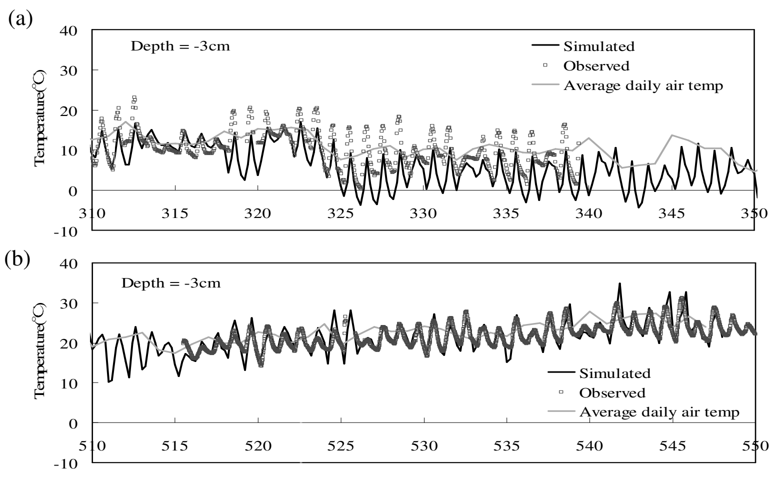

Figure 3. Comparison between simulated and observed soil temperature at the depth of 3cm (a) from DOY 250 (6th Sept., 2008) to DOY350 (15th Dec., 2008), (b) from DOY 510 (24th May, 2009) to DOY 550 (3rd July, 2009).

Figure 4 depicts daily rainfall record and simulated and measured soil moisture at four depths 7cm from DOY526 (9th June, 2009) to DOY609 (28th August, 2009). We could obtain the simulated soil moisture change reacting to the frequent rainfall and evaporation which is characteristic of the monsoon region. Recently, several kinds of GCM have been produced and improved in physical reliability and both spatial and temporal resolution. For example, some models provide predicted climate change in daily maximum, minimum and mean air temperatures, daily total precipitation, and daily accumulated shortwave radiation (Okada *et al.* 2009). Using these predicted climate data at such high temporal resolution, it will be possible to predict effects of climate change on soil physical condition in vadose zone with HYDRUS model as future work.

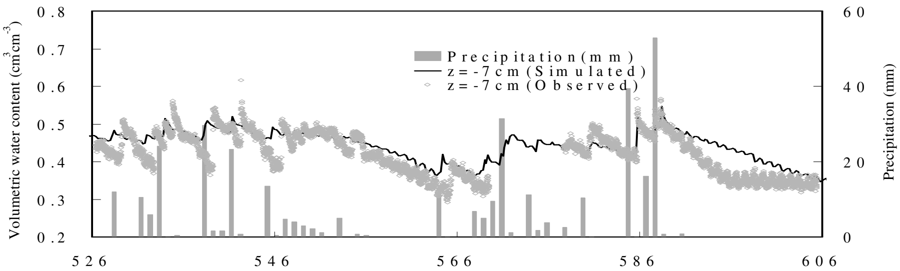

Figure 4. Comparison of predicted and observed soil temperature at the depth of 7cm from DOY 526 (9th June, 2009) to DOY609 (28th August, 2009).

Conclusions

We validated the model of simultaneous liquid water, vapor and heat transport across the border between atmosphere and vadose zone of arable land under a monsoonal climate with HYDRUS by comparing numerically simulated and observed values of surface energy balance, soil temperature and soil moisture. In calculation, soil hydraulic and thermal parameters were obtained by laboratory experiments and meteorological data being distributed to public had been used for input data for B.C.s. The simulation in general represented the monitored data well. So HYDRUS models could be considered to be proper and reasonable for the future use under monsoonal climate region. To improve the accuracy of the model, it would be necessary to consider the effect of soil freezing in winter.

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