Development of a Physically Based Model for Soil Water and Heat Transfer Processes in Semi-Arid Cold Region

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Introduction

In high latitude and altitude region, permafrost and seasonal frozen soil widely exist. Freezing and melting processes of soil moisture in frozen soil region affect greatly to soil water and heat transfer processes. Especially in Asia, frozen soil region is considered to affect the Asia monsoon. Therefore, in order to elucidate seasonal and annual change of climate system, it is required to understand quantitatively the soil water and heat transfer processes. The objective of this study is the development of a physically based model for soil water and heat transfer processes in semi-arid cold region.

One dimensional analysis of soil water and heat transfer processes

When considering soil water and heat transfer processes in soil with frozen soil, it is necessary to make a model representing the behavior of both water and heat. In this study, the following equations are used as basic equations,

$$\frac{\partial \theta w}{\partial t} = \frac{\partial}{\partial z}\left(K\frac{\partial \Phi}{\partial z}\right) \tag{1}$$

$$\frac{\partial \rho C T}{\partial t} = \frac{\partial}{\partial z}\left(\lambda\frac{\partial T}{\partial z}\right) \tag{2}$$

where θ_w is volumetric water content and Φ_b is total potential, T is surface temperature, C is specific heat of the soil, ρ is density of the soil, λ is heat conductivity of the soil.

Calculation of heat transfer processes: In order to calculate the heat transfer within a soil column, surface temperature has to calculate from heat balance equation for land surface. Heat balance equation of land surface is

$$F(Ts) = Rn + H_{rain} - \varepsilon\sigma T_s^{\ 4} + H + lE + G \tag{3}$$

$$Rn = S^{\downarrow}(1-\alpha) + L^{\downarrow} \tag{4}$$

$$H_{rain} = PCw(T_a - T_s) \tag{5}$$

$$H = \rho_a C_p C_H U (T_a - T_s) \tag{6}$$

$$lE = \frac{\rho_a C_p}{\gamma} C_E U \beta (e_a - e_s(T_s)) \tag{7}$$

$$G = \lambda(0)\frac{T(1) - T_s}{z(1) - z(0)} \tag{8}$$

where Rn is net radiation; H_{rain} is heat from rainfall; H is sensible heat flux; lE is latent heat flux; G is ground heat flux; $S^{\downarrow}$ is downward short wave radiation; $L^{\downarrow}$ is downward long wave radiation; T_s are surface temperature and Ta is air temperature; ε is emissivity; σ is Stefan-Boltzmann's constant; α is albedo; e_a is vapor pressure of air at voluntary height; e_s is saturated vapor pressure of temperature T_s; ρ_a is density of dry air; C_p is specific heat at constant pressure; U is wind speed; C_H and C_E are bulk coefficients; γ is psychrometer constant; and β is evaporation efficiency.

In this model, coefficient of resistance is used to calculate sensible and specific heat flux. Therefore, we can rewrite Eq. (6) and (7) to

$$H = \frac{\rho_a C_p (T_a - T_s)}{r_a} \qquad (9)$$

$$lE = \frac{\rho_a C_p (e_a - e_s(T_s))}{\gamma (r_a + r_{soil})} \qquad (10)$$

$$r_a = \frac{1}{C_H U} = \frac{1}{C_E} \qquad (11)$$

$$r_{soil} = \frac{216(\theta_{sat} - \theta_w)^{7.5}}{D_{atm}} \qquad (12)$$

where r_a is resistance of the air; r_{soil} is resistance of the soil, D_{atm} is vapor diffusion. And emissivity of land surface is calculated as function of surface soil water content.

$$\varepsilon = \varepsilon_s + (\varepsilon_w - \varepsilon_s)\theta(0) \qquad (13)$$

where ε_s and ε_w are emissivity of soil and water. ε_s equals 0.95 and ε_w equals 0.99 in this model. Heat conductivity of soil is calculated as weighted average of all components of the soil, namely water, ice, sand and air.

$$\lambda = \frac{\sum k_i \theta_i \lambda_i}{\sum k_i \theta_i} \qquad (14)$$

$$i = water, ice, sand, air$$

In Eq.(14), λ is heat conductivity, k is weighting coefficient, θ is volumetric water content of each components.

$$\rho C = \sum C_i \rho_i \theta_i \qquad (15)$$

$$i = water, ice, sand$$

And heat capacity equals the sum of heat capacity of all components.

Calculate soil water transfer processes: Movement of soil water is calculated to use result which is updated temperature in computation of heat transfer processes. At that time, Φ and K are needed (Φ is capillary potential, K is unsaturated hydraulic conductivity). They are estimated from volumetric water content by using Brooks-Corey's model.

$$\Psi = \Psi_b \left(\frac{\theta_w}{\theta_{sat}} \right)^{-b} \qquad (16)$$

$$K = K_s \left(\frac{\theta_w}{\theta_{sat}} \right)^{2b+3} \qquad (17)$$

In these equations, Φ_b is bubbling pressure, θ_{sat} is the porosity of soil, Ks is saturated hydraulic conductivity, b is parameter. Different values can be set at each layer in this model.

Computing procedure

In this model, soil is divided (n-1) layer. Calculation nodes are put at each layer surface. The number of layers and nodes can be arranged arbitrarily. Statement variables of each node are volumetric water content, ice content, soil temperature. They are calculated to use Eq.(1) and Eq.(2). Complete computing procedure is as follows.

1. Surface temperature is calculated from initial conditions and observation data in order to solve heat balance equation of land surface.
2. The right side of Eq.(2) is calculated. And soil temperature is calculated and updated to consider phase change of water.
3. If freezing occurred, excessive liquid water air porosity is dropped to lower layer.
4. Finally, the right side of Eq.(1) is calculated. And volumetric water content of soil is updated.

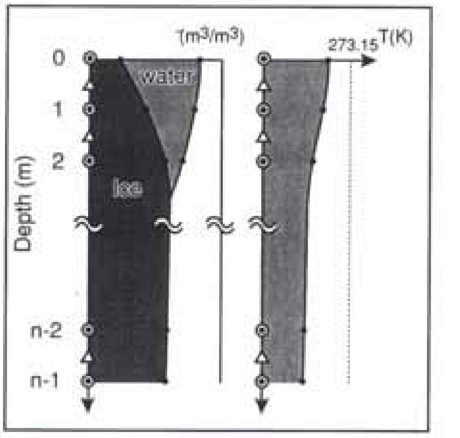

Fig.1.Calculate nodes of this model

Application of model

Study area and period: Study area is the Kherlen river basin in east Mongolia. Air and land surface temperature of this basin is lower than freezing point in winter season. And frozen soil exists. In this study, developed model is adapted to a place chosen from observation station of the Kherlen river basin. The study period that each observation value doesn't have missing value in summer is chosen. Because, it is important to verify first the validity in summer when freezing do not occur.

Using data: This model is driven by meteorological data after setting initial condition, profiles of soil temperature and water content. In this study, observed profiles are used. The soil temperature and water content are then calculated. Parameters used in study are shown table 1. For porosity and saturated hydraulic conductivity, observed values are used. About division of soil layers, calculation nodes are set at top of fifteen layers. Because parameters of soil were measured at depth of 0~0.05 and 1~1.5, 2.5~3, 5~5.5, 1.0~1.05m, and each measured layer is divided into three computational layers. For Φ_b and *b,* commonly used values are used for all layers. Their values can be determined by analyzing the soil samples taken from the Kherlen river basin.

Table.1 soil characteristic values

No	depth[m]	θ s [m3/m3]	Ψb[m]	b	Ks[m/s]
1	0	0.5168	-0.121	4.05	1.0272×10-5
2	0.025	0.5168	-0.121	4.05	1.0272×10-5
3	0.05	0.5168	-0.121	4.05	1.0272×10-5
4	0.1	0.4491	-0.121	4.05	4.9057×10-5
5	0.125	0.4491	-0.121	4.05	4.9057×10-5
6	0.15	0.4491	-0.121	4.05	4.9057×10-5
7	0.25	0.3985	-0.121	4.05	9.4917×10-5
8	0.275	0.3985	-0.121	4.05	9.4917×10-5
9	0.3	0.3985	-0.121	4.05	9.4917×10-5
10	0.5	0.4052	-0.121	4.05	2.2736×10-4
11	0.525	0.4052	-0.121	4.05	2.2736×10-4
12	0.55	0.4052	-0.121	4.05	2.2736×10-4
13	1	0.3932	-0.121	4.05	6.3258×10-5
14	1.025	0.3932	-0.121	4.05	6.3258×10-5
15	1.05	0.3932	-0.121	4.05	6.3258×10-5

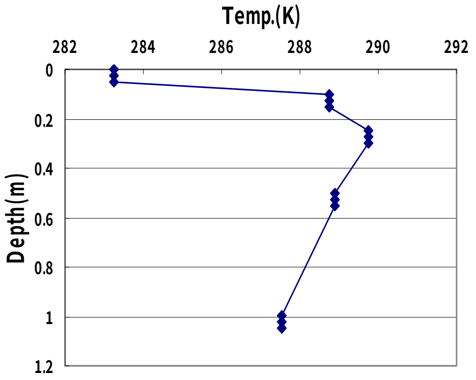

Fig.2.Initial soil temperature profile

Verification of this model

Calculated and observed soil temperature at depth of 0.05 and 0.1, 0.3, 0.5, 1.0m is shown in Fig.3. About land surface temperature, the night-time observed temperature can be represented quite well. However, the day-time values can not be represented. Our model made underestimated surface temperature. The reason for this is not very clear. One possible reason may be the observational error in land surface temperature. Another weather station KBU2 near by KBU1 used in this study shows lower land surface temperature. At KBU1, maximum daily temperature is about 40 degrees, but in KBU2 is about 25 degrees. This is a large difference. The correlation of air temperatures and surface temperatures at these two stations are shown in Fig.4. About air temperature, good correlation exists, however about surface temperatures, KBU1 shows much higher values than KBU2. Since the distance of two points is very small, it is hard to consider that such a difference exists in surface temperature. Observation of KBU1 may include some observational error.

The result about volumetric water content is shown in Fig.5. In this figure, the calculated values are compared with the observed ones at depth 0.05m, the shallowest observation point at KBU1 and 0.1m, 1.0m. The behavior of soil moisture is represented qualitatively. However, the calculated volumetric water content is always higher than the observed ones. This implies the soil parameters controlling the water movement with the soil column need to be evaluated more carefully. It is expected the analysis of soil samples will be helpful to improve the model performance.

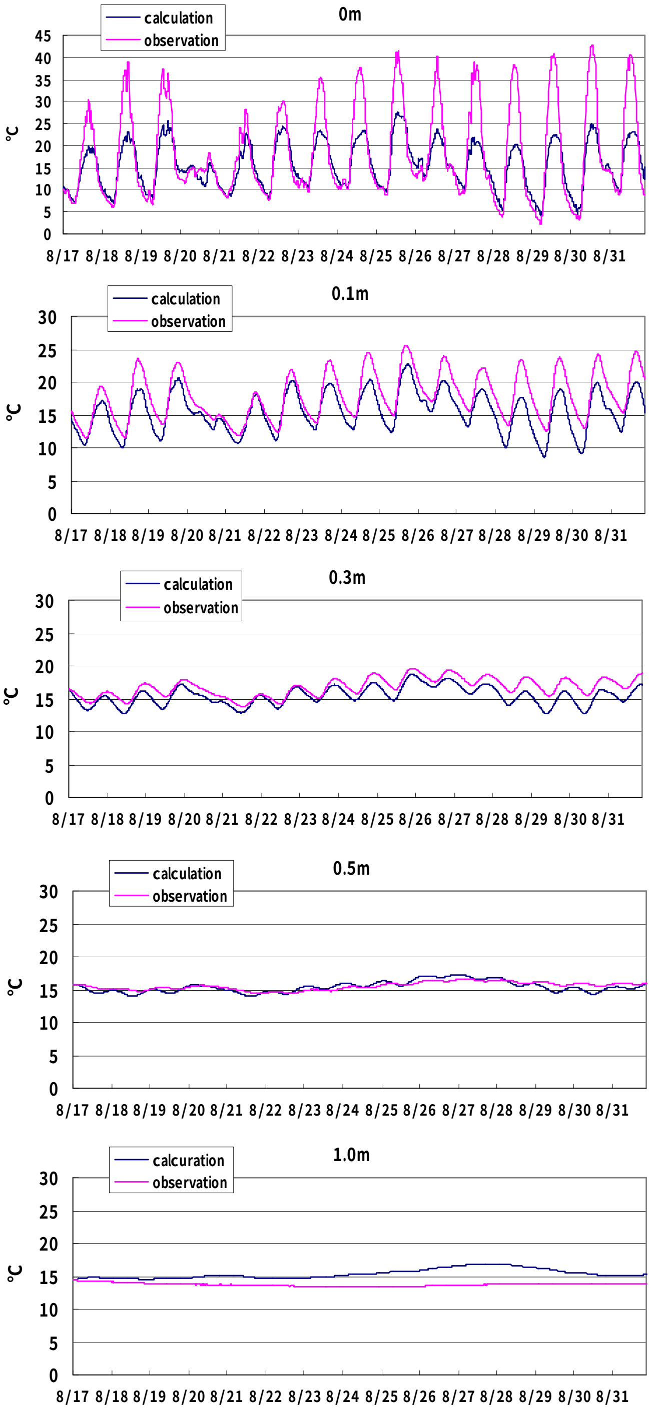

Fig.3.Comparision of calculated and observed soil temperature.

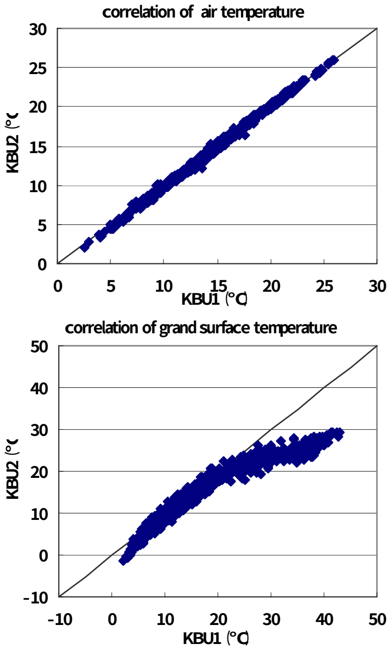

Fig.4.Correlation of temperature of KBU1 and KBU2.

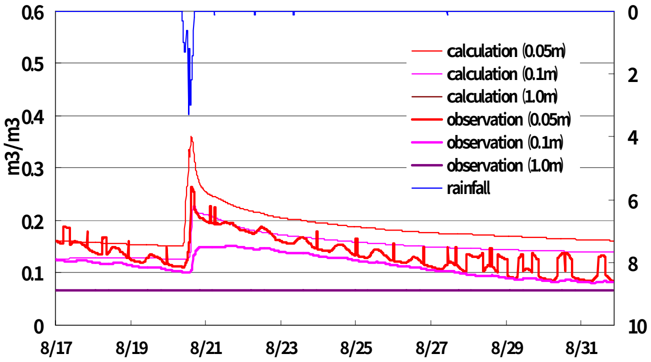

Fig.5. Comparison of calculated and observed volumetric water content.

Conclusion

In this paper, soil water and heat transfer processes are analyzed at KBU1 in summer. As a result, approximate tendency is expressed. However obtained result may be still not perfect. In order to improve this model, determination of model parameters is considered to be of great importance.

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