Validation of the process for generating soil moisture distribution in the Tibetan Plateau

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Abstract

Soil moisture plays two important roles in hydrology and atmospheric science. Many researchers pointed out the importance of soil moisture in global and local scale based on the GCM simulation. Therefore, the temporal and spatial variability of soil moisture has to be measured to estimate energy and water flux to the atmosphere. However, the land surface shows a high spatial variability and heterogeneity compared to the atmosphere. To estimate water and heat fluxes from land surface to the atmosphere, the effect of soil moisture heterogeneity on water and heat fluxes should be considered. To do so, we developed a land surface model which considers the soil moisture heterogeneity and showed its effect on the estimation of spatially averaged evaporation. To apply the developed model to the whole Tibetan Plateau, we have to validate it based on the field observation. Our objectives are two fold. One is to validate the generation process of the soil moisture heterogeneity and the other is to apply the developed model to four observation sites.

At first, we confirm the process for generating the soil moisture distribution in the plain area, which is the basis of our model. We identify two important relationships in this process based on the field observation. One is the effect of micro-topography on soil moisture and the other is the interaction between soil moisture and thawing process in the frozen soil. After and, to evaluate the model representation, the model is applied to four observation sites. The results are compared with the observed soil moisture distribution at each site. The model simulations agree with observed soil moisture distribution.

Keyword: soil moisture distribution, permafrost, Tibetan Plateau.

1. Introduction

1.1. Importance of soil moisture on the global climate system

Soil moisture plays an important role in both the meteorology and hydrology. It affects the evaporation from the land surface to the atmosphere and also affects the river discharge through surface and subsurface runoff. Therefore, soil moisture affects the global climate system. An understanding of the effect of soil moisture helps in the prediction of global climate change, which leads to appropriate policies for preventing serious damage caused by floods and droughts. Many researchers have noted the importance of soil moisture in the global climate system according to simulation results of GCMs (Global Circulation Models).

The land surface is more heterogeneous than the atmosphere. To correctly estimate the water and heat flux from the land surface to the atmosphere, it is necessary to develop a model which considers the effect of the soil moisture heterogeneity. Nakaegawa (2000) derived an equation of regionally-averaged surface heat fluxes and their aggregation criteria, and indicated the effects of the intrasubarea-scale distribution of the temperature and soil moisture content using numerical experiments based on their derived equations. The reader is referred to his paper for the definition and explanation of the term "intrasubarea". Chen (1991) introduced a spatially-averaged equation for predicting the soil water dynamics by comparing with the results from the spatially horizontally-averaged Richards equation (SHARE). However, previous studies have highlighted some of the problems associated with this equation. The results are based on model simulations, and have yet to be evaluated using field observations. The model developed in these studies does not include the physical processes involved in the generation of the soil moisture heterogeneity. Therefore, we have developed a model for considering the soil moisture heterogeneity based on field observations in the Tibetan Plateau, and evaluated its effect on the spatially-averaged evaporation (2002).

1.2. Estimation of the spatially-averaged evaporation by considering the spatial variability of soil moisture

Recently, the advanced microwave radiometers AMSR and AMSR-E have been launched. These satellites enable us to observe the soil moisture at global coverage three or four times per day. However, because of low spatial resolution, they cannot observe the spatial variability of soil moisture in a footprint. Therefore, we need to predict it using spatially-averaged high-temporal-resolution soil moisture data retrieved from the microwave radiometers. To reach our final target, first we need to understand the characteristics of the soil moisture variability using the developed model. However, the model has yet to be evaluated.

In this paper, there are two objectives in the basic research carried out to predict the soil moisture heterogeneity based on microwave radiometer observations. One is to evaluate the process for generating the soil moisture heterogeneity based on field observations. The model was developed considering this process. The other is to apply the model to the whole of the Tibetan region.

2. Soil moisture heterogeneity in the Tibetan Plateau

The process for generating soil moisture heterogeneity in a plain area is different from that required for generating the same information in a sloped area. Ishidaira *et al*(1998) on the one hand implemented field observations, and developed a model for sloped areas. They evaluated the processes in a sloped area based on field observations. On the other hand, Hirose et al (2002) only speculated on the generation process for plane areas. In this section, we try to evaluate the processes using field observations.

The soil moisture heterogeneity in plane areas is assumed to depend on the "micro-topography" during and after rain events. In this paper, "micro-topography" refers to surface undulations that do not appear in ordinary topographical maps. Concave regions tend to be wetter while convex areas tend to be drier. Due to the larger thermal capacity of soil water and the larger amount of latent heat flux in wetter areas, the active layer remains shallow, even though the conductivity of heat flow becomes large. In contrast, a deeper active layer appears in the dryer area. The surface soil of the shallow active layer remains wet for longer, while one of the thick active layers dries up more rapidly due to percolation to the thicker unsaturated zone.

To evaluate this process, we have identified two important relationships using field observations. One is the effect of micro-topography on soil moisture, and the other is the interaction between soil moisture and the thawing process in frozen soil.

3. Evaluation of the process for generating the soil moisture heterogeneity in plain areas

3.1. Field observations in the Tibetan Plateau

To evaluate the process for generating soil moisture heterogeneity, we have implemented field observations during the summer of 2002. The field observations consist of horizontal observations for identifying the relationship between micro-topography and surface soil moisture and vertical observations for understanding the land surface-to-atmosphere interaction.

To understand the horizontal variability of the micro-topography and soil moisture, we observed the elevation and temporal variability of soil moisture before and after a rainfall event at 10m intervals along a transect. The elevation is measured by leveling. The temporal variability in the soil moisture is measured using the Time Domain Reflectometry (TDR) method.

Other field experiments have been carried out to understand the 1-D vertical land surface-atmosphere interaction. It consists of meteorological measurements using an Automatic Weather Station (AWS) and a boundary layer tower and vertical profiles of soil moisture and temperature under the surface using a Soil Moisture and Temperature Measurement System (SMTMS). These systems have been established at eight observation sites, and observations have been made since 1997.

3.2. Effect of micro-topography on soil moisture

To understand the hydrological processes in Tibet, we need to separate the land area into sloped and plain areas. In this paper, micro-topography refers to surface undulations which consist of concavities and convexities in the plain area. The difference between low and high elevations is less than 1 meter within 100-meter intervals. On the other hand, it is more than 1 meter in sloped areas.

We focus on the plains at the Amdo and BJ sites. To investigate the relationship between the micro-topography and soil moisture, we apply a moving average to the soil moisture change in order to reduce the short-term fluctuations in the observed data. Fig. 1a) and b) show the relationship between the micro-topography and the soil moisture at the Amdo and BJ sites. The thick and dotted lines indicate the difference between the observed and moving average data of micro-topography and soil moisture.

These figures show that the difference in the soil moisture is negative (positive) when the difference in the micro-topography is positive (negative). The negative and positive differences in the micro-topography represent the concavity and convexity in the plains. These figures indicate that the soil moisture in a concavity is larger than in a convexity because the soil moisture in concavities increases according to the surface water storage. Therefore, they indicate the relationship between the micro-topography and the soil moisture in the plain.

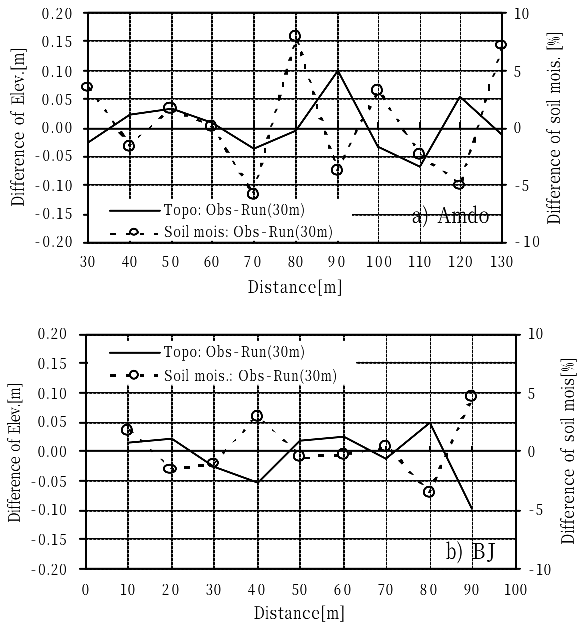

Fig.1: The relationship between topography and soil moisture in a plane area. Fig.1a) and b) show the Amdo and BJ sites. The thick and dotted lines indicate the difference between the observed and moving average data in the micro-topography and the soil moisture.

3.3. Interaction between the soil moisture and the thawing process in the frozen soil

In speculating the process involved in the generation of the soil moisture heterogeneity, the following process enhances the difference in the soil moisture in concavities and convexities. Higher (lower) soil moisture in concavities (convexities) leads to smaller (larger) heat flows into the soil because of a large (small) heat capacity and evaporation. The thawing depth in the concavity is shallower than in the convexity. The higher soil moisture in the concavity is kept because the melting water cannot infiltrate the frozen table. Therefore, the difference in the soil moisture between concavities and convexities increases due to the interaction between the soil moisture and the thawing process in frozen soil.

To validate this interaction, we need to study to decrease the heat flow into the soil by increasing evaporation and the soil heat capacity.

At first, we investigated the effect of soil moisture on the surface heat budget at the BJ site. We estimate the fluxes based on the Bowen ratio method. Our results show that the ratio of the latent heat flux increases with soil moisture. However, they indicate that the temporal variability of G observed by the heat plate does not change with soil moisture.

Secondly, we estimate the heat flow into the soil based on the estimation method presented by Rouse (1982). Some researchers have pointed out that the accuracy of the heat plate observations is low. He mentions that there are two problems associated with the heat plate observations. One is the large difference between the heat capacity of the plate and that of soil. The other is that the heat plate cannot measure the change in the heat flow caused by the water flow within the soil. He presents a heat budget equation which includes the thawing and freezing processes in the soil. However, his equations are not applied directly to the observed data because the thermal conductivity and the soil ice content cannot be observed in the field observations. Therefore, we address the small temperature gradient in the observed data These observed periods are seven days from Apr. 29 to May 5 in 1998 at the Amdo site and ten days from Apr. 26 to May 5 in 2001 at the D66 site.

Fig.2 shows the vertical profiles of soil moisture (Fig.2a and c) and temperature (Fig.2b and d) which are addressed to estimate the heat flow into the soil. Fig. 2a-b and c-d indicate the D66 and Amdo sites. In these figure, the doted and thick lines indicate the initial and terminal conditions of the vertical profiles. Fig.3a) shows the comparison between the vertical profiles of heat capacity at the D66 and Amdo sites. The profiles of heat capacity are estimated from the soil moisture profiles, as shown in Fig. 2a) and c). This figure indicates the clear difference in the heat capacity between the two sites. Fig.3b shows the ratio of the estimated heat flow, Q_s to Rn at the D66 and Amdo sites. This figure shows that this ratio is smaller at the Amdo site compared with the D66 site. These figures reveal that a high (low) soil moisture leads to a small (large) heat flow into the soil because of the high (low) heat capacity and the large (small) amount of evaporation.

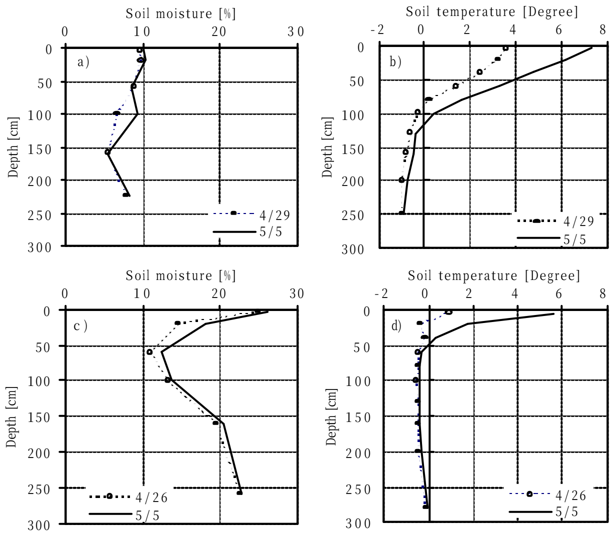

Fig.2: The vertical profiles of soil moisture (Fig.2a and c) and temperature (Fig.2b and d). The dotted and thick lines indicate the initial and terminal conditions of the vertical profiles

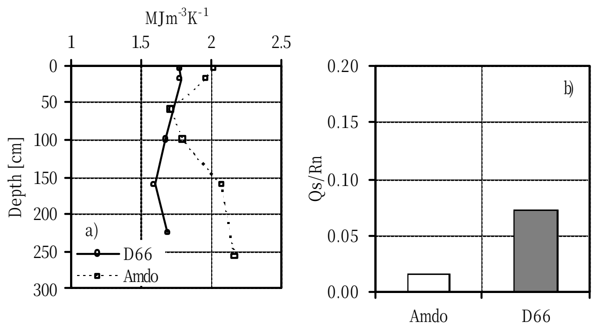

Fig.3: Comparison between the vertical profiles of heat capacity at the D66 and Amdo sites

4. Validation of the model simulation

4.1. The model for considering the soil moisture heterogeneity

Ishidaira and Toike (1998) developed a 1-D model to apply to the permafrost regions. It has a different number of layers between the water and the heat flow in the model calculations. For water flow, the calculation consists of five layers and uses the finite difference of the Richards equation. The heat flow simulation implements a fine grid (60 layers) based on the thermal diffusion equation. One of Its characteristics is the determination of the freezing boundary, independent of the five layers.

To consider the soil moisture heterogeneity, the model needs to include the surface water storage effect because of the micro-topography. We add this to a tank model to represent the water storage effect. The maximum height of the water storage in this tank model depends on the micro-topography (surface undulations). Therefore, the boundary condition in the developed model is the maximum height distribution. This model neglects the lateral flow between grids. The overland flow out of the basin is generated when the water storage is larger than the maximum height. In calculating the evaporation, the surface moisture availability, ß is unity when water storage occurs.

4.2. Estimation of the model parameters

To estimate the model parameters, we make the assumption that a lot of the model parameters are the same at the four observation sites, except for the distribution of the maximum storage height. The model reproducibility for changing the vertical profile of the soil moisture and temperature is insufficient for comparing with the observed data. The differences in the model parameters between the observation sites need to be detected and taken into consideration in future research plans.

The following procedures were carried out to determine the model parameter and the distribution of the maximum storage height. At first, we determined the model parameter to represent the vertical profile of the soil moisture and temperature at each of the observation sites. Secondly, we determined the maximum height distribution to represent the observed soil moisture heterogeneity at each of the observation sites. Thirdly, we compared the model simulation with the observed data. Finally, we determined the model parameters and the maximum height distribution at each site by iteration.

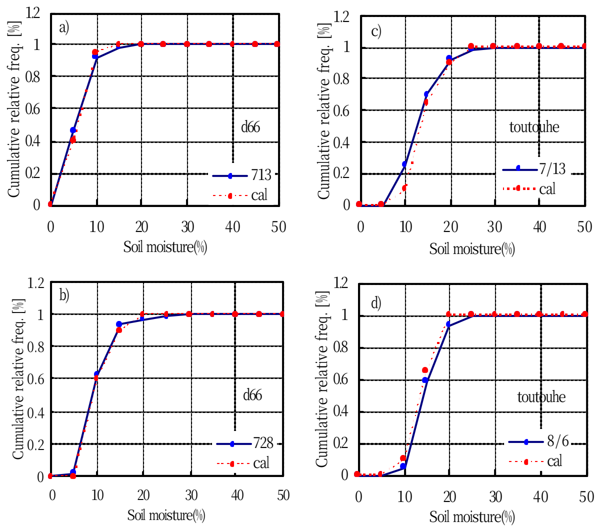

Fig.4: Comparison between the simulated and observed soil moisture distribution at D66 (Fig.4a and b), and Toutouhe (Fig.4c and d)

4.3. Validation of the model simulation at the four observation sites

We have evaluated the model predictability by comparing the simulated soil moisture heterogeneity with the observed. Fig. 4 and 5 show a comparison between simulated and observed soil moisture distributions at the D66 (Fig.4a and b), Toutouhe (Fig.4c and d), Amdo (Fig.5a, b and c) and BJ (Fig.5d, e and f) sites. In these figures, the thick and dotted lines indicate the observed and simulated soil moisture distributions. Its distribution is accumulated. These figures show that the model simulation is in good agreement with the observed data.

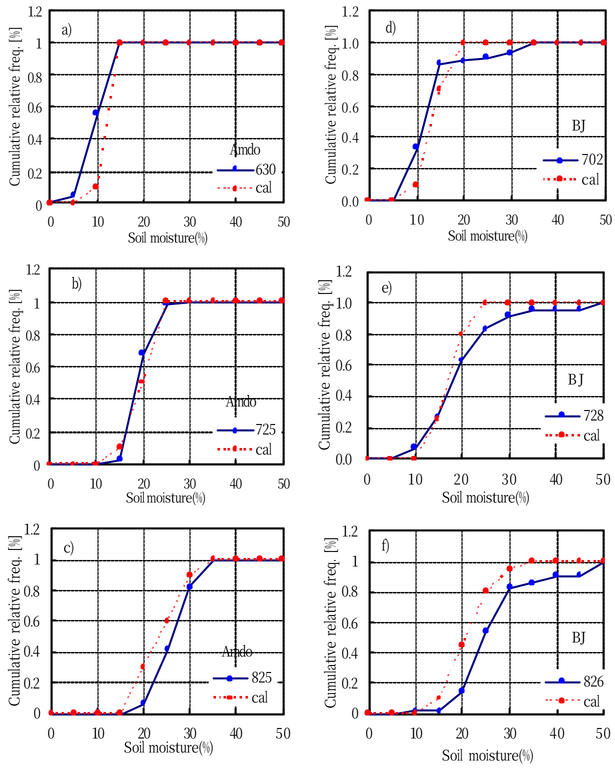

Fig.5: Comparison between the simulated and observed soil moisture distribution at the Amdo (Fig.5a, b and c) and BJ (Fig.5d, e and f) sites

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