Surface Soil Moisture Estimation by TRMM/PR and TMI

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***Abstract*—A surface soil moisture estimation algorithm by microwave radiometer is developed with radiative transfer model for soil-vegetation-atmosphere layers (especially, vegetation layer is focused).**

I. INTRODUCTION

The microwave radiometer has been recognized as a tool to estimate surface soil moisture especially when it observes brightness temperature using lower frequency [1], [2]. At present (April, 2003), six microwave radiometers including TRMM (Tropical Rainfall Measuring Mission)/TMI (TRMM Microwave Imager) are in space. In near future (2007, hopefully), eight microwave radiometers would contribute to global observation with high temporal resolution (3hourly) under GPM (Global Precipitation Measurement). The development of soil moisture retrieval algorithm have some difficulties because brightness temperature is significantly affected by many physical parameters of land surface and the atmosphere other than soil moisture. Therefore, a radiative transfer model is necessary for the development of algorithm and it should contain physical processes as much as possible.

In this paper, we introduce a soil moisture estimation algorithm and apply it into TRMM/TMI data with monthly time step. In previous studies, vegetation layer was modeled with two parameters such as optical thickness and single scattering albedo. The problem is that these two parameters are not physical ones, then they should be given a priori [1] or should be estimated simultaneously with soil moisture [2]. Instead of those, vegetation is modeled with multiple physical parameters in this study. In the following sections, the data of TRMM/TMI, the radiative transfer equation, soil moisture estimation algorithm, and the results will be introduced. Because of the shortage of the space, the soil moisture estimation by TRMM/PR (Precipitation Radar) is not explained. Please refer to [3].

II. DATA

TRMM/TMI observes the brightness temperature in 10.65, 19.35, 37.0, 85.5GHz with both horizontal/vertical polarization and in 21.3 GHz with horizontal polarization (frequency is denoted as integer later on). Here, the instantaneous brightness temperature data in 1998 (TRMM standard product 1B11, version5) were accumulated into monthly 0.25° grid. To avoid the effect of precipitation, all the observations of the day when rainfall is observed (judged by the product 2A12) are omitted for each grid.

III. RADIATIVE TRANSFER MODEL

In this section, a radiative transfer model for soil, vegetation, and the atmosphere used in this study is briefly introduced. Microwave reflection and emission at land surface is considered, but penetration through soil layer is not treated at all because microwave is almost attenuated only at a few centimeters below soil surface. Therefore, soil moisture and temperature are defined at surface. The dielectric constant of soil is calculated by the equation of Dobson [4] with dry soil density, bulk soil density, β (a parameter dependent on soil type), and soil moisture. Reflectivity at soil surface can be induced by soil dielectric constant with Fresnel's Law, while roughness effect on reflectivity is involved. Actual reflectivity R is calculated by $R=r \exp(-h)$. Here, h denotes roughness parameter and r means the reflectivity of ideal smooth surface.

Vegetation layer is modeled based on the paper [5]. In this model, vegetation is composed of leaf, stem, and branch. Leaf area index (LAI) is defined as a ratio of total surface area (one side only) of leaves to the corresponding land surface area. In addition to LAI, leaf thickness (as it is dry) and an index for the distribution of leaf inclination δ are parameters regarding to leaf. Stem is modeled as a cone vertical to the land surface. As a parameter of stem, stem area index (SAI) is defined as a ratio of total surface area of stems to the corresponding land surface area. Branch is modeled as a cylinder horizontal to the land surface. Branch and stem ratio (B/S) is defined as the ratio of projection area of total branches on the land surface to the projection area of total stems on the land surface. In addition to that, vegetation water content is a parameter common to leaf, stem, and branch. An atmospheric radiative transfer model by Liu [6] is combined with the soil and vegetation part mentioned above..

IV. SENSITIVITY ANALYSIS

Sensitivity of brightness temperature to each land surface parameter is examined in this section. A focused parameter is changed from its minimum to its maximum value (shown in column 2 to 4 of Tab.I), then brightness temperature is calculated with other parameters being the standard value. In the most of the case, brightness temperature

TABLE I. PARAMETERS OF RADIATION TRANSFER MODEL AND SENSITIVITY OF BRIGHTNESS TEMPERATURE TO EACH PARAMETER

Common Parameter	Min	Max	Std	10V	10H	19V	19H	37V	37H	PD10	FDH
Physical Temp.[K]	280	330	300	44.8	42.5	45.5	43.5	46.1	44.4	2.3	1.9
Soil Moisture	0.0	0.5	0.1	-2.5	-9.6	-1.7	-7.1	-0.9	-4.6	7.1	5.0
β	1.3	1.8	1.78	0.2	1.8	0.1	1.3	0.1	0.8	-1.6	-1.0
Dry Soil Density	1.0	2.0	1.15	0.0	-0.4	0.0	-0.3	0.0	-0.3	0.4	0.1
Bulk Soil Density	2.0	3.0	2.65	-0.2	-2.3	-0.1	-1.9	-0.1	-1.6	2.1	0.7
Roughness	0.0	1.0	0.3	0.1	6.8	0.1	5.5	0.0	4.3	-6.7	-2.5
LAI[m2/m2]	0.0	5.0	1.0	-53.7	-27.7	-39.1	-14.1	-30.2	-4.8	-26.0	22.9
Leaf Thickness	0.1	1.0	0.3	14.8	20.1	13.1	18.1	9.0	12.8	-5.3	-7.3
Leaf Inclination	-0.3	0.6	0.0	-1.6	-0.7	-1.2	-0.3	-0.8	0.1	-0.9	0.8
SAI	0.0	1.0	0.3	13.6	19.5	10.4	13.2	7.8	7.9	-5.9	-11.6
B/S	2.0	6.0	3.0	3.9	-2.8	2.8	-3.7	2.0	-4.4	6.7	-1.6
Vegetation Water Content	0.1	0.7	0.3	-18.9	-13.1	-18.9	-14.4	-20.6	-17.7	-5.7	-4.6

is a monotonous function of land surface parameter. The results are shown from column 5 to 10. For example, column 5 (which is labeled as 10V) shows the sensitivity, that is, the difference between $T_{B,10V}$ (the brightness temperature observed with 10GHz, vertical polarization) when the parameter is maximum and that when the parameter is minimum. Column 11 indicates the sensitivity of PD(10). PD(10) is the Polarization Difference of 10GHz; it is defined by PD(10)= $T_{B,10V}$-$T_{B,10H}$.Column 12 shows the sensitivity of FD(H). FD(H) is the Frequency Difference of horizontal polarization; it is defined by FD(H)= $T_{B,37H}$-$T_{B,10H}$.

Brightness temperature of each channel shows high sensitivity to the physical temperature of land surface, which naturally varies well in space and time. This sensitivity can be reduced by using PD or FD instead of brightness temperature itself, while the sensitivity to soil moisture doesn't change so much when we use PD or FD. Therefore, in order to estimate soil moisture, PD and FD are suitable than brightness temperature. In the rest of this section, the sensitivity of PD(10) and FD(H) is described. Their sensitivity to LAI is especially strong, and roughness, leaf thickness, SAI, B/S, and vegetation water content have effects on PD(10) and FD(H) as well as soil moisture. These parameters are called ``important parameters''. They can not be neglected to estimate soil moisture. Atmospheric profile has much effects on brightness temperature observed with higher frequency. It is because precipitation has large effects on microwave observation that the data during rainfall is excluded in this study.

V. METHOD AND RESULTS

The resolution of soil moisture product as a goal of our study is monthly and 0.25°. In the estimation process, parameters except for soil moisture are given in advance and soil moisture is retrieved from an index such as PD(10).LAI, which has high spatial and temporal variation by nature and affects PD(10) well, is derived from monthly NDVI (Normalized Differential Vegetation Index) observed by NOAA/AVHRR (Advanced Very High Resolution Radiometer). Other important parameters are tuned for each 0.25 ° grid to be fixed in time. The other parameters are negligible, then fixed to the standard values shown in Tab.I. Look-up tables were prepared in advance by forward calculation of radiative transfer equation. If one can not find

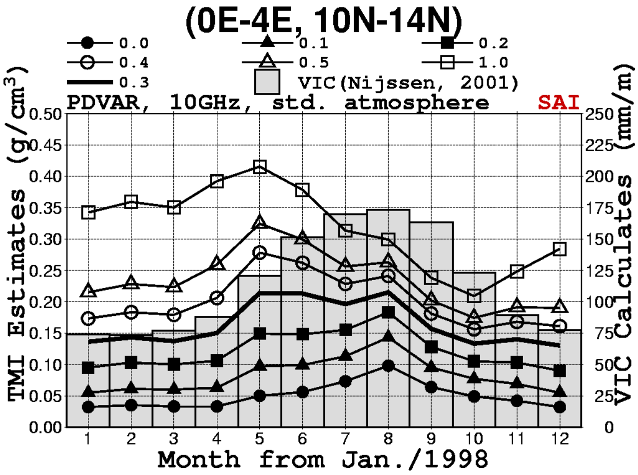

Figure 1. Soil moisture estimates with different SAI and calculation by VIC model

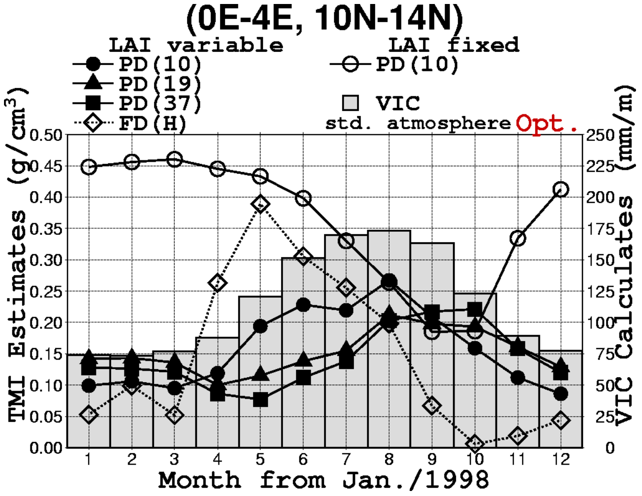

Figure 2. Soil moisture estimates with and without temporal change of LAI

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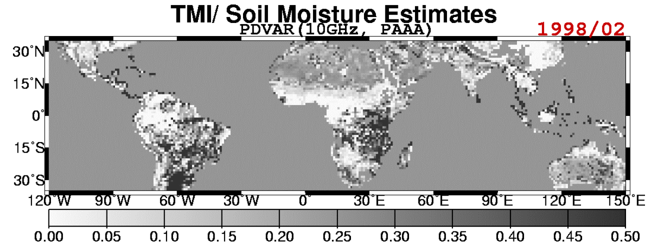

Figure 3. Global map of soil moisture estimates for February in 1998

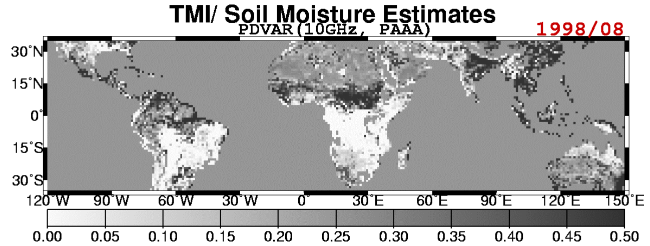

Figure 4. Same as Fig.3 for August in 1998

any solution with the look-up tables, virtual estimate is given as follows. If observed (monthly average) PD(10) is smaller than PD(10) corresponded with the soil moisture of 0%, estimate is set to be 0%, and if observed PD(10) is larger than PD(10) corresponded with the soil moisture of 50%, estimate becomes 50%.When one can find solution within 0% and 50%, it is called ``real estimate".The U.S. standard atmospheric profile of temperature, humidity, and pressure is used. Cloud and precipitation is always set to be zero.

The results are introduced mainly by the example of the Sahel region (10-14^{o} N, 0-4^{o} E) in 1998. This region belongs to semi-arid region, and annual plants grow caused by summer rainfall. Figure1 shows the soil moisture estimates with different SAI (one of important parameters).SAI affects not only the absolute value but also the seasonal pattern of soil moisture estimates.If SAI is set to be large, soil moisture estimates show similar seasonal pattern with PD(10). That is because LAI doesn't affect PD(10) well if SAI is large. 14 year average of soil moisture calculated by land surface water and energy balance model (VIC=Variable Infiltration Capacity model) [7] is put in the figure just as reference of climatological value. Supposing that the surface soil moisture should show similar seasonal pattern with one calculated by VIC (maximum in August),estimate with smaller SAI is judged to be better. Small SAI doesn't contradict with geographical common sense. Similar problem can occur with other important parameters, and it is necessary to give suitable values for important parameters to simulate valid seasonal pattern of soil moisture. Optimum value of SAI is determined for each grid so as to maximize the number of months when real estimate is gotten. The same way is applied for other important parameters, and finally only one important parameter which can increase the number of months with "real estimate" most is tuned. Estimates with the tuning are well correlated with VIC calculation (correlation coefficients R=0.94) and 94% of the total estimation get ``real estimates" in this case, it is much improved from the case without tuning (standard values are used, then the correlation coefficients is $R$=0.70 and 60% of the total estimation is ``real estimate").

Figure2 shows the comparison of estimates by different methods. Parameter tuning is done in the same way for all the cases. If the LAI is fixed so that the minimum of soil moisture estimates be 0% for each grid, seasonal pattern of estimates become unrealistic. Temporal change of LAI should be considered especially for highly variable vegetated area such as the Sahel. In other cases, indices FD(H), PD(19), PD(37) are used instead of PD(10).FD(H) yields quite different seasonal pattern, and PD(19) and PD(37) give worse seasonal pattern than PD(10), if we judge by the correlation coefficients with VIC calculation. One of the reasons may be that the microwave observation in higher frequency is much subject to the atmosphere.

Figure3 and 4 show the tentative products of global soil moisture map derived by the above method (PD(10) and monthly LAI are used, tuning is done). Seasonal pattern is almost simulated, but the absolute value is unrealistic in some regions, e.g. wet in the Sahara desert. In this paper, important parameters are tuned and valid seasonal pattern is simulated well. To make estimates more accurate as absolute value, the actual database of vegetation parameters should be prepared, and the temporal change of vegetation water content should be taken in consideration.

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