DEVELOPMENT OF A NEW SOIL MOISTURE RETRIEVAL ALGORITHM USING TRMM/TMI POLARIZATION RATIO AND NDVI

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1. INTRODUCTION

Recently, many countries have been suffering from water related disasters (severe storm, flood, draught etc.). The better understanding of the hydrological cycle, especially the prediction of these phenomena, is indispensable for dealing with these water disaster and water resources problems. There has been a significant growth in the recognition of the importance of soil moisture information in large scale hydrology and climate modelling. The soil moisture is one of the key surface parameters that controls the partitioning of net radiation into sensible and latent heat fluxes. Through the energy and water exchange processes between land surface and atmosphere, the soil moisture controls the formation of climate/weather and its variability, and in reverse, the soil moisture status is updated. Also, since the time scale of variation of the soil moisture is large, the error in its initial condition affects for a long period. Thus, the initialization of the soil moisture is an acute problem in the numerical weather prediction.

The best way for gathering the actual soil moisture information is to distribute many sensors with adequate spacial resolution. However, due to many constraints, it is impossible to obtain the time-space distribution of soil moisture field from in-situ measurements only. Furthermore, it is rather difficult to obtain the grid averaged value from in-situ measurement since it is basicaly a value of the measurement point.

The utilization of the microwave remote sensing technology is expected to provide a information of surface soil moisture. Remote measurements from space have the possibility of obtaining frequent, global sampling of soil moisture over a wide area of the land surface. Microwave measurements have the benefit of being largely unaffected by solar radiation and cloud cover. Many studies have been made to retrieve the soil moisture from microwave remote sensing data (Jackson[3], Koike et al.[4], Njoke et al.[5], Paloscia et al.[6]). Some are empirical ones and others are physically-based ones. Currently, all of them are still under development/testing stage. In this study, a new algorithm for retrieving surface soil moisture from passive microwave sensor is proposed.

2. DATA DESCRIPTION

2.1. TRMM/TMI data

Recently, a new sensor AMSR (Advanced Microwave Scanning Radiometer) has been developed and launched in May 2002. While TMI was launched in November 1997, and data period covers the GAME(GEWEX Asian Monsoon Experiment). Now good dataset for the soil moisture and soil temperature (surface temperature) has been established and opened to scientific community by GAME-Tibet group (http://monsoon.t.u-tokyo.ac.jp/tibet/). That is why TRMM/TMI was selected, in this study, for the passive microwave sensor. The major characteristics of TRMM/TMI are listed in Table 1.

The TRMM official data product 1B11 is used in this analysis. This dataset includes the brightness temperatures (after geometrical and sensor correction) measured by each band together with observation location and time information. Although the horizontal resolution becomes worse (see Table 1), low frequency (10.7GHz) is known to be sensitive to soil moisture, and this frequency is used for data analysis. Furthermore, the effects of atmosphere can be negligible in this band.

Table 1. Major characteristics of TRMM/TMI

Orbit	Non-Sun-synchronous circular orbit				
Sensor	TMI (TRMM Microwave Imager)				
Observation band (GHz)	10.7	19.4	21.3	37.0	85.5
Horizontal resolution (km)	63 x 39	30 x 18	27 x 17	16 x 10	7 x 4

2.2. GAME-Tibet ground-truth data

Among the four regional experiments in the GAME project, GAME-Tibet is most suitable for this study. GAME-Tropics region has dense vegetation (tropical forest), GAME-HUBEX does not have continuous measurement of soil moisture, and GAME-Siberia is out of the TRMM measurement range (S38-N38). Furthermore, since the measurement of the soil moisture and surface temperature is one of most important research activity in GAME-Tibet, the dataset is almost continuous (no missing value) and highly qualified.

Among the many measurement sites in GAME-Tibet, three sites are selected for analysis. D66, Tuotuohe, Amdo are located in the north-east, central, south-west part of the GAME-Tibet region, respectively. The measurements were done at different depth from surface to 200cm, and the surface values (average from surface to 4cm) are used as the ground truth data. NDVI data (SPOT VEGETATION 10day-composite dataset) is used to treat the vegetation change (phenology). Although the original horizontal resolution of this dataset is 30second, NDVI data is averaged over 0.1 degree × 0.1 degree. Since this dataset still includes the cloud effect, BISE method (Viovy et a.[8]) is applied to smooth the time series. Target period is from June to August in 1998. During this period, the climate changes from dry to wet, and the vegetation also changes accordingly. For example, the value of NDVI increases from 0.2 to 0.4 at Amdo site.

2.3. Sampling time of TMI measurement

In this study, all the measurements within a circle with radius 0.1 degree are sampled to increase the sampling number (time resolution). As mensioned above, the horizontal resolution of 10GHz is about 60 × 40 km, then the radius of 0.1 degree (about 10km) is small enough. The distribution of the TMI measurement point (center of pixel) for July 1998 is shown in figure 1. The distance between the edge of the pixel of TMI measurement and ground measurement site can be about 70km at maximum. Considering the uniformity of the land surface condition in the Tibetan Plateau, the maximum distance of 70km is not so large, and the effect of the difference in foot print might be negligible.

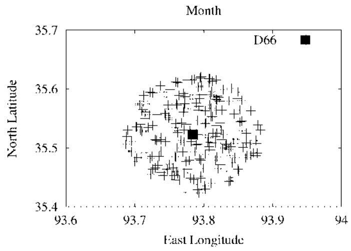

Figure 1. The location of TMI measurement around D66 site(1998 July)

The measurement of TMI is twice or three times per day, while the ground measurement is hourly (24 times per day). Therefore, the values for the TMI measurement time are extracted from the original(hourly) time series.

3. ALGORITHM DESCRIPTION

3.1. Microwave transfer theory

The dependency of soil emissivity on soil moisture is caused by the large difference in the dielectric constant for soil and liquid water. The complex dielectric constant of soil (ϵ_s) is written by following equation (Dobson et al.[1]).

$$\epsilon_s = 1 + \frac{\rho_d}{\rho_s}(\epsilon_d^\alpha - 1) + M_v^\beta \epsilon_f^\alpha - M_v \quad (1)$$

$$\epsilon_d = (1.01 + 0.44\rho_s)^2 - 0.062 \qquad \epsilon_f = 4.9 + \frac{74.1}{1 + if/18.4} \quad (2)$$

Here, ρ_d and ρ_s are the densities of dry soil and soil particle, and M_v is the volumetric soil moisture content. α and β are parameters depending on dielectric constant and soil type, respectively. i is an imaginary unit, and f is a frequency of sensor. By assuming that the soil surface is smooth and neglecting the volume scatter, the surface microwave reflectivities for each polarization of the sensor (r_H and r_V) are expressed by Fresnel reflection equations.

$$r^H = \left| \frac{\cos\theta - (\epsilon_s - \sin^2\theta)^{1/2}}{\cos\theta + (\epsilon_s - \sin^2\theta)^{1/2}} \right|^2 \qquad r^V = \left| \frac{\epsilon_s \cos\theta - (\epsilon_s - \sin^2\theta)^{1/2}}{\epsilon_s \cos\theta + (\epsilon_s - \sin^2\theta)^{1/2}} \right|^2 \tag{3}$$

Here, θ is a viewing angle. The surface microwave reflectivities for the rough soil surface (R_H and R_V) can be written as follows.

$$R^H = \left\{ q_s r^H + (1 - q_s) r^V \right\} \exp(-h) \quad R^V = \left\{ q_s r^V + (1 - q_s) r^H \right\} \exp(-h) \tag{4}$$

Here, q_s and h are the polarization mixing ratio and roughness parameter of the soil surface. At these frequencies the emissivity (ε) is equal to 1 minus the reflectivity (R).

$$\varepsilon^H = 1 - R^H \qquad \varepsilon^V = 1 - R^V \tag{5}$$

Following the standard values of Seto et al. [7], the value of each parameters are prescribed (see Table 2).

Table 2. List of parameters

symbol	definition	unit	value
ρ_{d}	dry density of the soil	g/cm^3	1.15
ρ_{s}	density of the soil particle	g/cm^3	2.65
α	parameter depending on dielectric constant	—	0.65
β	parameter depending on soil type	—	1.78
θ	viewing angle	deg	54.7
q_{s}	polarization mixing ratio	—	0.7
h	roughness parameter	—	0.2

The measurement provided is the brightness temperature(T_B) that includes contributions from the atmosphere, reflected sky radiation, and the land surface. At low frequencies, the first two terms are negligible. Taking the effects of vegetation layer into account (Jackson et al.[2]), T_B can be written as the following equation.

$$T_B = e^{-\tau_{\mathrm{c}}} T_s + (1 - \omega_c)(1 - e^{-\tau_{\mathrm{c}}}) T_c \tag{6}$$

Here, T_s and T_c are the brightness temperatures for soil surface and vegetation, τ_c and ω_c are the optical depth and the single scattering albedo for vegetation layer. T_s is equal to its emissivity (ε) multiplied by its physical temperature (T_g).

In eq.(6), assuming that the scattering emission from vegetation is negligible (ω_c=0) and the phisical temperatures for soil (T_g) and vegetation (T_c) are the same, microwave transfer equation can be written as follows.

$$T_B = \left(1 - \frac{1-\varepsilon}{e^{\tau_c}}\right) T_g \tag{7}$$

Then, T_B is expressed by a function of T_g, ε, and τ_c. If the parameter values are prescribed as in Table 2, the unknown quantity in soil emissivity (ε) is only the soil moisture (M_v). While the optical depth for vegetation (τ_c) is written as a function of frequency and water content of vegetation (Jackson[3]). But in-situ measurement of water content of vegetation is very limited and its parameterization is under development stage.

3.2. A new algorithm without microwave transfer equation

In this study, focusing on the relationship between T_B and ε, we try to formulate a new soil moisture retrieval algorithm without microwave transfer equation like eq.(7). Two types of formulation (linear and power) are proposed to express the effects of vegetation in a simple way.

$$f(\varepsilon) = P\ f(T_B) \qquad f(\varepsilon) = f(T_B)^P \tag{8}$$

Here, $f(\varepsilon)$ is a function of soil emissivity, and $f(T_B)$ is a function of brightness temperature, P is a vegetation parameter. As shown by past studies, the polarization difference and polarization ratio of brightness temperature are expected to have good correspondence with soil moisture. From a theoretical point of view, ε is a function of soil moisture, and, as will be shown by Figure 2 later, other variables derived from ε should be a function of soil moisture. Then, three types of function (difference, simple ratio, and normalized difference) are examined (see Table 3). Taking the logarithm of both $f(\varepsilon)$ and $f(T_B)$ and using linear function is equal to using power function as well.

$$\log\left[f(\varepsilon)\right] = P\ \log\left[f(T_B)\right] \quad \Leftrightarrow \quad f(\varepsilon) = f(T_B)^P \tag{9}$$

Table 3. List of examined function for ε and T_{B} and correlation coefficient

name	$f(\varepsilon)$	$f(T_{\mathsf{B}})$	CC(linear)	CC(power)
DF	$\varepsilon_{\mathsf{V}} - \varepsilon_{\mathsf{H}}$	$T_{\mathsf{V}} - T_{\mathsf{H}}$	0.273	0.263
SR	$\varepsilon_{\mathsf{V}} / \varepsilon_{\mathsf{H}}$	$T_{\mathsf{V}} / T_{\mathsf{H}}$	0.327	0.326
ND	$(\varepsilon_{\mathsf{V}} - \varepsilon_{\mathsf{H}})/(\varepsilon_{\mathsf{V}} + \varepsilon_{\mathsf{H}})$	$(T_{\mathsf{V}} - T_{\mathsf{H}})/(T_{\mathsf{V}} + T_{\mathsf{H}})$	0.326	0.316

Firstly, using ground measured soil moisture as M_v in eq.(1), $f(\varepsilon)$ was calculated (through eq.(1) to eq.(5)). Secondly, $f(T_B)$ was calculated from the TMI measured value. Lastly, the correlation coefficient between $f(\varepsilon)$ and $f(T_B)$ was calculated. Here, we expect the linear relationship by factor of P, and P may change according to vegetation status. Thus, the data were divided according to NDVI value (by 0.01 increment), and the correlation coefficients were calculated for each sub-dataset. The results (average value of the correlation coefficients) for all cases are also shown in Table 3. In general, the values of correlation coefficient are not so high (around 0.3). But, as will be discussed later, the depth of ground measurement is 4 cm and that of TMI is surface. So, the fluctuation (time variation) of TMI measurement tends to be larger than that of ground measurement. Anyway, among three types of function, simple ratio shows high correlation for both linear and power cases. Here, changing the soil moisture from 0 to 1, sensitivity of the $\varepsilon_V/\varepsilon_H$ and $\log(\varepsilon_V/\varepsilon_H)$ are compared (see Figure 2). As a result, the latter case is highly sensitive, and it is most suitable for the soil moisture retrieval. Accordingly, the following formulation is a proposed algorithm.

$$\log\left(\frac{\varepsilon_{10V}}{\varepsilon_{10H}}\right) = P\ \log\left(\frac{T_{B,10V}}{T_{B,10H}}\right) \tag{10}$$

Here, $T_{B,10V}$ is a brightness temperature for vertical polarization, and ε_{10H} is a soil emissivity for horizontal polarization in 10GHz. P is a time varing parameter to express the effect of vegetation phenology.

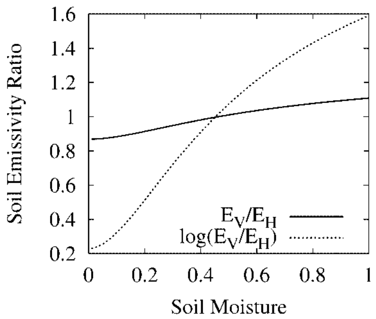

Figure 2. Sensitivity of the simple ratio (normalized by average value)

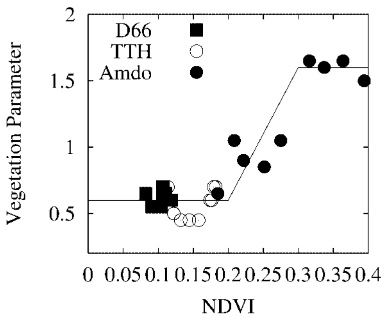

Figure 3. Relationship between NDVI and vegetation parameter P

4. CALIBRATION OF THE VEGETATION PARAMETER

From the rough analysis, the vegetation parameter P was adjusted. And the value of the wet season (August) tends to be larger than that of dry season (June). From this result, P value is assumed to be correlated with vegetation amount. Here, we try to clarify the relationship between P and NDVI, since the NDVI data can be easily obtained in the global scale.

For a certain value of P, soil moisture can be estimated from TMI data, and this value is compared with ground measurement. Here, the ratio of soil emmisivity is calculated from the ground measurement and P values are optimized for every 10-day period by the following condition.

$$f(P) \to \min \qquad f(P) = \sum_{day=1}^{10} \left\{ \log\left(\frac{\varepsilon_{10V}}{\varepsilon_{10H}}\right) - P\ \log\left(\frac{T_{b,10V}}{T_{b,10H}}\right) \right\}^2 \tag{11}$$

The result of the optimized parameter is plotted with NDVI (Figure 3). For the low NDVI value (less than 0.2), P values are almost constant ($P \simeq 0.6$). While P is nearly propotional to NDVI as it increases from 0.2 to 0.3. And P values are almost constant ($P \simeq 1.6$) for moderately large NDVI (more than 0.3). The formulation of P still needs further study using ground measurement for different climatic condition and different vegetation types. For the moment, it is implied that P and NDVI have a linear relatonship with lower and upper limit. Finally, the new soil moisture algorithm is summarized as follows.

(1) deciding the soil parameters (Table 2) and vegetation parameter P

$$P = \begin{cases} 0.6 & (NDVI < 0.2) \\ 10NDVI - 1.4 & (0.2 < NDVI < 0.3) \\ 1.6 & (0.3 < NDVI) \end{cases}$$

(2) calculating the simple ratio $\varepsilon_{10V}/\varepsilon_{10H}$ from $T_{B,10V}/T_{B,10H}$ (eq.(10))
(3) finding the soil moisture from the theoretical relationship (Figure 2)

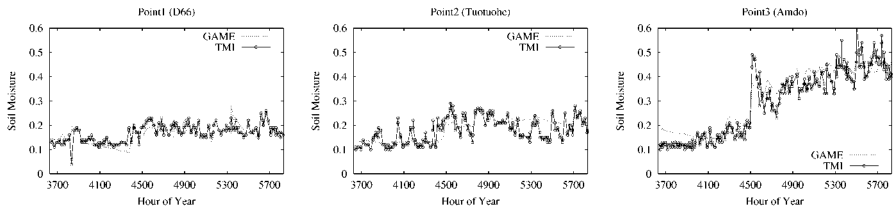

Figure 4. Comparison of ground measured and TMI estimated soil moisture

Time series of ground measured and TMI estimated soil moisture for three sites are shown in Figure 4. TMI estimation does express the difference between dry season (June) and wet season (July, August) very well at D66 and Amdo sites. Also TMI estimation can reflect the increase of soil moisture for each precipitation event. Here, the ground measurement is the average of the top 4cm. While the TMI measured brightness temperature includes much contribution from surface skin layer which can be influenced by surface evaporation and small rain. So, the TMI estimation fluctuates a little bit more than ground measurement.

5. CONCLUSION

In this study, a new algorithm for retrieving surface soil moisture from TRMM/TMI data is proposed by utilizing the GAME-Tibet dataset. Assuming that some soil physical parameters are prescribed, soil emissivity for each frequency and polarization can be derived from Fresnel's law and Dobson's formula, and it can be expressed by a function of soil moisture. The soil emissivities for each polarization ($\varepsilon_{10H}, \varepsilon_{10V}$) are calculated from the ground measured soil moisture data. Also, the Brightness Temperatures from TRMM/TMI ($T_{B,10H}, T_{B,10V}$) for the same period are prepared. Through the analysis of these values, the ratio of these two polarization values are found to be roughly expressed by a power function. Furthermore, the ratio $\varepsilon_{10V}/\varepsilon_{10H}$ itself is theoretically derived to be a function of soil moisture. As a result, soil moisture can be retrieved from $T_{B,10V}/T_{B,10H}$ and one vegetation parameter P. Although the algorithm is so simple, time series of TRMM/TMI retrieved surface soil moisture agrees well with ground measurement.

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