A time series based method for estimating relative soil moisture with ERS wind scatterometer data

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[1] The radar backscattering coefficient is mainly determined by surface soil moisture, vegetation and land surface roughness under a given configuration of the satellite sensor. It is observed that the temporal variations of the three variables are different, the variation of vegetation and roughness are at the longer temporal scales corresponding to climate and cultivation practices, while soil moisture varies at a shorter temporal scale in response to weather forcing. Based on this hypothesis, a robust method for the determination of relative soil moisture is proposed for application to the ERS Wind Scatterometer database and the Pathfinder AVHRR dataset. Ground measured soil moisture data collected during GAME/Tibet field experiment are used to validate the proposed method. The results show that the estimated relative soil moisture corresponds closely to local precipitation at two GAME/Tibet field sites. The volumetric soil moisture converted from the Wind Scatterometer estimated relative soil moisture is in good agreement with the measured 0–4 cm topsoil volumetric soil moisture. The regional distributions of relative soil moisture are evaluated and correlated well to the ground measured volumetric soil moisture. It is concluded that the large footprint Wind Scatterometer dataset can capture ground soil wetness variation in arid and semi-arid zone with the aid of vegetation information derived from other sensors. *INDEX TERMS:* 1866 Hydrology: Soil moisture; 0933 Exploration Geophysics: Remote sensing; 1655 Global Change: Water cycles (1836); 1719 History of Geophysics: Hydrology; 1836 Hydrology: Hydrologic budget (1655); *KEYWORDS:* soil moisture, Wind scatterometer, backscattering coefficient, GAME/Tibet. **Citation:** Wen, J., and Z. Su, A time series based method for estimating relative soil moisture with ERS wind scatterometer data, *Geophys. Res. Lett.*, *30*(7), 1397, doi:10.1029/2002GL016557, 2003.

1. Introduction

[2] Water is a critical resource for life on our earth. Although the water stored in land surface soil layer is very limited, which is only about 0.005% of the global water, it is essential to all continental life. On the other hand, water stored in soil integrates precipitation and evaporation over periods of hours to weeks, prominently controls the interactions among hydrosphere, biosphere and atmosphere systems. Soil moisture variation is also a direct indicator for monitoring drought disasters. Therefore, many disciplines and scientists focus their studies or research topics on the measurements or indirect determination of soil moisture and its variation at various temporal and spatial scales [*Calvet et al.*, 1996; *Dobson and Ulaby*, 1986; *Famiglietti et al.*, 1999; *Grayson and Western*, 1998; *Jackson and Schmugge*, 1989; *Lakshmi et al.*, 1997; *Lin et al.*, 1994; *Mancini et al.*, 1999; *Shi et al.*, 1997; *Su et al.*, 1997; *Verhoest*, 2000].

[3] In the active microwave remote sensing process, the signal intensity received by the satellite sensor is mainly determined by soil moisture, vegetation and surface roughness. The variations of these three variables are at different temporal scales. Since the variations of the latter two variables can be represented by seasonal or average values, the main factor that affects the variation of the measured back-scattering coefficient will be soil moisture. Considering the different contributions from land surface components, a robust method for evaluating the relative soil moisture will be developed in this study for using the data collected by an active microwave instrument, the Wind Scatterometer, aboard the European Remote sensing Satellites-ERS-1/2, the ERS Wind Scatterometer database [*Wismann*, 1998] containing backscattering coefficient time series at monthly temporal and resampled to 50 km spatial resolution will be used in this study. The backscattering coefficient data are normalized to 40° incidence angle to ensure that for the same ground point the backscattering coefficients from different repeat visits can be compared easily. The Pathfinder AVHRR Normalised Difference Vegetation Index (NDVI) dataset can provide vegetation information time series, the contribution of vegetation can be parameterised with this dataset. The in-situ temporal variation of relative soil moisture are estimated over two field observation sites of the Global Energy and Water Cycle Experiment (GEWEX) Asian Monsoon Experiment in Tibet (GAME/Tibet). The regional distribution of relative soil moisture will be mapped over GAME/Tibet meso-scale experimental area. The ground measured volumetric soil moisture data collected during GAME/Tibet will be used to validate the proposed method.

2. Method for Determination of the Relative Soil Moisture

[4] Suppose that the bare soil and the soil beneath the vegetation layer have the same surface roughness and soil moisture at one pixel scale, the bulk back-scattering coefficient can be expressed by the following equation [*Wen and Su*, 2001]

$$\sigma^0(\theta) = \left[1 - F_C\left(1 - T^2(\theta)\right)\right]\sigma^0_{soil} + F_C\left(\sigma^0_{\mathrm{int}} + \sigma^0_{veg}\right) \quad (1)$$

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where $\sigma^0(\theta)$ is the bulk back-scattering coefficient, θ is the incidence angle, F_C is the vegetation fractional coverage, $T^2(\theta)$ is the canopy transmittance in the two ways of incoming and outgoing path, σ^0_{soil} is the contribution from the soil, σ^0_{veg} is the contribution from the vegetation volume, σ^0_{int} is the contribution from the land surface-vegetation interaction.

[5] The L-Band radar backscattering coefficient depends upon volumetric soil moisture in the upper 2–5 cm topsoil for bare soil surface with distinctive surface roughness and soil texture, the linear correlation coefficient is approximately 0.90 [*Ulaby et al.*, 1982]. In the most cases, particularly for large footprint satellite remote sensing data in the arid and semi-arid areas, the soil moisture is constrained within a limited range, so that the relationship between backscattering coefficient and soil moisture for bare soil can be expressed in a linear relationship

$$\sigma^0_{pp} = A + B \cdot M_v \tag{2}$$

where M_v is the volumetric soil moisture, σ^0_{pp} is the pp-polarised backscattering coefficient in linear units, A and B are site-specific empirical constants. Similar linear relationship has been proposed in various studies based on field studies [*Giacomelli et al.*, 1995; *Weimann*, 1996].

[6] Vegetation fractional coverage can be parameterised with AVHRR derived Normalised Difference Vegetation Index [*Carlson and Ripley*, 1997]. If vegetation layer is considered as effective contribution which is only parameterised with vegetation fractional coverage, then σ^0_{int} and σ^0_{veg} can be parameterised with the scheme by [*Frison et al.*, 1993; *Wagner*, 1998]. Define $\phi = 1 - F_C\,[(1 - T^2(\theta)]$ and $\varphi = F_C(\sigma^0_{\text{int}} + \sigma^0_{veg})$, which are functions of vegetation fractional coverage with the following constraints

$$\begin{cases} \phi = 1 \quad \varphi = 0 \quad \textit{No vegetation} \\ \phi = \phi_{\max} \quad \varphi = \varphi_{\max} \quad \textit{Maximum vegetation} \end{cases} \tag{3}$$

[7] Combining (2) and (3), the extreme volumetric soil moisture values can be expressed as

$$\begin{cases} M_v^{\min} = \dfrac{\sigma^0_{\min} - A}{B} \\ M_v^{\max} = \dfrac{\sigma^0_{\max} - A.\phi_{\max} - \varphi_{\max}}{B.\phi_{\max}} \end{cases} \tag{4}$$

[8] If a relative soil moisture variable is defined as

$$\theta_R = \frac{M_v - M_v^{\min}}{M_v^{\max} - M_v^{\min}} \tag{5}$$

where θ_R can be understood as a variable - relative soil moisture with respect to the saturation capacity and minimal soil moisture for a given soil. With (4) inserted into (5), the relative soil moisture can be derived as

$$\theta_R = \frac{\phi_{\max}\left(\sigma^0 - \varphi - \phi.\sigma^0_{\min}\right)}{\phi\left(\sigma^0_{\max} - \varphi_{\max} - \phi_{\max}.\sigma^0_{\min}\right)} \tag{6}$$

[9] To derive the relative soil moisture time series, the time series of vegetation variables ϕ, φ and backscattering coefficient σ^0 need to be provided in advance. ϕ and φ can be parameterized with vegetation fractional coverage [*Frison et al.*, 1993; *Wagner*, 1998], which can be derived from

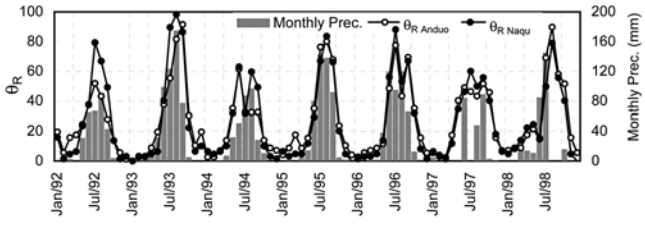

Figure 1. Wind Scatterometer estimated relative soil moisture (RSM) and local precipitation.

Pathfinder NDVI dataset [*Carlson and Ripley*, 1997]. Backscattering coefficient can be extracted from Wind Scatterometer database [*Wismann*, 1998]. In practice, the extreme values will be extracted from its time series to derive the relative soil moisture time series for a single pixel area. The extreme values will be in regional representative to estimate the regional distribution of relative soil moisture over the GAME/Tibet meso-scale experimental area. Because the available Wind Scatterometer database is in monthly temporal resolution, only the monthly regional distribution of relative soil moisture will be estimated in this study.

3. Results and Analysis

[10] Five GAME/Tibet soil moisture observation sites are available within the study area, the volumetric soil moisture of 0–4 cm topsoil was measured at hourly intervals at these sites using Time Domain Reflectometry (TDR) soil moisture sensors. In order to validate the Wind Scatterometer estimated soil moisture with ground measured volumetric soil moisture, the monthly average value had been computed from the original measured soil moisture. With the proposed method applied to the available ERS Wind Scatterometer database and the Pathfinder AVHRR vegetation dataset, the temporal and regional relative soil moisture over the GAME/Tibet field observation sites and the entire meso-scale experimental area will be estimated.

3.1. The Temporal Variation of Relative Soil Moisture at In-Situ Observation Sites

[11] In order to estimate a time series of the relative soil moisture using the above proposed method and database, two GAME/Tibet field observations sites Anduo (91.6°E, 32.2°N) and Naqu (92.1°E, 31.5°N) are selected in this study. The surfaces of these two sites have homogeneous regional representative characteristics for the entire Wind Scatterometer single pixel. The two sites have a typical plateau climate, where the surface soil is drier and colder in winter and spring, but wetter and warmer in summer and autumn, plateau grass and tundra are growing on both sites during the summer which is the monsoon rainfall season. Because the backscattering coefficient is at 50-km spatial and monthly resolution, the corresponded Pathfinder NDVI data are also resampled into the same resolution. The derived relative soil moisture therefore will be at 50-km spatial and monthly temporal resolution, it is hereafter defined as monthly relative soil moisture. The derived relative soil moisture at Anduo and Naqu sites and monthly precipitation are plotted in Figure 1. The estimated relative soil moisture reveals obvious temporal variation at the two GAME/Tibet field observation sites, the variation patterns are very close to each other. It is shown that the estimated

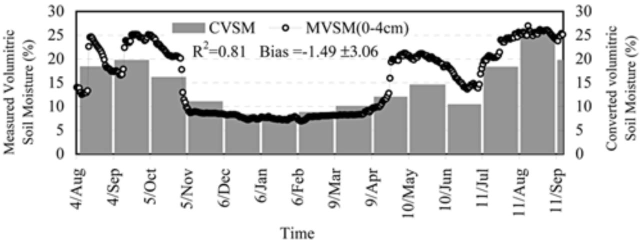

Figure 2. Comparison between the ground measured volumetric soil moisture (MVSM) and the Wind Scatterometer converted volumetric soil moisture (CVSM).

soil moisture variation is sensitive to the local monthly precipitation. The estimated monthly relative soil moisture has a good relationship with the local monthly precipitation, the correlation coefficients reach 0.83 and 0.81 at Anduo and Naqu respectively. To validate the proposed method, the relative soil moisture needs to be converted to the volumetric soil moisture using the ground measured extreme volumetric soil moisture. The monthly ground soil moisture is the mean values of the all soil moisture samples during one month. A comparison between the converted volumetric soil moisture (CVSM) and ground measured volumetric soil moisture (MVSM) is plotted in Figure 2. The tendency of the two soil moisture variables is almost the same, it is also observed that the decrease of ground-measured volumetric soil water content in June 1998 can be detected by the satellite estimates, indicating the robustness of the proposed method. The correlation coefficient between the converted volumetric soil moisture and ground measured volumetric soil moisture is 0.92 for 0–4 cm topsoil, the average differences between the converted soil moisture and ground measured volumetric soil moisture is $-1.49 \pm 3.06\%$. All above correlation coefficients have passed the significance test within a 0.05 significance level. Therefore, the estimated relative soil moisture is a variable that describes the actual temporal variation of soil moisture in the time series.

3.2. The Regional Distribution of Relative Soil Moisture

[12] The study region covers 91–92.5°E, 30.5–33.0°N, its average altitude is higher than 4000 meter above the sea level, the precipitation decreases from south to north in the summer, which is controlled by the Tibetan plateau monsoon. The southern area is covered by grassland and tundra, the development of vegetation is mainly controlled by the local precipitation. The northern area is typical plateau desert with bare or sparely vegetated surface.

[13] With the proposed method applied to the ERS Wind Scatterometer and Pathfinder AVHRR NDVI database, the regional distributions of relative soil moisture in October 1997, January 1998, April 1998 and August 1998 are mapped over the GAME/Tibet meso-scale experimental area in Figure 3. The maps illustrate that the central area gives lower soil moisture, while the southern area has large soil moisture especially in summer 1998. The regional average values are 32.6 ± 12.71%, 15.11 ± 12.95%, 16.86 ± 14.16% and 37.69 ± 16.13% in October 1997, January 1998, April 1998 and August 1998 respectively. The estimated relative soil moisture have lower value in dry season, January 1998 and April 1998, and higher value in October 1997 and August 1998. These results are consistent with the regional climate property and in good agreement with ground measurement.

[14] Although five GAME/Tibet field observation sites are available within the study area, two of them are located in the transition area of two pixels, the dada at these two sites not suitable to validate the satellite estimates, only the ground data measured from D110, Anduo and MS3608 sites will be used to validate the regional results. The correlation coefficient between the converted and measured soil moisture is 0.65, but it still pass the significance test within 0.05 significance level, the average difference is 1.96 ± 7.02%. Taking into account of the large footprint of the Wind Scatterometer data and spatial representative of the ground observation sites, the estimated regional distribution of relative soil moisture reflect the real soil moisture status over the study area.

3.3. Error Analysis and Discussions

[15] Finally, it needs to be pointed out that the measurement errors of the backscattering coefficient and involved vegetation fractional coverage will cause uncertainties in the estimated relative soil moisture, the uncertainty of estimated relative soil moisture could be analysed by taking partial derivatives to equation (6). If σ^0_{max}, σ^0_{min}, F_{cmax} and F_{cmin} are assigned as the extreme values in the dataset in this analysis, and the vegetation single scattering albedo and optical thickness are taken as 0.076 and 1.00 respectively, the uncertain-

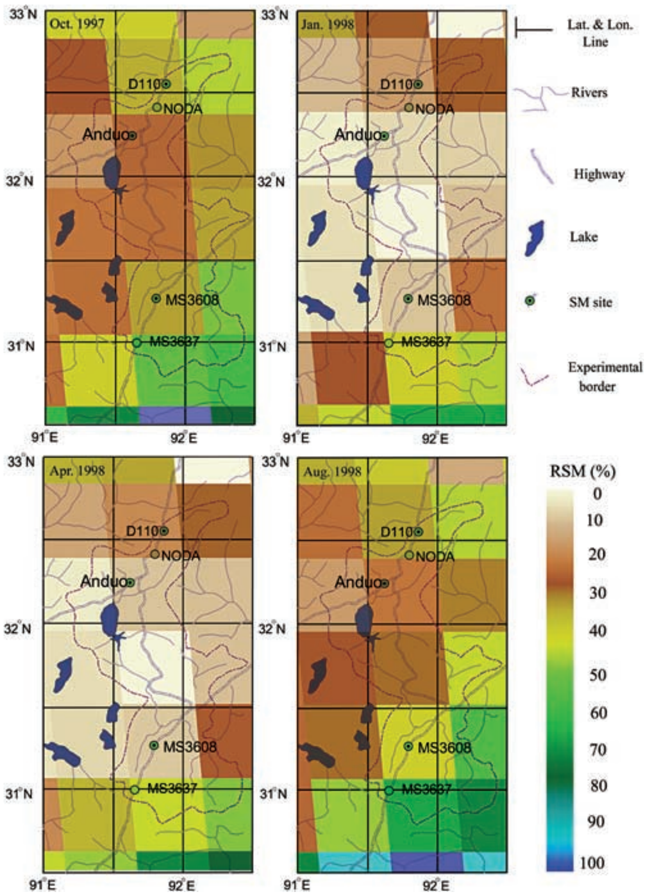

Figure 3. Regional distribution of the Wind Scatterometer estimated relative soil moisture (RSM) over GAME/Tibet meso-scale experimental area.

ties of estimated relative soil moisture are ranged from 0.17% to 2.16% and −3.34% to 1.76% for 0.1 unit fractional coverage and 0.3dB backscattering coefficient. This result is consistent with previous field studies and theoretical modelling [*Su et al.*, 1997].

4. Conclusions

[16] A method for estimating the relative soil moisture has been proposed for the application of the ERS Wind Scatterometer observation and the Pathfinder AVHRR NDVI database, the computation and validation of the proposed method are performed over the GAME/Tibet meso-scale experimental area.

[17] The temporal variation of the estimated relative soil moisture is in good agreement with local precipitation at the GAME/Tibet field sites, the correlation coefficients reach 0.83 and 0.81 respectively. The volumetric soil moisture converted from ERS Wind Scatterometer estimated relative soil moisture (CVSM) is in agreement with the ground measured volumetric soil moisture (MVSM) in GAME/Tibet field observation site Anduo, the correlation coefficient is 0.92 for 0–4 cm topsoil with an average difference −1.49 ± 3.06%. The regional distribution of relative soil moisture reflects the soil moisture climatology over the GAME/Tibet meso-scale experimental region, which is smaller in winter and spring and bigger in summer and autumn. The regional average values are 32.6 ± 12.71%, 15.11 ± 12.95%, 16.86 ± 14.16% and 37.69 ± 16.13% in October 1997, January 1998 April and August 1998 respectively, the correlation coefficient between CVSM and MVSM is 0.65 with an average difference 1.96 ± 7.02%. The error analysis reveals that the proposed method will not give serious error to the estimated relative soil moisture. All these correlation coefficients have passed the significance test within 0.05 significance level. It is concluded that the proposed method is successful and merits further investigation for its applicability to other climatically different regions and even at global scale.

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