The estimation of soil moisture from ERS wind scatterometer data over the Tibetan plateau

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Abstract

With the consideration of microwave radiation transfer process, physically based simple algorithms have been proposed to estimate land surface soil Fresnel reflectivity or soil moisture and vegetation fractional coverage from ERS wind scatterometer data. The proposed algorithms have been successfully applied over the Tibetan plateau where large amount of ground measurements are available from the Intensive Observation Period (IOP'98) field campaign in 1998 of the Global Energy and Water Experiment (GEWEX) Asian Monsoon Experiment in Tibet (GAME/Tibet). The variation tendency of the retrieved monthly soil moisture variable is in good agreement with both local monthly precipitation and ground measured volumetric soil moisture. The regional distribution of land surface soil moisture and vegetation fractional coverage are in agreement with ground measurement and consistent with the local climatic characteristics. If the discrepancies of the geographical co-ordinates and the different spatial resolutions are carefully considered, the retrieved result and its validations can be considered successful.
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1. Introduction

Researches in recent years show that satellite remote sensing techniques are the only available tools in determination of the land surface soil moisture at a large spatial scale (e.g. Schmugge et al., 1986; Jackson and Schmugge, 1989; Calvet et al., 1996; Su et al., 1997; Shi et al., 1997; Fujii and Koike, 2001; Woodhouse and Hoekman, 2000a,b). Three types of satellite sensors are available to determine soil moisture: visible and infrared radiometer, microwave radiometer and active radar. Techniques based on the second and third types are also classified as passive and active microwave remote sensing methodology. Visible and infrared remote sensing technique has already been well developed and widely applied in the determination of land surface parameters. One such example is the thermal inertia algorithm developed for NOAA/AVHRR data (Carlson, 1996).

However, the effects of atmospheric and vegetation layer make the thermal inertia algorithm very complicated and questionable especially when there is very thin cirrus clouds or heterogeneous aerosol in the view field of satellite sensor, land surface parameters derived from optical or infrared remote sensor will be perturbed or uncertain under such cases. Since clouds frequently occur in satellite view field during rainy season and vegetation is also developed very well during the rain season, it becomes very difficult to gain a useful cloud-free image under such cases. For example, for the Intensive Observation Period field campaign in 1998 (IOP'1998) during the Global Energy and Water Experiment (GEWEX) Asian Monsoon Experiment in Tibet (GAME/Tibet), although three months' NOAA/AVHHR data are available, it is still difficult to select a total cloud-free case during the whole campaign period. Therefore, the estimation of soil moisture from the optical and infrared remote sensing has been largely unsuccessful. This is one reason why more attentions have been focused on the determination of land surface variables from microwave remote sensing.

Active microwave remote sensing data may be more useful in determination of land surface geophysical

parameters including soil moisture, especially with the possibilities of multiple angular and multiple-bands observations. The European Remote Sensing Satellites—ERS-1/2 carries an active microwave instrument, which combines the functions of SAR and wind scatterometer. Wind scatterometer operates at a frequency of 5.3 GHz (C-Band) with vertically like-polarised antennas both in transmission and reception (VV-polarisation). It continuously provides global measurement of radar cross-section since August 1991. With a spatial resolution of about 50 km, ERS wind scatterometer provides a near global coverage within 3–4 days and thus is suitable for a wide range of operational monitoring tasks. The measurement error of ERS wind scatterometer is about 0.3 dB backscattering coefficient. While it is originally designed to obtain information on wind speed and direction over sea surface, there are increasing applications on determination of land surface soil moisture and study of Antarctic ice or snow melting (Wismann, 2000).

Despite of the coarse spatial resolution of ERS wind scatterometer, it is recognised that the spatial and temporal variability of a variety of geophysical parameters could be evaluated and monitored over land surfaces. The obvious correlation that exists between land surfaces geophysical parameters and the backscattering coefficient gives an enlightened idea to determine land surface variables. Based on the ERS wind scatterometer data set, several researches had been performed such as the interpretation of seasonal ERS-1 wind scatterometer data (Frison and Mougin, 1996a,b; Frison et al., 1997), large-scale soil moisture mapping (Wagner and Scipal, 2000), the regional distribution of soil moisture retrieval (Woodhouse and Hoekman, 2000a,b) and Antarctic ice and snow melting (Wismann, 2000). These studies are successful but some aspects need to be improved. The interpretation of ERS-1 wind scatterometer data which corresponded local soil moisture and vegetation did not provide a regional distribution of soil moisture and vegetation fractional coverage. The distribution of the initial values for the retrieved parameters must be provided in advance, while these initial values will give serious error to the retrieval results if they are far from the actual values. In this study, a simple algorithm will be developed for sparsely vegetated or bare soil surfaces to derive soil Fresnel reflectivity and roughness slope from ERS wind scatterometer database. For the instantaneous observations which can provide backscattering coefficient and its slope in a resolution cell, another algorithm will be used to retrieve soil moisture and effective vegetation fractional coverage without the given initial value of the soil moisture and vegetation fractional coverage. This paper will therefore focus on the determination of soil Fresnel reflectivity or soil moisture and vegetation fractional coverage over GAME/Tibet field experimental area by applying the ERS wind

scatterometer data, two algorithms will be used to different datasheets respectively.

2. Theory and algorithms

Land surface geophysical parameters can be retrieved or evaluated from the wind scatterometer measured signal intensity and its property, such as the different polarisation and view or incidence angles. For the large footprint satellite remote sensing data, such as the spatial resolution of ERS wind scatterometer in 50 km, the backscattering coefficient of land surface is an integral contribution of bare soil and vegetated surface. If the azimuthal effect can be neglected in observation data, which is a reasonable assumption for sparely vegetated land surface or large footprint satellite data at the same incident angles, vegetation and soil moisture contributions can be expressed as incoherent sum after being weighted by their respective fractional coverage (Frison and Mougin, 1996a,b; Frison et al., 1997). Suppose that bare soil and the soil beneath vegetation layer have same property characterised by surface roughness and soil moisture, the radiative transfer process can be described as following

$$
\sigma^0(\theta) = [1 - FC(1 - T^2(\theta))]\sigma^0_{soil} \\
+ FC(\sigma^0_{interaction} + \sigma^0_{vegetation}) \tag{1}
$$

where $\sigma^0(\theta)$ is observed backscattering coefficient, FC is vegetation fractional coverage, $T^2(\theta)$ is canopy transmittance in two ways of incoming and outgoing path, σ^0_{soil} is contribution of soil, $\sigma^0_{vegetation}$ is vegetation volumetric contribution, $\sigma^0_{interaction}$ is the contribution from land surface–vegetation interaction.

If vegetation layer and bare soil have a distinct boundary or if vegetation scatters are not continuously distributed, the refection between interfaces of canopy layer and soil surface or the double-bounced radiance contribution cannot be neglected (Woodhouse and Hoekman, 2000a).

Ulaby et al. (1982) suggested that vegetation layer could be treated as "cloud droplet" as the water drop in atmosphere. In this so called "cloud model" hypothesis, vegetation layer is assumed as many small scattering and absorbing discrete particles. Suppose that vegetation scatters have the same shape and size distribution, volumetric scattering can be expressed as

$$
\sigma^0_{vegetation}(\theta) = \frac{\kappa_s \cos\theta}{2\kappa_e}[1 - \exp(-2\kappa_e \sec\theta)] \\
= \frac{1}{2}\omega_v \cos\theta[1 - T^2(\theta)] \tag{2}
$$

where κ_s and κ_e are scattering and extinction coefficient of vegetation discrete elements. ω_v is the single scattering albedo of the vegetation scatters. The single

scattering is a function of scattering and absorption coefficient, which is affected by the scatter size and vegetation water content. If vegetation scatters have the same size distribution, the single scattering albedo will be a function of the vegetation water content. Vegetation transmittance is determined by: (1) incidence angle of radiation beam; (2) water content of vegetation layer; (3) frequency of radiative beam. If the frequency is as low as that of ERS wind scatterometer with a small incidence angle, sparsely vegetation layer can be considered to be translucent to microwave radiation over sparsely vegetated land surface, Eq. (1) then can be simplified as following form

$$\sigma^0(\theta) \approx \sigma^0_{\text{soil}}(\theta) \tag{3}$$

This is a simplification of Eq. (1) that is the only case when the vegetation contribution can be neglected or under the bare soil surface. This simplification is not true for the vegetated land surface cases. For bare soil surface, radar backscattering coefficient can be expressed as the following expression for HH or VV polarisation cases (Woodhouse and Hoekman, 2000a).

$$\sigma^0_{\text{soil}}(\theta) = \frac{|\Gamma(0)|^2 \exp\left(-\dfrac{\tan^2 \theta}{2s^2}\right)}{2s^2 \cos^4 \theta} \tag{4}$$

where $s = \sqrt{2}\sigma/l$ is the root mean square (RMS) slope of surface height, σ is standard deviation of the surface height and l is horizontal distance between two different points on the surface, a Gaussian correlation function has been assumed. $\Gamma(0)$ is soil Fresnel reflectivity at normal incidence of a half-space with a relative permittivity. It is an indicator of soil wetness that can be evaluated from the soil dielectric constant. A linear or quasi-linear relationship exists between Fresnel reflectivity and soil moisture with different empirical constants in different frequency band and for different soil texture (Dobson and Ulaby, 1986). Eq. (4) can be only applied to very rough surface cases and at small incidence, the land surface of the Tibet plateau is assumed to suite for this kind roughness case. Since the database of Global C-Band wind scatterometer backscattering coefficient provides the normalised backscattering coefficient and its slope, it is possible to extract data at the lower incident angle.

To simplify the contribution of bare soil surface, soil backscattering coefficient can also be described directly with the following formula

$$\sigma^0_{\text{soil}} = C \exp(D \cdot m_{\text{v}}) \tag{5}$$

where C is a constant dependent on surface roughness, D is a constant for the given radiation frequency, polarisation and soil texture, and m_{v} is volumetric soil moisture (Ulaby et al., 1982; Dobson and Ulaby, 1986).

ERS wind scatterometer data provide two independent variables: the back scattering radar backscattering coefficient and its slope. In this study, the proposed al-

gorithms are classified as two catalogues: (1) in the first algorithm, soil Fresnel reflectivity and roughness slope can be estimated from Eq. (4) for the sparsely vegetated or bare soil surface with monthly normalised backscattering coefficient and its slope extracted from the database of Global C-Band wind scatterometer backscattering coefficient. It will only be applied to GAME/Tibet Anduo and Naqu sites; (2) in the second algorithm, Eqs. (1), (2) and (5) together with ERS wind scatterometer observed backscattering coefficient and its slope will configure a non-linear equations system. The solution of this equations system will provide an effective vegetation fractional coverage and soil moisture, no restriction is placed on vegetation status in this algorithm. The vegetation volumetric backscattering coefficient can be parameterised with Eq. (2) which depends on vegetation fractional coverage, backscattering coefficient, extinction coefficient and canopy transmittance. However, it is almost impossible to get all these parameters from field observations, as these parameters are temporal and spatial variables. To reduce the unknown variables of the algorithm, vegetation layer is assumed as an ideal random medium, that is to say, vegetation contributions only depend on incidence angle and an effective fractional coverage that is a lumped property of the canopy layer, with the typical values 0.85 and 1.0 assumed as the single scattering albedo and optical thickness in this study, C and D are 0.025 and 0.034 (Ulaby et al., 1982). Land–vegetation interaction can be parameterised with the method proposed by Wagner and Scipal (2000), as interaction term always gives an order of magnitude bellow −30.0 dB, leading to a negligible contribution to the total backscattering coefficient in sparse vegetation cases (Frison et al., 1997), hence this term will not be considered in this study. If the surface roughness is available, there are only two unknown variables in the equations system: vegetation fractional coverage and soil moisture, which can be solved out from this non-linear equations system.

There is a large amount of ground measurement data collected during GAME/Tibet field experiment, which can be used to validate the retrieved soil moisture from above two algorithms. The temporal and regional distribution of the soil Fresnel reflectivity or soil moisture and vegetation fractional coverage will be retrieved from ERS wind scatterometer data over the Tibetan plateau experimental area, validation will also be performed.

3. Descriptions of field observation sites and data

The Tibetan plateau is located at about 70–100 °E and 25–40 °N in Eurasia continent with average altitude about 4500 meter above sea level, its rugged landscape has caused a typical heterogeneous distribution in annual precipitation. The enormous Taklamakan desert is
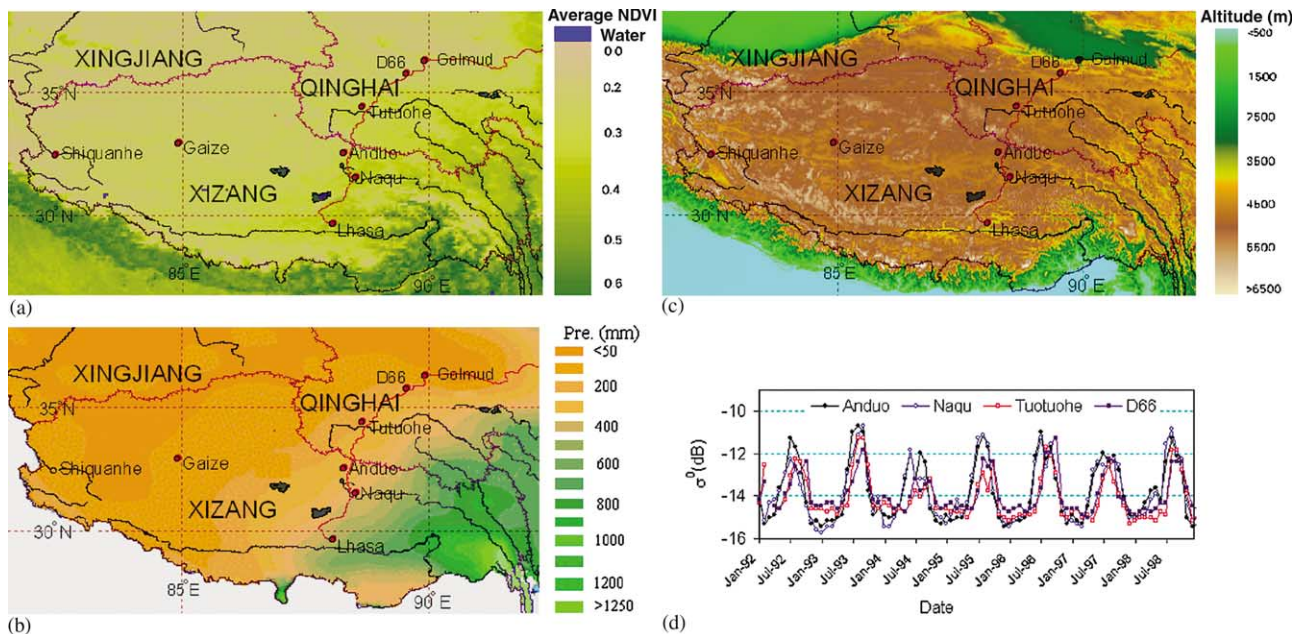
Fig. 1. The regional distribution of (a) normalised difference vegetation index, (b) annual precipitation and (c) topographic maps over Tibetan plateau, (d) the time series of back scattering coefficient at four GAME/Tibet sites.

located in the northern of Tibetan plateau, the southern slope is covered by mountainous monsoon forest or broadleaf forest. The northern plateau is an alpine desert with wind eroded residual hills. The middle area is mountainous steppe, and the southern area is plateau bog meadow interwoven with a few cultivated lands and sub-alpine or alpine shrubby meadow. There are also permanent frozen regions distributed in mountainous areas. The detailed distribution of average normalised difference vegetation index (NDVI), annual precipitation and topography are displayed in Fig. 1.

Recent researches on the Tibetan plateau have focused on the following issues: what is the role of the Tibetan plateau in global energy and water cycle? What is the characteristics of the boundary layer over the Tibetan plateau and how does soil moisture feedback to plateau rainfall? In order to improve the understanding of all these interesting scientific issues, an international co-ordinated project—GAME/Tibet was operated in 1997–2000, with an Intensive Observation Period taking place during May to September in 1998 (IOP'98). The detailed description and observation items of field sites can be found in GAME/Tibet database (GAME/Tibet data catalog, 2001).

As soil moisture in topsoil layer corresponds to the monsoon precipitation amount accumulated over a period of days to weeks, local monthly precipitation (Datasets/Global Precipitation, 2000) and ground measured volumetric soil moisture will be used to validate the monthly soil moisture retrieved from ERS wind scatterometer database. As the ERS wind scatterometer database has monthly temporal resolution, the retrieved

soil moisture is therefore defined as monthly soil moisture variable. To validate the retrieved result, the average value of periodically sampled soil moisture will be defined as the measured monthly soil moisture variable. Eight field sites with soil moisture ground measurement are available in this study. The volumetric soil moisture of 0–4 cm topsoil was measured every hour at these sites with time domain reflectometry (TDR) soil moisture sensors. The locations of these sites were carefully chosen before the experiment to make sure that they are regional representative, the site are normally located in a flat region with homogeneous vegetation coverage. The three antennas of ERS wind scatterometer measure the earth surface backscattering coefficient from three different view directions. All these three antennas form a fan beam with a narrow along-track pattern and a relative wide across-track pattern in order to cover a wide swath parallel to the sub-satellite track. Three antennas produce three beams of view at forward, sideways and backward at 500-km wide swath with respect to satellite orbit direction. Across the swath, the local observational incidence angles range from 18–47° for the mid-beam and 25–59° for the forward and aft beams. Azimuthal difference between the forward and aft views has a negligible magnitude over land surface in normal case. Therefore, only two independent variables: the strength of normalised radar cross-section and its incidence angular dependence can be derived. This study will focus on how to use the angular and temporal information to retrieve Fresnel reflectivity or soil moisture and vegetation fractional coverage in temporal and regional scale. Time series of the backscattering coefficient at four

GAME/Tibet sites are also given in Fig. 1. The yearly variations are very similar but the magnitude is not the same dependent on the yearly wetness situation and location of the sites.

The Institute For Applied Remote Sensing (IFARS) produced a database of Global C-Band wind scatterometer backscattering coefficient with a spatial resolution of 50 km and temporal resolution of three months, while the monthly land surface backscattering coefficient and its slope are also available for single pixels (User Manual Version 2.0, 1999). The data extracted from this database will be fed into the first algorithm. The monthly data from the database of Global C-Band Radar backscattering coefficient data will be used to estimate monthly soil moisture or soil moisture climatology at two GAME/Tibet field sites. In order to validate the wind scatterometer estimated monthly soil moisture with ground measured volumetric soil moisture, monthly averages were made to the original ground measurement dataset. Since the temporal resolution of this database is too low to describe the soil moisture property, as soil moisture varies on daily or weekly scale, the original wind scatterometer data, obtained from the French Processing and Archiving Facility for ERS-1 and ERS-2 (WNF products—User Manual, 2000) will be used to retrieve the soil moisture and vegetation fractional coverage when the satellite overpasses the experimental area on 19 May, 4 June, 1 July, 13 August and 9 September 1998, validations will also be performed to these results.

4. Results and discussions

Due to the special topographic characteristics, the cold climate and the influences of Asian monsoon, the northern Tibetan plateau is desert or very sparsely vegetated land surface, the southern region is steppe interwoven with a few cultivated lands. The temperate forest is only distributed in the southern slope of the plateau. The backscattering coefficient time series at four sites are given in Fig. 1(d), although the values are not close to each other, the variation tendency are similar, the dry year kept lower backscattering coefficient while the wet year corresponded high values. The north sites corresponded lower backscattering coefficient while the southern sites have the bigger values. These characteristics can be found in distribution of average NDVI, annual precipitation and topographic maps in Fig. 1.

The yearly average NDVI derived from the Pathfinder NOAA/AVHRR data is very low at two GAME/Tibet field sites Anduo (32.24 °N, 91.63 °E) and Naqu (31.37 °N, 91.90 °E), so vegetation layer can be considered as translucent medium to ERS wind scatterometer at these sites. The monthly surface soil Fresnel reflectivity and roughness parameter can then be evaluated with the proposed first algorithm and the data extracted from the database of Global C-Band wind scatterometer backscattering coefficient. The temporal variation of monthly soil Fresnel reflectivity combined together with local monthly and annual precipitation in Anduo and Naqu sites are given in Fig. 2. Since the two sites have very similar variation in Fresnel reflectivity, an average is plotted in the figure.

As summer is the main rainfall season in the Tibetan plateau, soil moisture should also be higher in this season. Fig. 2 reveals that the variation tendency of the retrieved soil Fresnel reflectivity is in good agreement with monthly precipitation. The annual precipitation reached the biggest in 1993 during 1992–1998, while the retrieved surface soil Fresnel reflectivity also gives the biggest value in 1993 during the same period. The correlation coefficient between monthly precipitation and soil Fresnel reflectivity reaches 0.87 and 0.88 for Naqu and Anduo sites respectively. Soil moisture is a response of the periodic rainfall accumulation, the retrieved soil Fresnel reflectivity therefore exhibits the climatic variation of soil
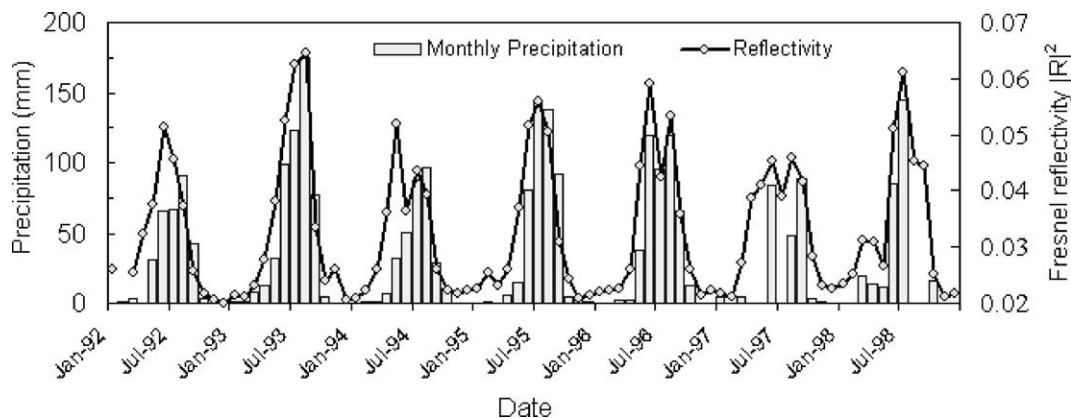

Fig. 2. The average temporal variation of the soil Fresnel reflectivity and local monthly precipitation (mm) at two GAME/Tibet Anduo and Naqu sites.

moisture at these GAME/Tibet field observation sites. The retrieved reflectivity curves in some year shifted before the rainfall curves has also been noticed such as in 1994, this is caused by the difference between the rainfall and ERS observation. The rainfall concentrated in some period, while satellite retrieved Fresnel reflectivity is the average value during the whole month. Time series of the retrieved surface roughness parameter are relatively stable with average values 0.3389 and 0.3418 at these two sites as shown in Fig. 3, there is no obvious temporal variation. The values at Anduo are a little bigger than those in Naqu, which is in agreement with the real local topographic situation.

The comparison between the estimated Fresnel reflectivity and ground measured daily average volumetric soil moisture is presented in Fig. 4. It is shown that the variational tendency of estimated Fresnel reflectivity and ground measurement is almost in coincidence with each other, even the decrease of ground measured volumetric soil water content in June 1998 can be detected by satellite results too. The correlation coefficient between the relative soil moisture and ground measured volumetric soil moisture is 0.78 for 0–4 cm topsoil.

The above results suggest that the developed first algorithm is successfully applied to the global C-band backscattering coefficient database to estimate the regional land surface variables. However, the available ERS wind scatterometer global database is only suitable to study soil moisture climatology because of its lower temporal resolution. An attempt has been performed with the observed backscattering coefficient data which are acquired instantaneously when satellite overpasses the ground observation sites. The second algorithm will be used to derive vegetation fractional coverage and soil moisture with this data set, the results are shown in Fig. 5. Compared with the yearly average NDVI and annual precipitation mapped over the Tibet plateau, it is shown that the eastern plateau gains big soil moisture with high precipitation and vegetation, the southern slope of plateau has high vegetation too. The central Tibet area gains smaller soil moisture with little precipitation where land surface must be very dry.

In general, the regional characteristics of vegetation and soil moisture are well illustrated by ERS wind scatterometer derived instantaneous vegetation fractional coverage and soil moisture over the GAME/Tibet experiment area. The western and northwestern of the
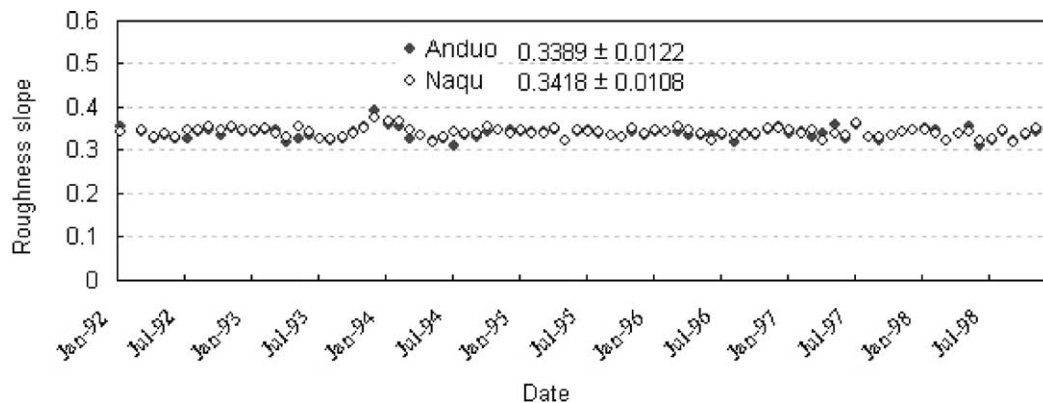

Fig. 3. The temporal variation of roughness variable at two GAME/Tibet Anduo (solid symbol) and Naqu (empty symbol) sites.
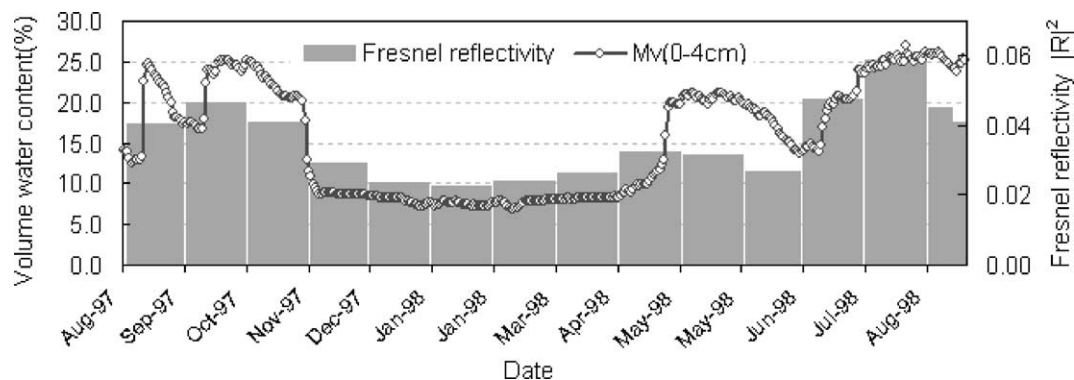

Fig. 4. The comparison between ERS wind scatterometer estimated Fresnel reflectivity and GAME/Tibet ground measured volumetric soil moisture at Anduo site.
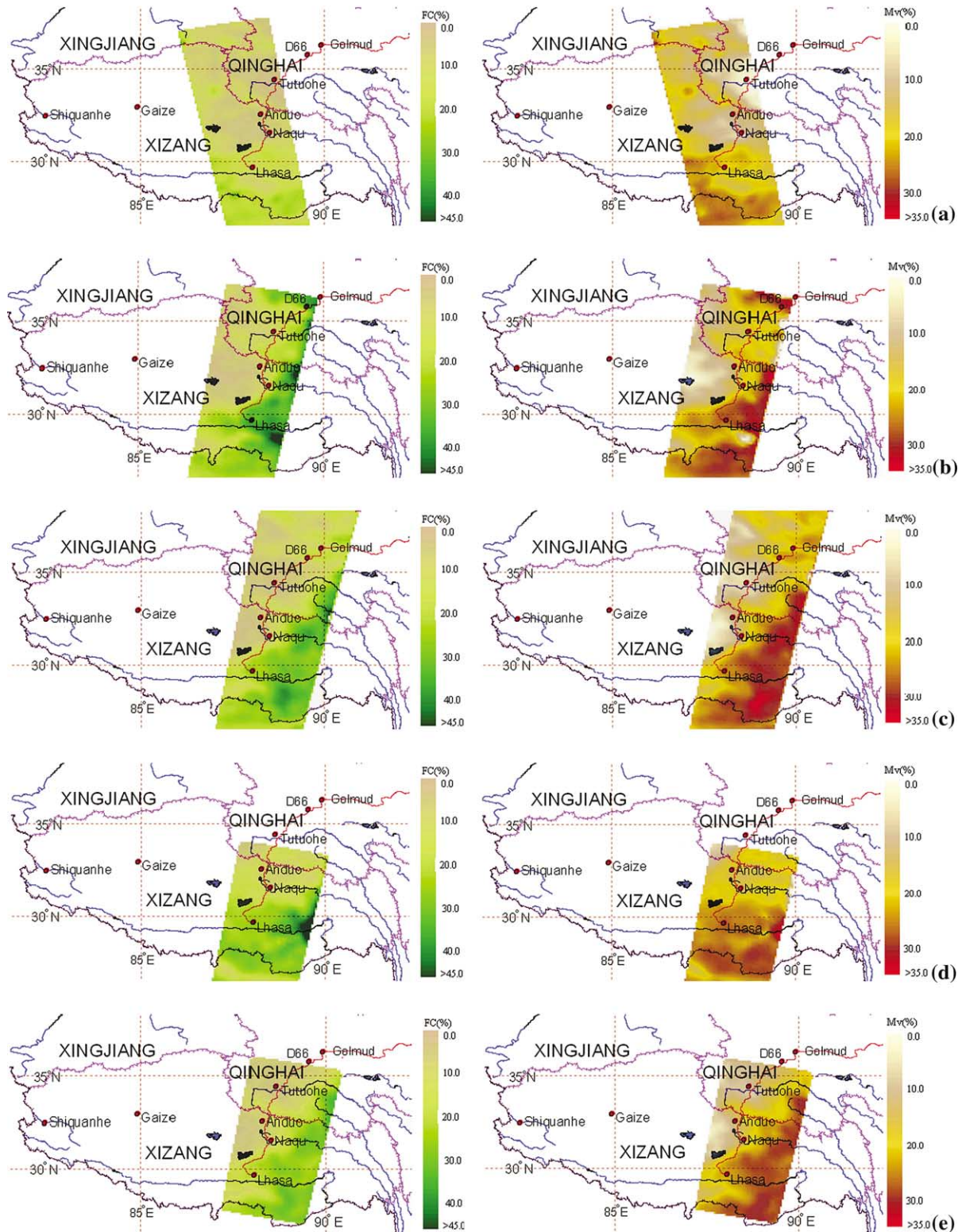
Fig. 5. The regional distributions of the estimated vegetation fractional coverage and soil moisture on (a) 19 May, (b) 4 June, (c) 1 July, (d) 13 August and (e) 9 September, 1998 over GAME/Tibet experiment area.

scatterometer swath gives lower vegetation fractional coverage and lower soil moisture. The southeastern region, Tsangpu river basin has higher vegetation frac-

tional coverage and higher soil moisture. Vegetation fractional coverage is higher from June to August and lower in May and September, soil moisture reaches the
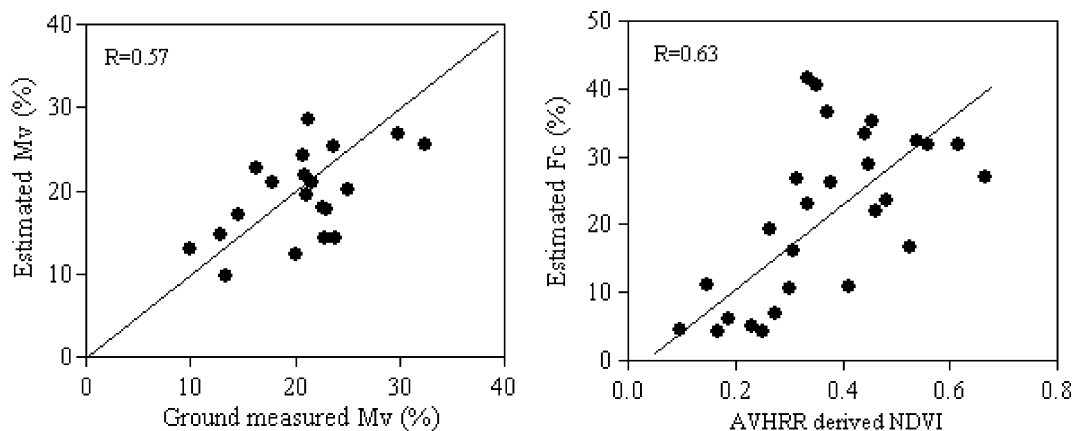
Fig. 6. The comparison between (a) ERS wind scatterometer estimated volumetric soil moisture and ground measurement and (b) wind scatterometer estimated vegetation fractional coverage and NOAA/AVHRR derived NDVI.

highest in July, which is the main rainfall season in the Tibetan plateau.

For the validation purpose, scatter plots between the GAME/Tibet ground measured soil moisture and ERS wind scatterometer estimated volumetric soil moisture, ERS wind scatterometer estimated vegetation fractional coverage and NOAA/AVHRR derived NDVI are presented in Fig. 6.

The comparison shows that ERS wind scatterometer estimated soil moisture and ground measurement, ERS wind scatterometer estimated vegetation fractional coverage and NOAA/AVHRR derived NDVI exhibit positive correlation with correlation coefficients of 0.56 and 0.63 respectively. Although the comparison figures are scattering, the retrieved high soil moisture corresponded high ground measured value and the large vegetation fractional coverage corresponded large NDVI. With consideration of the difference between the ground measurement and satellite retrieved parameter, the variables derived from different sensor are difficult to be compared to each other, because of difficulty in geographical co-ordinates matching caused by different spatial resolutions. For example, the ground measurement of Tutuohe site only takes into account the local underlying surface, its spatial representativeness is very limited, while satellite observation integrates both local and Tuotuo river's information to the observation data. When all these factors are carefully considered, the retrieved results and its validations can be considered very successful.

5. Conclusions

In this study, two algorithms have been developed to estimate land surface variables—soil Fresnel reflectivity or volumetric soil moisture and vegetation fractional coverage with ERS wind scatterometer data. With the first algorithm under sparsely vegetated conditions, the

soil Fresnel reflectivity and surface roughness slope can be simply evaluated from an empirical algorithm. The temporal variation of the retrieved soil Fresnel reflectivity coincides with the local monthly precipitation at two GAME/Tibet Anduo and Naqu sites. ERS wind scatterometer estimated soil Fresnel reflectivity is in good agreement with the ground measured volumetric soil moisture in GAME/Tibet Anduo site, it can detect the variation of ground measured volumetric soil moisture as well. Linear relationship exists between the estimated Fresnel reflectivity and ground measured soil moisture with a correlation coefficient 0.78 for 0–4 cm topsoil. With the second algorithm and the original ERS wind scatterometer observation data, the vegetation fractional coverage and soil moisture can be retrieved at a regional scale. The regional distribution of land surface soil moisture, vegetation fractional coverage are in agreement with ground measurement and consistent with the local climatic characteristics.

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