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Soil moisture retrieval over the Mackenzie River basin using AMSR-E 6.9 GHz brightness temperature

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Abstract An approach is proposed to estimate soil moisture and to monitor its change from AMSR-E 6.9 GHz passive microwave data acquired over a large northern basin. The lack of *in situ* direct measurements is a major issue to be resolved to reach the aim of this work. Therefore, "external" ancillary data were used as a surrogate for available measurements. The methodology is based on the inversion of a microwave radiative transfer model. A sequential method based on the sensitivity of the emitted microwave signal to soil roughness and vegetation parameters was applied to calibrate the model. The roughness parameter was determined from AMSR-E data acquired under dry watershed conditions. The vegetation parameters were estimated under wet conditions. The method was first applied in the Peace-Athabasca Delta area located in Northern Alberta, Canada. The estimated geophysical parameters were then used to retrieve soil moisture estimates for sites with similar LAI values. It was found that the variations of the estimated soil moisture compared well with soil moisture imported from NARR data. A satisfactory agreement was obtained between soil moisture, precipitation and temperature.

Key words AMSR-E brightness temperature; C-band emission; soil moisture; vegetation parameter

INTRODUCTION

Surface soil moisture is a key parameter that plays an important role in explaining water and energy exchange at the land–atmosphere interface. The spatiotemporal variation of soil moisture complicates its retrieval with only *in situ* measurements. Satellite passive microwave remote sensing data offers the possibility to estimate surface soil moisture over large areas and with high temporal frequency. However, corrections are required to account for roughness and vegetation effects. Many correction approaches and soil moisture retrieval methods are described by various authors (Njoku & Li, 1999; Njoku *et al.*, 2003; Wigneron *et al.*, 2003; Paloscia *et al.*, 2006).

In this paper, an inversion method to retrieve vegetation and soil parameters from the AMSR-E 6.9 GHz passive microwave data and a simplified radiative transfer model is described. The method was tested on two sites in the Mackenzie Basin located in northwest Canada, see Fig. 1. Results were compared to the North American Regional Reanalyses (NARR) data.

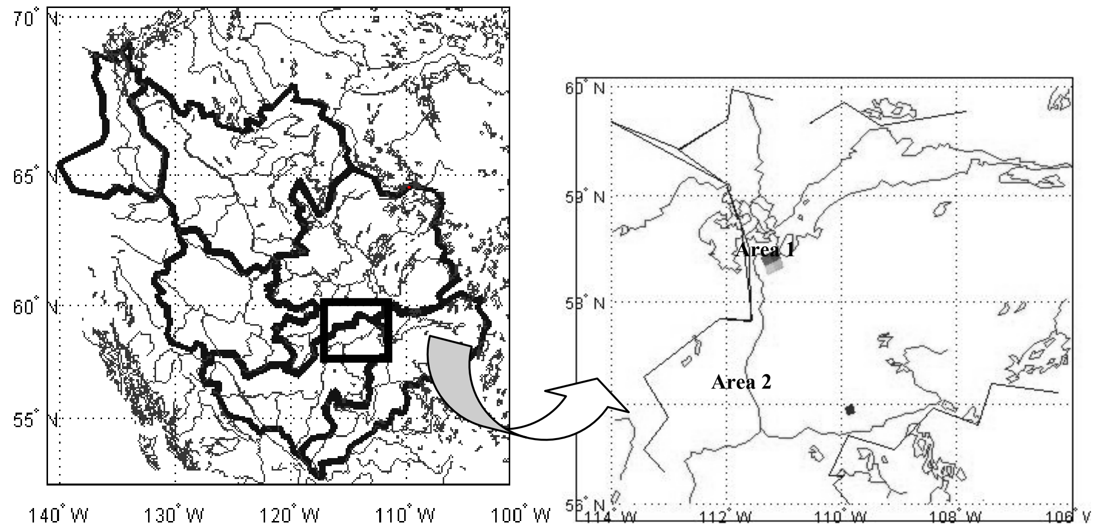

Fig. 1 Mackenzie River Basin and study areas. Area 1: Peace Athabasce Delta. Area 2: La Loche Area.

DATA DESCRIPTION

The AMSR-E instrument was launched in December 2002. It is a modified version of the AMSR instrument developed for the Japanese Advanced Earth Observing Satellite-II (ADEOS-II). The satellite navigates according to a polar sun synchronous orbit, and it crosses the equator twice during the day at local time 01:30 and 13:30 h. AMSR-E measures the brightness temperature at six frequencies between 6.9 GHz and 89 GHz, each with vertical and horizontal polarizations, at an incidence angle of 54.8°. At 6.9 GHz, the mean footprint diameter is 56 km. Two images per day are taken over the Mackenzie basin, corresponding to ascending and descending orbits. In this paper, dual-polarization 6.9 GHz data measured on the ascending orbit were considered for three consecutive summers, 2002, 2003 and 2004.

The study sites are located in the Peace-Athabasca Delta (PAD) area and near La Loche area located in the southeast portion of the Mackenzie basin (Fig. 1). Both are considered as boreal forest zones with approximately the same leaf area index (LAI) range. The LAI values were retrieved from the MODIS Terra Leaf Area Index 8-day data. Soil properties, namely the wilting point, porosity and percent content of clay and sand were extracted from the International Satellite Land Surface Climatology Project (ISLSCP) data base (Global Soil Data Task, 2000).

For the study sites, meteorological data were imported from the NARR database. They include precipitation, soil temperature at a 10-cm depth, and air temperature at 2 m above the surface. Soil moisture at a depth of 10 cm was also retrieved from the NARR database. The NARR data were available every 3 hours.

MODEL DESCRIPTION

In the microwave frequencies, brightness temperature is proportional to soil emissivity and to soil temperature (Njoku & Entekhabi, 1996):

$$T_b = \varepsilon T \tag{1}$$

where ε (= $1 - r_0$) is the soil emissivity over a smooth surface and r_0 is the smooth surface reflectivity. The emissivity and the brightness temperature depend on the incidence angle, polarization and dielectric constant of the soil.

The vegetation emits a depolarized microwave signal and attenuates the contribution of the soil. At lower microwave frequencies, the brightness temperature above the canopy can be described by a simplified radiative transfer model, also referred to as the τ–ω model, where τ and ω are vegetation optical depth and single scattering albedo. As noted by Ferrazzoli *et al*. (2002), the τ–ω model can be applied to forests where the vegetation parameters can be considered as "effective parameters", i.e. that refer to a nonscattering medium with the same emissivity as of forest. At C band, this model can be used to describe the AMSR-E brightness temperature (Njoku *et al*., 2003) as:

$$T_{bp} = \varepsilon_p T_e \exp(-\tau) + (1-\omega)T_c[1-\exp(-\tau)][1 + r_p \exp(-\tau)] \tag{2}$$

where T_c is the mean temperature of the canopy, T_e is the mean soil temperature, ε_p is the soil surface emissivity at polarization p which depends on soil moisture, τ is the vegetation optical depth and ω is the vegetation single scattering albedo.

Surface Roughness attenuates soil reflectivity and in consequence increases emissivity and brightness temperature in both polarizations. The reflectivity of the rough surface was related to that of an equivalent smooth surface with an empirical expression which takes in account a roughness parameter h (Choudhury *et al*., 1979):

$$r_p = r_{0p} * \exp(-h) \tag{3}$$

Combining equations (2) and (3), two types of unknowns appear: the vegetation parameters τ and ω, and the soil parameters h and soil moisture.

RETRIEVAL APPROACHES

The methodology is based on the inversion of the τ–ω model applied to H and V polarizations. The values of the geophysical parameters, h, τ, ω and soil moisture were adjusted iteratively to minimize the sum of the squared difference between the measured and the modelled brightness temperatures.

Calibration step

The calibration step was applied in the PAD area. A sequential method based on the sensitivity of the signal to those parameters was applied to calibrate the model. The mean vegetation temperature was assumed to be equal to air temperature at 2 m. The mean soil temperature was assumed to be equal to soil temperature at depth of 10 cm. Both air and soil temperatures were imported from NARR data.

The roughness parameter was determined from AMSR-E data acquired under dry (i.e. low soil wetness) watershed conditions during the months of May, late September or early October. During those time periods, the signal was assumed to be less sensitive to the vegetation. The τ–ω model was therefore approximated to the only contribution of the soil. The estimated roughness parameter h was found to be nearly constant throughout the three summers, with a mean value of 0.9. This value corresponds to a rough surface (Choudhury *et al*., 1979). For forested areas, a soil surface roughness of 1 cm and 2 cm rms height has been considered by various authors (Lang *et al*., 2001; Ferrazzoli *et al*., 2002; Saleh *et al*., 2003).

Vegetation parameters were estimated under very wet conditions with the roughness parameter established at 0.9. Under the assumption that τ and ω are independent of polarization, they were simultaneously estimated. The retrieved τ was related to the polarization index defined as: IP = (Tbv − Tbh)/(Tbv + Tbh). The relationship between the IP and the optical depth was found to be logarithmic, with a correlation similar to that noted by Owe *et al*. (2001). The inverted w followed a polynomial function for all the three considered summer periods. The albedo value (ω) was around 0.2, except in the beginning of the summer season where it has higher value (0.3).

Soil moisture retrieval

Soil moisture retrieval is based on the inversion of the τ–ω model (equation (2)) in which the vegetation and the roughness parameters are substituted by their values determined during the calibration step. The problem was therefore reduced to a system of two equations of brightness temperature with one variable, namely soil emissivity which is related to soil surface moisture.

The geophysical parameters extracted for the Peace-Athabasca Delta area were next used to retrieve soil moisture estimates for La Loche region. This allows the validation of the inversion method in other areas with similar vegetation covers.

RESULTS AND DISCUSSION

The estimated soil moisture was analysed with respect to precipitation data (Fig. 2(a)). It can be noted that the soil moisture values are lower for the months of July and August where temperature is higher and vegetation is well developed. During this period, the optical depth of the vegetation increased which causes more attenuation of the signal coming from the underlying soil surface. Earlier in May and later in September, the soil moisture values are high and appear to respond to variations in precipitation amounts. This trend may be attributed to lower vegetation amounts and temperature values. As a consequence the signal is more sensitive to the soil parameters and the detection of soil moisture is less complicated than in July and August.

It was also noted that the variations of the estimated soil moisture compared rather well with soil moisture at the 10-cm depth imported from NARR data, especially at the end of the summer (Fig. 2(a)). The estimated values *per se* do not match with the NARR data but they exhibit similar trends. Recall that the NARR soil moisture were acquired at the 10-cm depth while at 6.9 GHz (C-band) the penetration depth of the

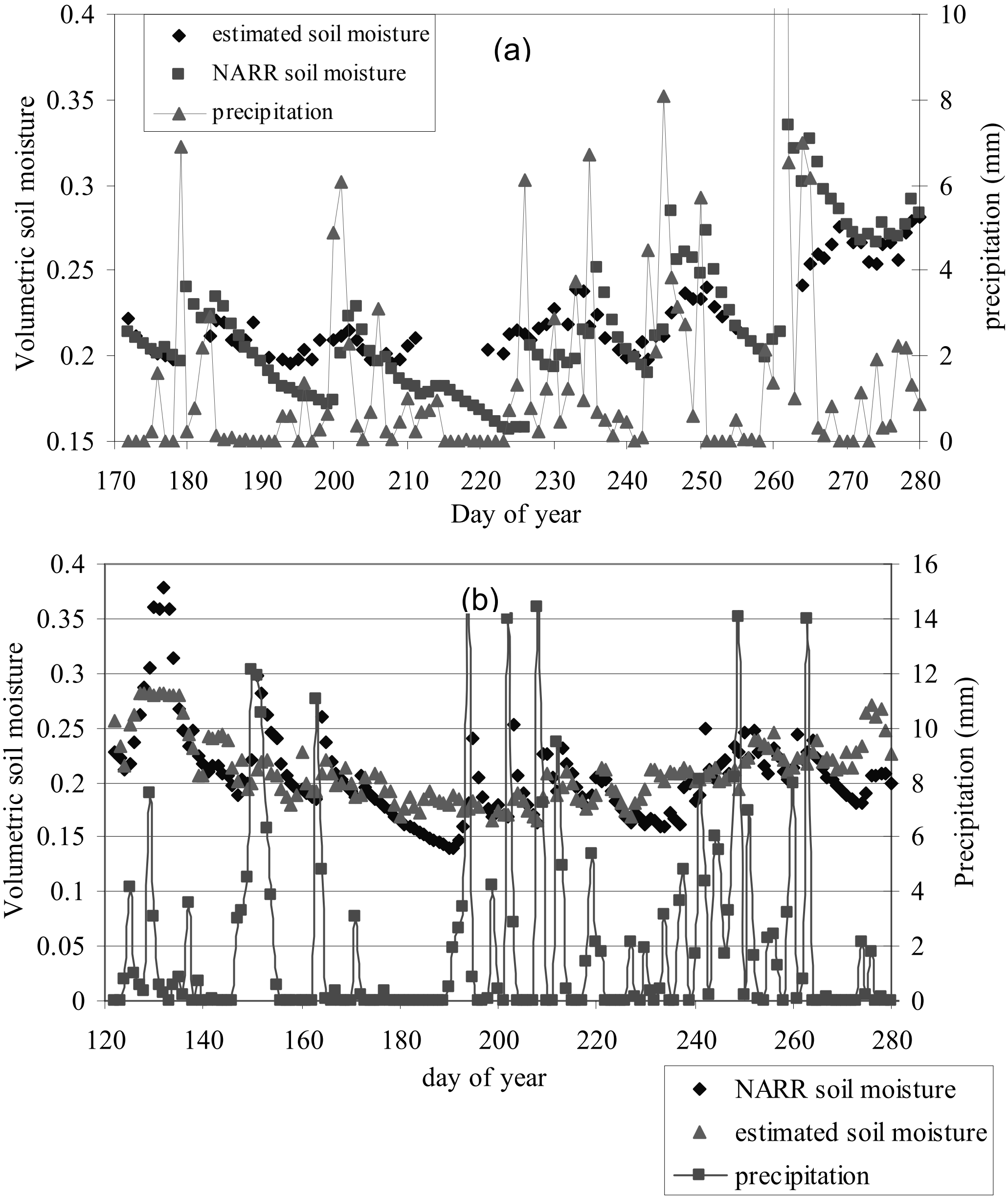

Fig. 2 Comparison of estimated soil moisture with the NARR precipitation data for (a) zone 1, the Peace Athabasca Delta, year 2002, (b) zone 2 during 2004.

signal does not exceed 5 cm. Soil moisture is usually greater at larger soil depths as soil evaporation diminishes (Maidment, 1993). This can explain, at least partly, the bias between the two soil moisture values obtained from different sources. In addition, errors inherent to each of the two soil moisture retrieval methods also contribute to this bias.

The estimated geophysical parameters (roughness and vegetation) estimated over the area 1 were also used to retrieve surface soil moisture values over the area 2 near the La Loche area. Similar conclusions can be reached (Fig. 2(b)). It can be assumed that applying the same estimated geophysical parameters for regions with the similar LAI values and vegetation type as the Peace Athabasca Delta allows retrieval of reasonable surface soil moisture values. It is however essential to test the approach to several other sites with different vegetative covers in order to obtain more general conclusions that are not overly site-specific. This will be addressed in future research.

CONCLUSIONS

A sequential method was proposed to estimate soil moisture and to monitor its change using AMSR-E 6.9 GHz passive microwave data in large northern basins of Canada, where the lack of *in situ* direct measurements is a major issue to overcome. LAI, meteorological data, soil moisture estimates and soil properties data were imported from different databases generated from remote sensing observations (e.g. MODIS) and models (e.g. NARR). The values of the geophysical parameters, surface roughness, vegetation optical depth and single scattering albedo and near-surface soil moisture were adjusted iteratively to minimize the sum of the squared difference between the modelled and the measured brightness temperatures, the latter being provided by the 6.9 GHz AMSR-E passive microwave sensor.

It was found that the sequential method is adequate to retrieve near surface (i.e. 0–5 cm) soil moisture variation when *in situ* observations are scarce. The simplified radiative transfer model, herein referred as the τ–ω, model can be applied over boreal forest areas.

The temporal variability of the estimated near-surface soil moisture was found to be in general agreement with that of the precipitation and also with the 10-cm NARR soil moisture estimates. The bias found between the two soil moisture time series can be explained, at least partly, by the difference in the soil depths corresponding to NARR and the AMSR-E 6.9 GHz estimates and also to errors inherent to the modelling procedure used to retrieve the values.

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