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The effects of scene heterogeneity on soil moisture retrieval from passive microwave data

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ABSTRACT

The τ–ω model of microwave emission from soil and vegetation layers is widely used to estimate soil moisture content from passive microwave observations. Its application to prospective satellite-based observations aggregating several thousand square kilometres requires understanding of the effects of scene heterogeneity. The effects of heterogeneity in soil surface roughness, soil moisture, water area and vegetation density on the retrieval of soil moisture from simulated single- and multi-angle observing systems were tested. Uncertainty in water area proved the most serious problem for both systems, causing errors of a few percent in soil moisture retrieval. Single-angle retrieval was largely unaffected by the other factors studied here. Multiple-angle retrievals errors around one percent arose from heterogeneity in either soil roughness or soil moisture. Errors of a few percent were caused by vegetation heterogeneity. A simple extension of the model vegetation representation was shown to reduce this error substantially for scenes containing a range of vegetation types.

1. Introduction

Until recently, two passive L-band microwave satellite-based instruments were planned with an appropriate configuration to measure soil moisture – the European Space Agency SMOS [1] and NASA Hydros [2]. These differ chiefly in the look angles at which data is acquired, Hydros would acquire data at 40° from the vertical, whilst SMOS will acquire data at a range of angles between nadir and up to 60°, depending on the target-swathe geometry. Whilst development on Hydros is suspended at the time of writing, it is likely that a single-angle spaceborne L-band passive microwave system will be deployed in the future, so in the work here we compare multiple- and single-angle microwave systems. The most widely used model to predict microwave emission from vegetated soil, and the one planned for use in the soil moisture retrieval algorithms for both systems, is the τ–ω model [3,4]. We have previously [5] shown how, for homogenous scenes, the retrieval of soil moisture is dependent on uncertainty in the variables used in the model to describe the scene, such as surface temperature, soil surface roughness, and the vegetation optical depth and single scattering albedo. The wavelength of L-band radiation and technical limitations on space-based antenna will enforce a mean spatial resolution of the order of 50 km. Any single observation will, therefore, almost invariably enclose a region of the Earth's surface with a range of each of the variables. In this paper, we consider the effects of heterogeneity within a scene on a simple retrieval. In the case of a single-angle sensor, we will need to estimate some surface variables to retrieve soil moisture. We consider how best to incorporate estimates of heterogeneous variables, and question whether simple averages are adequate. For multiple-angle sensors, there may be enough information within the brightness temperature curves to accommodate some heterogeneity. In the absence of any existing observations covering the spatial extent covered by a satellite-based passive microwave instrument, and because of the impracticality of making reliable measurements over such a special extent, we have approached this problem by generating synthetic scenes, assuming that the τ–ω model is a realistic representation of microwave emission.

Past work in this area, conducted in the context of earlier passive microwave instruments operating at higher frequencies such as SSM/I and AMSR-E, has included studies of the effect of soil texture variability [6] and of heterogeneity in specific areas, using hydrologic models to estimate the extent of local surface feature variability [7,8]. In this paper we take a more general approach, examining the direct effects of variation in features of the soil surface and vegetation cover without limiting the range of variation to that expected at a particular site. In Section 2 we describe the model used for the variable retrieval, the methodology used to assess the effects of heterogeneity, and describe the four sources of heterogeneity to be investigated. We consider the effects of heterogeneity in soil surface roughness by simulating a surface with a plausible range of roughnesses. We examine the effects of soil moisture, analysing the retrieval error for a soil surface with a

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known mean moisture, but a range of actual values. We look at the effects of waterlogging, coastal water and inland water bodies by assuming a proportion of the scene is standing water. We evaluate both the effects of ignoring standing water, and incorporating a water fraction estimate into the retrieval. By varying vegetation optical depth within a scene, we examine the effects of retrieving soil moisture from a pixel which contains either a mixture of bare soil and vegetation, or a range of vegetation density. We discuss the problem posed by the non-linear effect of vegetation on observed microwave radiation through a heterogeneous canopy, and present a means of reducing this effect by extending the representation of vegetation within the model. Section 3 presents the results of the analyses, in Section 4 we discuss the results, and in Section 5 we draw together the conclusions to compare the relative effects of the sources, and consider what measures can be taken to reduce the effects of heterogeneity.

We do not present here any analysis of the effects of heterogeneity in temperature and vegetation single-scattering albedo. While any scene with a spatial extent of hundreds of square kilometres will exhibit some variability in these factors, this should have a negligible effect. Brightness temperature scales linearly with surface temperature, or more accurately the effective surface temperature, accounting for the optical depth of the surface, at any given look-angle when all other variables remain constant. Thus, the brightness temperature curve for a site comprised of a number of different soil temperature regions is identical to the brightness temperature curve for the mean temperature of the region. As long as the mean surface temperature is known, heterogeneity within it should contribute no error. Similarly, the dependence of brightness temperature on single-scattering albedo of vegetation within the model is also linear, and so whilst it is possible that in reality non-linearity may have an effect, this will be not evident from this modelling approach.

2. Method

2.1. Model description

As in our previous work, we use a simple radiative transfer formulation, the τ–ω model [3,4], to describe the emission of microwave radiation from the soil surface. In the τ–ω model, the brightness temperature, T_B, of a top layer (soil and vegetation) medium is the sum of three terms: the canopy-attenuated soil emission, the direct vegetation emission and the vegetation emission reflected by the soil and attenuated by the canopy. A fourth term representing the soil-reflected and two way canopy-attenuated down-welling sky brightness temperature is sometimes implemented, but is considered negligible here. Hence, the brightness temperature can be expressed as:

$$T_B = \varepsilon_{soil} \cdot T_{soil} \cdot e^{\frac{-\tau}{\cos\alpha}} + (1-\omega) \cdot T_{veg} \cdot \left(1 - e^{\frac{-\tau}{\cos\alpha}}\right) + (1-\varepsilon_{soil}) \cdot (1-\omega) \cdot T_{veg} \cdot \left(1 - e^{\frac{-\tau}{\cos\alpha}}\right) \cdot e^{\frac{-\tau}{\cos\alpha}}, \quad (1)$$

where ε_{soil} is the soil emissivity, ω is the single scattering albedo within the canopy, τ is the optical depth of the canopy, α is the instrument look angle from nadir, T_{soil} is the soil temperature and T_{veg} is the vegetation temperature, which in this case we assume to be the same as the soil temperature.

The soil emissivity is calculated from the Fresnel equations, incorporating the dielectric permittivity of the soil which is derived from the Wang and Schmugge [9] model, assuming a soil texture of SAND = 60%, CLAY = 20%, incorporating the wilting point of soil [10] assuming a bulk density of 1.3 g cm^{-3}, and component relative dielectric permittivity of 3.2, 1 and 5.5 for bound water, air and soil particles respectively. The dielectric permittivity of water was derived by the modified version of the Debye equation for the relative dielectric permittivity [11], the high frequency dielectric permittivity [12], the static dielectric permittivity of water as described by Klein and Swift [13] and the relaxation time of pure water [14].

2.2. Methodology

The effects of heterogeneity in soil surface roughness and soil moisture on retrieval accuracy are considered individually in the following sections. The brightness temperature curve produced by heterogeneity in each variable is simulated by combining brightness temperature curves produced by different values of the variable in the forward model. To simulate a multiple angle system, brightness temperature curves are generated at the angles 0°, 10°, 20°, 30°, 40°, 50° from nadir at *H* and *V* polarisations, and for a single-angle system, the brightness temperatures at 40° from nadir are calculated at *H* and *V* polarisations. In each case, the retrieval then inverts the composite brightness temperature curves as described in [5] to recover the soil moisture content, vegetation optical depth and surface temperature, constraining the surface temperature to within 2 K of the target, and using a single value of the heterogeneous variable. With observations at multiple angles, it is also often possible to retrieve a value for an additional unknown variable, so we also perform retrievals which attempt to retrieve a value for the heterogeneous variable. This becomes more difficult with a single-angle radiometer, which produces only two measurements, one at each of *H* and *V* polarisation. Since it is necessary to retrieve three variables, soil moisture content, vegetation optical depth and surface temperature, some constraint of the variables is necessary to produce solutions. It is commonly assumed that the surface temperature will be estimated to an accuracy of about 2 K for this purpose, so to simulate this we carry out a set of retrievals assuming a uniform range of surface temperatures within the 2 K extent, and calculate error statistics based on these runs. Whereas a multiple-angle retrieval from a pair of brightness temperature curves will result in one unique best solution and a distinct error in each variable, a single-angle retrieval result will be based on a range of solutions based on the different surface temperature assumptions, and the range of possible solutions are included within the error statistics.

2.3. Heterogeneity in surface roughness

Soil roughness on the vertical scale of a centimetre can affect the microwave reflectivity, and consequently the emissivity of the surface, in a manner dependent on the look-angle [13]. This has an impact on the brightness temperature curves recorded by an observing system, and consequently the retrieval of the soil moisture, vegetation optical depth and surface temperature from these observations. Measurement of the soil surface roughness will in most cases be infeasible over the spatial scale of several hundreds of square kilometres covered by a satellite microwave radiometer (though a smaller scale technique is described in [14]). While this effect has a relatively minor influence on retrievals from a single-angle system in a homogeneous scene [5], accurate retrieval from a multiple-angle system relies upon allowing the algorithm to extract the roughness from the observations. This proves successful for a surface with a uniform roughness, however, the soil surface over hundreds of square kilometres is likely to have a range of surface roughnesses.

The soil surface roughness modification to the τ–ω model suggested by Choudhury et al. [15] modifies the microwave reflectivity of the soil

$$R = R_0 e^{-h.\cos^2\alpha}, \quad (2)$$