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Review

Spatially enhanced passive microwave derived soil moisture: Capabilities and opportunities

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ABSTRACT

Low frequency passive microwave remote sensing is a proven technology for providing soil moisture estimates, but the coarse resolution of its data restricts the range of applications. Downscaling, otherwise known as disaggregation, has been proposed as the solution to spatially enhance these coarse resolution soil moisture observations, through association with complementary observations, or ancillary information about land surface features at higher spatial resolution. Such information includes solar reflectance, thermal emission, passive microwave emissions at a higher frequency, radar backscatter, soil or surface attributes such as topography and soil properties, and land surface modelling. Each of these ancillary data sources has its own strengths and limitations in terms of, for example, sensitivity to surface soil moisture dynamics and availability. This paper provides an extensive review of the capabilities and opportunities of current soil moisture downscaling approaches which provide a deterministic pattern of soil moisture, together with their strengths and limitations.

1. Introduction

Land-atmosphere interactions are affected by soil moisture on a global scale (e.g. Entekhabi et al., 1996; Petropoulos et al., 2015), thus exerting an impact upon the climate and weather (e.g. Entekhabi, 1995; Western et al., 2002; Seneviratne et al., 2010; Jung et al., 2010; Lakshmi, 2013; Taylor, 2015) by influencing the partitioning of the incoming radiant energy at the land surface into sensible and latent heat fluxes (Xia et al., 2014). Soil moisture variation also controls the water and energy cycle components through the amount of evapotranspiration which affects soil surface wet and dry patterns that in turn affect precipitation (Koster et al., 2004; Hirschi et al., 2011). The volume of surface run-off and groundwater recharge also depends upon the soil moisture by way of the infiltration rate of precipitation into the soil (Tuttle and Salvucci, 2014). Regional characterization of soil moisture variability at short time intervals would therefore greatly assist understanding of the land-atmosphere system.

Obtaining accurate information on soil moisture at an appropriate temporal and spatial scales is challenging to achieve with global coverage using traditional approaches, due to the high spatial and temporal variability of soil moisture. This variation is caused by the heterogeneous nature of soil properties, topography, land cover, and meteorology (e.g. rainfall and evapotranspiration) that vary as a function of scale (e.g. Crow et al., 2012; Vereecken et al., 2008). Meteorological forcing has a dominant control on the soil moisture spatial pattern at watershed, regional and continental scales (Jana, 2010; Crow et al., 2012), unlike the field and point scales at which the soil moisture varies due to land cover, topography and soil properties. Accordingly, multi-scale soil moisture measurements can provide a vital piece of information for economic, social and environmental planning. Development of field and watershed scale soil moisture measurements is of benefit to agricultural production and better understanding of rainfall-runoff responses, respectively (Robinson et al., 2008). Moreover, measurement of soil moisture at regional and continental scales is important for interpreting land-surface-atmosphere interactions (Kerr et al., 2001; Robinson et al., 2008).

Historically, ground sampling was the only possible approach to measuring soil moisture. However, the sparseness of point measurement stations makes the use of in situ measurements for capturing the spatially variable nature of soil moisture impractical due to their high maintenance and operation expenses. The need for global soil moisture monitoring that compliments the sparsely distributed ground measurements has led to the development of space-borne remote sensing (e.g. Entekhabi et al., 1999; Njoku et al., 2002; Entekhabi et al., 2010; Kerr et al., 2012), covering the Earth's surface with a temporal frequency of a few days. Consequently, a number of sensors have been

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launched on space-borne platforms over the past four decades to acquire the electromagnetic emission, reflection and/or scattering from the land surface, but not necessarily designed for soil moisture.

Sensors are classified according to the electromagnetic spectrum in which they monitor the Earth's surface. The regions of the spectrum of greatest interest for soil moisture are the optical and microwave. Optical remote sensing measures the solar reflective (VIS, Near Infrared (NIR), and Short-Wave InfraRed (SWIR) bands) and/or thermal emissive (Thermal InfraRed (TIR) band) regions of the electromagnetic spectrum. These measurements have been used to determine spatial soil moisture variations by monitoring changes in surface albedo (e.g. Liu et al., 2002; Leone and Sommer, 2000; Dalal and Henry, 1986) and soil heat capacity (Petropoulos et al., 2015). While this information can be observed at a 1 km or better spatial resolution on a (cloud free) daily basis, the signal is directly related to only the very top millimetres of the soil surface for bare soil, or to the surface of the leaves if vegetated. Moreover, the relationship to soil moisture typically depends on evaporative demand and/or vegetation variation across seasons, which limits the potential application of optical observations for direct soil moisture retrieval (Petropoulos et al., 2015). These optical observations also suffer from being attenuated by the atmosphere, and are unable to provide useful data under cloudy skies. This makes the interpretation of optically-based soil moisture predictions complicated because data on the surface micro-meteorological and atmospheric information is required for corrections (Zhang and Wegehenkel, 2006). Access to such data is limited at global scale, thus restricting the application of optical remote sensing for direct soil moisture estimation.

The conversion of remotely sensed solar reflection/albedo data to soil moisture is primarily based on the color of the soil or vegetation. Thus, information about soil mineral composition, organic matter, local incidence angle and vegetation type is required (e.g. Wang and Qu, 2009). For bare soil the determination of soil moisture is limited to observing and interpreting changes in soil color, with moist soil being darker than dry soil. When there is a layer of vegetation, observations primarily reflect changes in vegetation color and/or water in the vegetation. Several land surface indices e.g. Normalized Difference Vegetation Index (NDVI) by Rouse et al. (1974), Normalized Difference Water Index (NDWI) by Gao (1996), and Normalized Multiband Drought Index (NMDI) by Wang and Qu (2007) were developed to suppress vegetation and/or plant color impact. However, their application is limited by the factors mentioned previously.

The utility of TIR remote sensing for soil moisture mapping has been demonstrated in several studies (e.g. Schmugge et al., 1980; Friedl and Davis, 1994; Verhoef et al., 1996; Muller and Décamps, 2001; Anderson et al., 2007). These studies have shown that while there is a negative correlation between the diurnal range in surface soil temperature and the surface soil moisture content, moist soil is cooler in daytime and warmer at night-time than dry soil. This is because the presence of water, which has a greater heat capacity, leads to moist soil having a greater resistance to temperature change than dry soil. These TIR techniques, which use the thermal inertia concept for estimation of soil moisture, are often based on using the TIR imagery in energy balance calculations (e.g. Goward et al., 2002) or hydrological models (e.g. Coppola et al., 2007; Minacapilli et al., 2009). The thermal inertia principle correlates changes of soil temperature to changes of soil moisture as well as heat capacity (e.g. Mallick et al., 2009; Van Doninck et al., 2011). Moreover, the TIR data is either used alone or combined with vegetation indices to adjust for the vegetation impact on the degree of heat transferred into the soil (Carlson et al., 1994). For example, Hain et al. (2009) used the TIR-based Atmosphere Land EXchange Inversion (ALEXI) surface energy balance model (Anderson et al., 1997; Mecikalski et al., 1999; Anderson et al., 2007) to estimate available water fraction, from which volumetric soil moisture was indirectly derived.

Microwave emission (collected by passive sensors) and backscatter (from active sensors, otherwise known as radars) are directly related to near surface soil moisture ($<$ 5 cm) through the dielectric contrast between that of liquid water (~80) and dry soil (~4) (Schmugge et al., 1974). The observations can be made under almost all weather conditions due to the atmosphere being transparent at the wavelengths most suitable for soil moisture (X- to L-band). The difference between the active and passive microwave techniques lies in the source of the signal; radar observations measure the proportion of a transmitted signal being backscattered to the sensor proportional to the surface reflectivity and roughness, while the radiometer observations are measurements of a natural emission proportional to the surface emissivity and physical temperature (Ulaby et al., 1981).

Active microwave remote sensing of soil moisture has the advantage of being at high spatial resolution, especially Synthetic Aperture Radar (SAR) which has the capability of observing the earth's surface at resolutions as high as 10 m (Torres et al., 2012). However, this high spatial resolution results in a revisit time of 35 days or longer. The temporal repeat issue has been recently addressed through a constellation of sensors by the European Space Agency (ESA); Sentinel-1 consists of two polar orbiting satellites having a global coverage of at least once every 6 to 12 days in Interferometric Wide Swath (IWS) mode (Wagner et al., 2009). The higher temporal resolution of Sentinel-1 SAR observations compared to that of previous SAR missions improves the feasibility of using SAR radar backscatter for a wider range of soil moisture applications. Nevertheless, its narrow imaging swath cannot achieve the temporal resolution of 3 days or better that is required for many soil moisture mapping needs (e.g. Walker and Houser, 2004; the National Research Council's Decadal Survey). Radar imagery is also highly sensitive to surface roughness, vegetation biomass and vegetation water content, making the direct soil moisture retrieval from radar backscatter alone a complex process. One solution proposed to overcome this problem is to use temporal change detection approach (Engman and Chauhan, 1995; Wagner et al., 1999; Njoku et al., 2002; Moran et al., 2000), which assumes that factors such as surface roughness remain fixed with only the soil moisture varying. However, to date accurate and global soil moisture retrieval from SAR backscatter remains a challenge.

Passive microwave emissions at L-band (e.g. Schmugge et al., 1974; Jackson, 1993; Ulaby et al., 1996; Njoku and Entekhabi, 1996; Schmugge et al., 2002) have been of great interest because of their better sensitivity to soil moisture dynamics (Ulaby et al., 1982) than radar and optical observations, and their favourable signal-to-noise ratio. Consequently, the European Space Agency (ESA) and National Aeronautics and Space Administration (NASA) have launched dedicated soil moisture missions using L-band passive microwave instruments aboard the Soil Moisture and Ocean Salinity (SMOS) satellite in 2009 and Soil Moisture Active Passive (SMAP) satellite in 2015, respectively, to monitor global surface soil moisture at a temporal resolution of at least 3 days. SMOS uses an interferometric radiometer with aperture synthesis by which multi-angular brightness temperature data sets are collected. In contrast, the SMAP radiometer has a scanning real aperture antenna which provides single angle (~40°) but high accuracy brightness temperature observations. Both the SMOS and SMAP satellites have an approximately 40 km resolution of their brightness temperature measurements, due to the trade-offs in antenna (aperture) size needed for high resolution and the technical challenge of launching and operating a large antenna in space. As the 40 km spatial resolution restricts the applications to hydro-climatological studies (Entekhabi et al., 2008b), spatial enhancement approaches are required if the passive microwave missions are to satisfy hydro-meteorological and agricultural applications (Entekhabi et al., 2010). Fig. 1 summarizes the temporal and spatial resolution requirements of soil moisture in a range of application areas.

No remote sensing technique utilizing a single electromagnetic region or approach can by itself satisfy the accuracy, spatial and temporal resolution requirements. While L-band passive microwave can yield accurate estimates of soil moisture content at low resolution, the radar