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Soil moisture variations monitoring by AMSU-based soil wetness indices: A long-term inter-comparison with ground measurements

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ABSTRACT

Soil moisture controls the partitioning of rainfall into runoff and infiltration and, consequently, the runoff generation. On the catchment scale its routine monitoring can be performed through remote sensing technologies. Within this framework, the purpose of this study is to investigate the potential of the Advanced Microwave Sounding Unit (AMSU), radiometer on board the NOAA (National Oceanic and Atmospheric Administration) satellites and operating since 1998, for the assessment of soil wetness conditions by comparing soil moisture data with both those measured in situ and provided by a continuous rainfall–runoff model applied to four catchments located in the Upper Tiber River (Central Italy). In particular, in order to perform a robust analysis an extensive and long-term period (nine years) of data was investigated. In detail, the Soil Wetness Variation Index, derived from the AMSU data modified in order to take account of the difference between the soil layer investigated by the satellite sensor and that used as a benchmark, was found to be correlated both with the in-situ and modeled soil moisture variations showing correlation coefficients in the range of 0.42–0.49 and 0.33–0.48, respectively. As far as the soil moisture temporal pattern is concerned, higher correlations were obtained (0.59–0.84 for the in-situ data and 0.82–0.87 for the modeled data set) partly due to the soil moisture seasonal pattern that enhances the correlation. Overall, the root mean square error was found to be less than 0.05 m^3/m^3 for both the comparisons, thus assessing the potential of the AMSU sensor to quantitatively retrieve soil moisture temporal patterns. Moreover, the AMSU sensor can be considered as a useful tool to provide a reliable and frequently updated global soil moisture data set, considering its higher temporal resolution now available (about 4 passes per day) thanks to the presence of the sensor aboard different satellites.

1. Introduction

Knowledge of soil moisture spatial–temporal variability is one of the most important issues in many scientific disciplines. In particular, for storm rainfall–runoff modeling, soil wetness conditions at the beginning of a rainfall event are fundamental to determining the hydrologic response of a catchment in many geographic regions (see e.g. Komma et al., 2008; Berthet et al., 2009; Brocca et al., 2009c).

However, for large areas soil moisture measurement with ground-based methods (Time Domain Reflectometry, gravimetric method, neutron probes, etc...) is not feasible due to the small volume investigated by these techniques. Therefore, in the last thirty years the reliability of satellite sensors for soil moisture monitoring has been widely investigated with particular attention to active and passive microwave sensors. The topic is of a great interest as demonstrated by two recent satellite missions specifically dedicated to soil moisture monitoring on a global scale: SMOS (Soil Moisture and Ocean Salinity, Kerr et al., 2001) launched in November 2009, and SMAP (Soil Moisture Active and Passive, Entekhabi et al., 2008) planned for 2015 (SMAP webiste, 2010). Nowadays, even though no specific or reliable soil moisture products are available (SMOS is still in the commissioning phase), four operational sensors could be used for inferring soil moisture monitoring on a global scale: two scatterometers (SCAT on board the European Remote Sensing satellites, ERS 1 and ERS 2 available from 1992, and ASCAT on board METOP-A satellite launched in 2006) and two radiometers (AMSR-E on board the Aqua satellite launched in 2002, and WindSAT on board the Coriolis satellite launched in 2003). These sensors are characterized by a spatial resolution of 25–50 km and a nearly daily revisit time that is particularly important for hydrological applications (Vischel et al., 2008). In fact, by using model simulations Walker and Houser (2004) inferred that a regular daily time step is needed to provide an accurate root-zone soil moisture product. Recently, in a synthetic modeling study De Lange et al. (2008) have analyzed the accuracy of the relation between root-zone and surface soil moisture proposed by Wagner et al. (1999) for different soil textures by varying the sampling frequency. The authors concluded that a daily temporal resolution is at least required to capture the strong

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variability in soil moisture temporal patterns. By using the same approach, Pellarin et al. (2006) showed that the sampling time should be daily for a noise level of 0.06 m^3m^{-3}, whereas one measurement every 3 days is sufficient for a noise level of 0.04 m^3m^{-3}. However, it has to be underlined that for early warning activities related to flood prediction and forecasting a shorter revisit time is required in order to have a quasi-continuous, near real time value of surface soil moisture. In fact, during flood season, in some regions the time interval between rainfall events can be very short (even less than one day) and, hence, for a correct estimation of the consequent hydrologic response, the knowledge of the soil moisture conditions before each storm event is required.

Such a requirement is easily assured by sensors aboard a satellite constellation or flying on board different missions, which enables an improvement in temporal resolution when compared to a single satellite. The AMSU (Advanced Microwave Scanning Unit) radiometer is a sensor which satisfies these requests. It consists of two modules: the AMSU-A and AMSU-B. The former (used in this study) includes 15 channels in the 23–89 GHz range with a spatial resolution of 48 km at Nadir, it was primarily designed for temperature soundings of the atmosphere from the surface up to about 2 mbar pressure altitude. The latter contains one channel centred at 89 GHz and four channels around the 183.21 GHz water vapour line, it was projected for deriving moisture profiles with a spatial resolution of 16 km (Goodrum et al., 1997). AMSU has been flying aboard NOAA (National Oceanic and Atmospheric Administration) satellites since 1998. At this moment it is operating on five NOAA satellites providing a temporal resolution of about 4–6 h at mid-latitudes. Moreover, given that it has also been operating on EOS-Aqua since 2002 (AMSU-A only) and EUMESAT-MetOpA (AMSU-A only) since 2006, AMSU sensor ensures a stable and long-term data collection, too. Although AMSU spectral features are not ideal for soil moisture retrieval, some of its channels (those at 23.8, 31.4, 50.3 89 and 150 GHz, respectively) are localized in window regions (Goodrum et al., 1997) and so they can provide information on land surface parameters (Ferraro et al., 2002) such as soil moisture (Gu et al., 2000; Grody et al., 2000; Kongoli et al., 2006) with a spatial resolution of about 20 km. In particular, an AMSU-based Soil Wetness Variation Index (*SWVI*) was proposed and applied with encouraging results to monitor soil wetness variations in the space-time domain during some extreme flooding events occurred in different areas of the world (Lacava et al., 2005a,b, 2006, 2007, 2009).

In order to further assess both the reliability and the sensitivity of these results, in this work a long-term quantitative assessment of the AMSU products is performed. This is pursued by comparing remotely sensed soil wetness indices with: i) in-situ measurements carried out in an experimental catchment of Central Italy (from 2002 to 2004); and ii) modeled soil moisture data derived through a continuous rainfall–runoff model (from 1999 to 2007).

2. Methods

2.1. The soil wetness variation index (SWVI)

Earth's emitted radiation measured from satellite (usually given in terms of brightness temperature, BT) strongly depends, in the microwave spectral region, on the emissivity and, at a lower extent, on surface temperature variations. In this spectral region water and soil (Eagleman and Lin, 1976; Jackson et al., 1981) have very different dielectric properties which strongly affect emissivity. In fact, moving from very wet to very dry conditions, soil emissivity can change from less than 0.6 to more than 0.9 (Njoku and Enthekabi, 1996). This corresponds to a BT change of about 100 K (on a soil at 300 K) which is a variation much greater than that expected as a consequence of whatever surface temperature fluctuation normally observable at the same location (e.g., less than 50 K of BT variation in correspondence with a surface temperature fluctuation up to 50 K). Emissivity also depends on other soil properties (particularly vegetation cover and roughness) which together with soil water content differently contribute to the measured BT within each satellite image pixel depending on their fractional amount (Njoku and Enthekabi, 1996).

Generally speaking, as soil wetness increases, the emissivity decrease is enhanced at lower frequencies so that the emissivity difference at low and high frequencies increases as well (Basist et al., 1998; Singh et al., 2005). The measurement of soil emissivity gradient between higher and lower frequencies can give a qualitative indication on the variations in superficial soil water content (Scofield and Achutuni, 1996; Jin, 1999; Gu et al., 2000, 2004; Grody, 2002; Kongoli et al., 2006) provided that the other relevant parameters remain almost unvaried.

In particular, exploiting also the knowledge coming from some SSM/I (Special Sensor Microwave Imager) studies carried out over several years (Heymsfield and Fulton, 1992; Teng et al., 1993; Scofield and Achutuni, 1996; Lakshmi et al., 1997; Prigent et al., 1997; Basist et al., 1998, 2001; Jin, 1999; William et al., 2000), such an indication may be inferred from AMSU by using the difference between the radiance (expressed in BT) measured in channels 15 (at 89 GHz) and 1 (at 23 GHz) (Gu et al., 2000, 2004; Grody, 2002; Kongoli et al., 2006). However, the derived Surface Wetness Index ($SWI = BT_{89} – BT_{23}$) cannot discriminate between variations related to different soil water contents and variations determined by vegetation and/or roughness effects. On the basis of a more general change-detection methodology for multi-temporal satellite data analysis (Robust Satellite Techniques, Tramutoli, 1998, 2005, 2007), a normalized *SWI* index, *SWVI* (Soil Wetness Variation Index), was proposed by Lacava et al. (2005a):

$$SWVI(x,y,t) = \frac{SWI(x,y,t) - \mu_{SWI}(x,y)}{\sigma_{SWI}(x,y)} \tag{1}$$

where: *t* is the acquisition time of the AMSU image at hand, *(x,y)* are the geographic coordinates of the pixel centre, $SWI(x,y,t) = BT_{89}(x,y,t) - BT_{23}(x,y,t)$ is the Surface Wetness Index computed on the AMSU image at hand; $\mu_{SWI}(x,y)$ and $\sigma_{SWI}(x,y)$ are, respectively, the monthly average and the standard deviation of *SWI*, both computed on the basis of a homogeneous multi-annual data-set of AMSU images all of them collected during the same month of the year and at around the same hour of the day of the image at hand. Therefore, the *SWVI(x,y,t)* represents the actual *SWI* excess at pixel level compared to its unperturbed conditions ($\mu_{SWI}(x,y)$) weighted by the normal variability ($\sigma_{SWI}(x,y)$) of *SWI(x,y,t)*, as derived by all the available observations at the same site under similar observational conditions (e.g. some month of the year, some hour of the day). In this way, the main (noisy) site effects (e.g., vegetation, roughness, permanent water bodies, etc…) are expected to be strongly reduced. In fact, unlike soil moisture, all these parameters are not expected to significantly change as far as one-month investigation period is considered (Engman, 1991). In addition, *SWI* seasonal trends are also removed by such a standardization process. Consequently, *SWVI(x,y,t)* index should be solely sensitive to *SWI* variations, mainly depending on soil moisture, and not to its absolute values also related to surface roughness and vegetation cover. Especially for large scale studies, when roughness and vegetation effects might be very difficult to model, *SWVI* assures a more reliable estimation of soil wetness changes without using any kind of ancillary information. However, when investigations are performed at a single pixel level, *SWI* can be also used thanks to the invariance of some soil features (for instance roughness). Generally speaking, high values of *SWVI(x,y,t)* are associated with a relative increase in soil wetness at each specific location and positive *SWVI* values indicate soil conditions wetter than “normal”. In the previous studies (Lacava et al., 2005a,b, 2006, 2007, 2009) *SWVI* was applied without using auxiliary information in order to analyze some past flooding events occurred in different areas of the world (i.e., in different conditions of observation). The results achieved so far have highlighted the potential of this indicator in following the space-time dynamics of such events, thus confirming its capability in detecting and monitoring high hydro-meteorological risk areas. In this