Soil moisture variability estimation through AMSU radiometer

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Abstract
The monitoring of soil moisture (SM) can be performed through remote sensing technologies. Among the operational microwave radiometers potentially able to provide information about SM and its variability in the space-time domain, in this work the capability of the AMSU (Advanced Microwave Sounding Unit) sensor has been investigated. In particular, SM information, achieved implementing two different AMSU-based indices, has been compared with both in situ measured and modeled observations for several sites spread out all over Italy. The results indicate that the AMSU sensor can be considered as a useful tool to provide quite reliable information about SM variability, mainly if its high temporal resolution is taken into account.

Keywords: Soil moisture, AMSU, remote sensing, microwave.

Introduction
Information regarding soil moisture (SM) spatial-temporal variability is important for many scientific disciplines. For instance, for storm rainfall-runoff modelling, the wetness conditions at the beginning of a rainfall event are fundamental to determine the hydrologic response of a catchment [Berthet et al., 2009; Brocca et al., 2009].

In the last years, the capability of microwave sensors, both active and passive, to provide reliable SM measurements has been largely investigated. The launch of the ESA-SMOS (European Space Agency-Soil Moisture and Ocean Salinity) mission on 5 November 2009 [Kerr et al., 2010], and the scheduling of the NASA-SMAP (National Aeronautics and Space Administration-Soil Moisture Active and Passive) program for 2014 [Entekhabi et al., 2010], both specifically dedicated to SM estimation, give a clear evidence of the relevance of the topic within the scientific community at international level. First analyses performed on data acquired by MIRAS (Microwave Imaging Radiometer with Aperture Synthesis) onboard SMOS have highlighted, as expected, their potential in providing accurate SM information [Corbella et al., 2010; Dall’Amico et al., 2010]. This is mainly due to the use of L-band, region where the sensitivity to SM presence is high and the effects of atmosphere and low vegetation are less important [Escorihuela et al., 2010]. SMOS, being an “explorative” mission, assures a temporal resolution of 1-3 days, therefore the
use of these data within an operational context, devoted to furnish frequent and updated information concerning SM, may result of a scarce operational utility. Such data could be used as benchmark for other satellite measurements which, in spite of a spatial resolution similar to that of MIRAS (i.e. 25 km), assure a higher temporal resolution than MIRAS. Several microwave sensors have been already used to retrieve indications about SM variability in the space-time domain, such as AMSR-E (Advanced Microwave Scanning Radiometer - Earth observing system, [Jackson et al., 2010]), ASCAT (Advanced SCATterometer, [Brocca et al., 2010]). In this paper, we further investigated the potential of AMSU (Advanced Microwave Sounding Unit) sensor, the radiometer aboard NOAA (National Oceanic and Atmospheric Administration) polar satellites series since 1998, in investigating soil moisture variations. In a recent study [Lacava et al., 2010], in fact, the capability of this sensor for soil moisture estimation has been studied through a comparison of two AMSU-based SM indices with both in-situ and simulated data for four catchments located in central Italy (i.e. in Umbria region). The results indicated correlation coefficients between satellite estimates and in-situ measured SM in the range of 0.42-0.84, and of 0.33-0.87 with modeled SM. Overall, the Root Mean Square Difference (RMSD) 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 SM temporal patterns.

In order to better assess the reliability of the AMSU sensor, as well as to verify the independence of the obtained results from a specific location or from different observational and environmental conditions, in this work SM AMSU retrievals have been compared with both in-situ observed and modeled SM observations for several sites over Italy. In particular, ground-based SM data coming from two sites in Emilia Romagna, Calabria and Campania regions and from one site located in Umbria region were used as an independent validation data set.

Methods

The AMSU-based soil wetness indices

AMSU-A is one of the two AMSU modules aboard NOAA KML satellites. It includes 15 channels in the 23-89 GHz range with a spatial resolution of 48 km at Nadir, and it was primarily designed for temperature soundings of the atmosphere from the surface up to about 2 millibar pressure altitude [Goodrum et al., 1997]. Two different indices have been generated from AMSU-A data, a detailed description of these indices as well as of the results already achieved by applying them to the analysis of several flooding events occurred in the past, can be found in Lacava et al. [2005, 2010]. Their potential in providing information about SM is related to the specific spectral features of AMSU. Some AMSU channels, in fact, being localized in atmospheric windows (those at 23.8, 31.4, 50.3 89 and 150 GHz), are able to provide information about surface parameters [Ferraro et al., 2002], such as SM. In particular, a combination of measurements achieved at high and low AMSU frequencies may give a qualitative estimation about variations in surface soil moisture [Grody et al., 2000; Gu et al., 2004; Kongoli et al., 2006; Lacava et al., 2010].

Starting from these insights, the Surface Wetness Index (SWI) is defined as:

$$ SWI(x,y,t) = BT_{89}(x,y,t) - BT_{35}(x,y,t) \quad [1] $$

where $t$ is the acquisition time, $(x,y)$ are the geographic coordinates of the pixel centre, $BT_{89}$ is the radiance (expressed in Brightness Temperature) measured in channel 15 (at 89 GHz)
and $BT_{23}$ is the same quantity, but measured in channel 1 (at 23 GHz). Positive values of such an index indicate a high soil water content within the instantaneous field of view (IFOV) of the sensor. In order to reduce the effects arising from the presence of vegetation, roughness and/or permanent water within the IFOV, Lacava et al. [2005] proposed a “standardized” version of $SWI$, the Soil Wetness Variation Index ($SWVI$):

$$SWVI(x,y,t) = \frac{SWI(x,y,t) - \mu_{SWI}(x,y)}{\sigma_{SWI}(x,y)} \quad [2]$$

$\mu_{SWI}(x,y)$ and $\sigma_{SWI}(x,y)$ being the monthly average and standard deviation of $SWI$, respectively (i.e. the reference fields). They are computed, following the prescription of the Robust Satellite Techniques (RST) approach [Tramutoli, 1998, 2007], on the basis of a homogeneous multi-annual data-set of AMSU images all collected during the same month of the year and at around the same hour of the day of the image at hand.

The $SWVI$, for its nature, gives an estimation of relative, rather than absolute, $SWI$ variations. Generally speaking, high values of $SWVI$ indicate a relative increase in SM at each specific location and positive $SWVI$ values indicate soil conditions wetter than the ones expected from the multi-temporal analysis already performed.

**The exponential filter**

Information about SM achievable by microwave satellite data is directly related to the surface soil layer (0.2-5 cm) [Escorihuela et al., 2010], so that every time they have to be compared with in-situ observations, which are usually referred to a deeper layer, it is necessary to average them along the vertical profile. For that, the semi-empirical approach proposed by Wagner et al. [1999], also defined as exponential filter, was employed:

$$X^*(t) = \sum_{n} X(t_n) \exp\left[-\frac{t-t_n}{T}\right]/\sum_{n} \exp\left[-\frac{t-t_n}{T}\right] \quad [3]$$

where $X(t_n)$ is the SM index retrieved from AMSU ($SWI$ and $SWVI$), $X^*(t)$ is the filtered SM index (thus obtaining $SWI^*$ and $SWVI^*$), $t_n$ is the acquisition time of $X(t_n)$ and $T$ is the characteristic time length parameter to be calibrated. The obtained $SWI^*$ and $SWVI^*$ indices are thus representative of a deeper soil layer and, hence, more comparable with ground measurements and modeled SM data.

**The soil water balance model**

In addition to in-situ direct observations, modeled SM data derived through the application of a soil water balance model were also used. For a detailed description of the adopted model and how its structure was developed the reader may refer to Brocca et al. [2008]. The model uses rainfall and temperature data as input and the output is the soil moisture values for a given depth. It is worth noting that the model parameters are physically based and their values range is limited, thus allowing to confidently use the model over large areas and for periods different from those employed for the parameter calibration. The model was already applied for several sites located across Europe providing a good agreement with observations [Brocca et al., 2008, 2010].
Study areas and soil moisture data set

In Situ Data
In-situ measurements of SM used for this study were carried out in 7 sites located in different Italian regions (see Fig. 1).

The two Emilia-Romagna test sites (Capofiume and Ozzano) were installed by the ARPA (Agenzia Regionale Prevenzione e Ambiente) Agency of Emilia-Romagna Region mainly for agricultural purposes. For these sites, SM measurements at 10 cm depth are available for the period 2004-2007.

The Spoleto site was installed by the Department of Applied Biology of Perugia University to study the production of mycorrhizal plants used for truffle crops. In the site, eight boreholes were established and weekly SM measurements were carried out in the period 2007-2008. For this site data at 20 cm depth for one representative location were used for the calibration of the soil water balance model. For this site, in order to have a continuous and temporally dense long time series, modelled data for the period 1999-2007 were employed for the comparison.

Four more sites located in South Italy were used for this study. In particular, two sites are located in the Campania region (Melizzano and Bagnoli) and two in the Calabria region (Torano and Mongrassano); they were installed by the regional Functional Centres for civil protection and agricultural activities. The sensors measure the volumetric SM at a depth of 30 cm and with an hourly time resolution, the data are available for the period 2001-2007.

It should be stressed that in situ and modelled soil moisture measurements referred to different soil depths (the range is 10-30 cm), which are very different from that investigable by satellite data, especially at high frequency. The exponential filter can contribute to reduce such a discrepancy, anyway, this issue has to be taken into account when analyzing the results.

AMSU data
For all the study sites, SWI and SWVI were computed for the period 1999-2007. While the SWI was obtained simply through the AMSU data acquired for every day of the considered period, a preliminary multi-temporal analysis has been performed for the computation of SWVI. In particular, two different datasets have been used for the identification of the above mentioned references fields (i.e. $\mu_{SWI}(x,y)$ and $\sigma_{SWI}(x,y)$) and, hence, for SWVI computation by equation [2]. The first including all the images acquired during the morning passes of NOAA 15 (between 05:00 and 07:00 GMT) and the second one corresponding to its afternoon passes (between 15:00 and 18:00 GMT) for every month of the year from 1998 to 2007. All pixels potentially affected by raining clouds and snow effects [Grody et al., 2000], or acquired at high zenith angles (>50°), hence potentially affected by spurious effects due to off nadir acquisition [Karbou et al., 2005] (AMSU-A is a cross-track scanner), were discarded during the processing procedures [Lacava et al., 2010].

Results and discussions
In the following, results of the comparison between AMSU derived SM indices, SWI and SWVI, and in-situ data are reported. Specifically, for each investigated site the following steps were carried out: 1) the data of the AMSU pixels closest to the site were selected; 2) the hourly SM data corresponding to the available AMSU passes were extracted; 3) in-situ data were rescaled between their maximum and minimum values thus obtaining the corresponding saturation degree (SD) varying between 0 and 1; 4)
a $SD$ variation index ($SDVI$) analogously to $SWVI$ was also defined for in-situ data by applying equation [2] and considering all quantities referring to “$SD$” in place of the “$SWI$” ones.

Therefore, for each site, three different comparisons were made. Firstly, the $SWVI$ and the $SDVI$ were related. It is worth noting that this comparison is the most robust test for the AMSU sensor because the seasonal effects (possibly enhancing correlation values) were mostly removed [Albergel et al., 2009]. However, since the actual $SD$ temporal pattern is needed for hydrological applications, a direct comparison between $SWI$ and $SD$ was also carried out, so that indications on AMSU sensor potential for $SD$ retrieval in the investigated areas can be inferred. Finally, by applying the exponential filter [equation 3] to the two AMSU indices (i.e. $SWVI$ and $SWI$), we defined two new variables: $SWVI^*$ and $SWI^*$ which were also analyzed. Table 1 summarizes the obtained results in terms of Pearson correlation coefficient, $R$, and Root Mean Square Difference, RMSD. The RMSD computation was carried out after linearly rescaling the AMSU indices, that are originally in Kelvin units, to match the variability of in-situ data.

As far as the $SWVI$ is concerned, its agreement with $SDVI$ was found to be very low with R ranging between 0.052 and 0.208 whereas slightly higher values (0.084-0.344) were obtained by applying the exponential filter to the AMSU data, and hence taking into account a thicker soil layer. Such results are in good accordance with those obtained by Lacava et al. [2010], thus indicating that the AMSU sensor provides the same reliability also in different physiographic areas.
Table 1 - Pearson correlation coefficient, R, and Root Mean Square Difference, RMSD, between AMSU derived (SWVI, SWVI*, SWI and SWI*) and in-situ saturation degree (SDVI and SD) data for all test sites.

| Site            | Period       | SWVI vs SDVI | SWVI* vs SDVI | SWI vs SD | SWI* vs SD |
|-----------------|--------------|--------------|---------------|-----------|------------|
|                 |              | R  | RMSD | R  | RMSD | R  | RMSD | R  | RMSD |
| Capofiume       | 2004-2007    | 0.208 | 0.920 | 0.344 | 0.882 | 0.175 | 0.223 | 0.455 | 0.205 |
| Ozzano          | 2005-2007    | 0.163 | 0.958 | 0.290 | 0.934 | 0.161 | 0.202 | 0.623 | 0.161 |
| Spoleto         | 1999-2007    | 0.120 | 0.986 | 0.218 | 0.969 | 0.244 | 0.116 | 0.568 | 0.098 |
| Bagnoli         | 2001-2007    | 0.132 | 0.998 | 0.180 | 0.993 | 0.228 | 0.214 | 0.661 | 0.166 |
| Melizzano       | 2003-2007    | 0.070 | 0.976 | 0.115 | 0.971 | 0.198 | 0.277 | 0.662 | 0.213 |
| Torano          | 2001-2007    | 0.052 | 0.977 | 0.154 | 0.966 | 0.159 | 0.235 | 0.568 | 0.196 |
| Mongrassano     | 2001-2007    | 0.058 | 0.913 | 0.084 | 0.911 | 0.148 | 0.138 | 0.551 | 0.117 |

Higher correlations (0.148-0.244) were detected, as expected, for the comparison between SWI and SD. Better results were achieved by applying the exponential filter: for SWI* R values ranged between 0.455 and 0.662 and the RMSD was found to be between 0.098 and 0.213. By assuming an average porosity value of 0.33 (as observed from in-situ observations), the RMSD values, in volumetric terms, correspond to the range 0.032-0.070 m$^3$/m$^3$.

For a visual analysis of the AMSU reliability, Figure 2 shows the SWI* and SD temporal pattern for four representative sites. As can be seen, a good agreement is evident for the overall seasonal pattern even though SWI* seems not able to capture the quick SD variations.

Conclusions

In this work we investigated the potential of AMSU radiometer to provide reliable soil moisture information. In particular, soil moisture variability information, arising from the implementation and application of two AMSU-based indices, has been compared with both modelled and in-situ measured soil moisture data, for several catchments spread out all over Italy. In particular, seven different test sites have been independently analyzed, comparing satellite estimates with in-situ direct measurements and modelled SM data. Test site locations, moving from north (i.e. ~ 44.6degN) to south (i.e. ~ 39.5degN) Latitudes, provide a geographically well-distributed data set, allowing for a wide assessment of AMSU-based indices in different environmental conditions. Moreover, long-term time domain analyses have been carried out for periods that, depending on specific test sites, ranged from 3 (2005-2007) to 9 (1999-2007) years of continuous observations, spanning for all seasons and including both morning and afternoon observations (i.e. at different illumination conditions). The results obtained in this work allow to infer that the AMSU derived SM products can be adopted for the assessment of SM conditions with an adequate level of accuracy, independently from a specific location and/or observational and environmental condition. Taking into account the high temporal resolution actually provided by AMSU sensor which, apart from NOAA satellite, is also presently flying aboard the European EUMETSAT/METOP-A and the US EOS-Aqua platforms, the relevance of these results become higher and higher.

Timely and frequently updated information, in fact, is fundamental within operational contexts and strongly required for developing advanced decision support systems, contributing to improve our capability not only for monitoring purposes but also for reliable flood prediction and risk assessment in small to medium catchments where flash floods can occur.
Figure 2 - Temporal pattern of in-situ observations, OBS, and filtered AMSU-based Surface Wetness Index, SWI*, for a) Ozzano, b) Spoleto, c) Bagnoli, and d) Torano sites.

Acknowledgments
We would like to thanks M. Bittelli from Bologna University; V. Marletto and A. Pasquali from ARPA Emilia-Romagna, the Functional Centre of Campania and Calabria region and G. Di Massimo from Perugia University for providing the in-situ SM observations. We would like also to thanks Dr. G. Calice for his contribution in AMSU data processing.
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Received 17/02/2011, accepted 7/11/2011

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