VALIDATION OF REMOTE SENSING SOIL MOISTURE PRODUCTS WITH A DISTRIBUTED CONTINUOUS HYDROLOGICAL MODEL

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ABSTRACT

The reliable estimation of soil moisture in space and time is of fundamental importance in operational hydrology to improve the forecast of the rainfall-runoff response of catchments and, consequently, flood predictions. Nowadays several satellite-derived soil moisture products are available and can offer a chance to improve hydrological model performances especially in environments with scarce ground based data.

The goal of this work is to test the effects of the assimilation of different satellite soil moisture products in a distributed physically based hydrological model. Among the currently available different satellite platforms, four soil moisture products, from both the ASCAT scatterometer and the SMOS radiometer, have been assimilated using a Nudging scheme. The model has been applied to a test basin (area about 800 km^2) located in Northern Italy for the period July 2012-June 2013.

Index Terms**—** Soil moisture, Scatterometer, Microwave Radiometer, Hydrological model, Data Assimilation.

1. INTRODUCTION

Soil moisture is a key variable for the description of many hydrological and climatic processes; it plays an important role for climate modeling and water management, as well as for operational applications. For instance, in operational hydrology, information on soil moisture can improve the forecast of the rainfall-runoff response of catchments and consequently the accuracy of flood predictions.

Soil moisture could be in principle monitored using in situ data, but local measurements are expensive and/or time consuming. Consequently, only satellite remote sensing allows for estimating soil moisture with complete and frequent coverage. In particular, remote sensing measurements present a direct sensitivity to surface soil moisture (~5 cm) at microwave bands (especially in the low frequency range, i.e., 1-5 GHz), where it influences the soil electrical permittivity, and the atmosphere can be considered as fairly transparent. Microwave remote sensing encompasses both active and passive forms. L-band (~1.4 GHz) is the optimal spectral range to observe soil moisture, because of its large penetration into the soil and its low sensitivity to the overlaying vegetation. However, ALOS-2 is still in commissioning phase (after its launch on May 24, 2014) and the launch of the Soil Moisture Active and Passive (SMAP) mission is foreseen in the last months of 2014 so that, at present, no L-band radar data are available. Conversely, measurements from both Synthetic Aperture Radars (SARs) and Scatterometers are presently available at C-band. But the former have a too long revisit time for an operational monitoring of soil moisture (although this problem will be overcome as soon as Sentinel-1 data will be available, see [1]). As for radiometers, the Soil Moisture and Ocean Salinity (SMOS) mission presently provides continuous L-band measurements over the globe.

The fact that active and passive systems measure different quantities and the scarcity of in situ reference data, make the validation of remotely sensed soil moisture products and their intercomparison a challenging task. However, these objectives can be pursued, at least at local scale, by taking advantage of the availability of hydrological models that provide physically based simulations of hydrological processes through simple but, at the same time, robust schematizations. In this work, different soil moisture products, derived from both the ASCAT scatterometer and the SMOS radiometer are used in combination with a hydrological model in order to perform a hydrological validation of the products themselves. The exercise is carried out for the Orba catchment (800 km^2), in Northern

Italy and for the period July 2012-June 2013. The saturation degrees derived from satellite data are firstly compared with those simulated by the model; then, the aforementioned data are assimilated into the hydrological model by using a Nudging scheme and the discharges predicted by the model are compared with in situ data.

2. THE HYDROLOGICAL MODEL AND THE AVAILABLE DATASET

The model used to validate the soil moisture products is Continuum [2]. It is a continuous distributed hydrological model that can be applied on a wide range of catchment classes. It combines the need of a complete description of the hydrological cycle with a simple structure requiring a limited number of parameters. It is able to reproduce the spatial-temporal evolution of soil moisture, energy fluxes, surface soil temperature and evapotranspiration. Soil moisture is expressed in terms of saturation degree (hereafter denoted as SD_{MODEL}) in the root zone, which is estimated as the ratio between the actual water volume and the maximum soil retention capacity. SD_{MODEL} is provided for each 100m x 100m pixel of the catchment where Continuum is run with a time step of 1 h. A complete description of the model can be found in [2].

The test basin is the Orba basin, which is located in the southern part of the Piedmont region in Northern Italy and has a total area of about 800 km^2. The catchment is covered by the meteorological networks of Piedmont and Liguria regions; data from rain gauges, thermometers, hygrometers, radiometers (shortwave) and anemometers are available, with a temporal resolution of 1 h. Data from two level gauges are available together with reliable stage-discharge rating curves; the two stations are located in quite far places in the basin, Tiglieto station in a head basin (Area: 75 km^2), Casalcermelli in the final part (800 km^2).

As for the satellite missions and sensors capable to provide information on soil moisture we have considered: 1) METOP Advanced Scatterometer (ASCAT) providing radar multiangle backscattering coefficient (σ_0) at 5.22 GHz (C-band) from a 817 km height orbit with 14 orbital passes per day, a spatial resolution of 25 km and a sampling interval of 12.5 km; 2) Soil Moisture Ocean Salinity (SMOS) mission and MIRAS radiometer, measuring surface emission at 1.427 GHz (L- band) from a 758 km height orbit with repetition time of 3 days and spatial resolution of 35 km.

Concerning ASCAT, the products SM-OBS-1 (H07), SM-OBS-2 (H08) and SM-DAS-2 (H14) have been used, available through the EUMETSAT Satellite Application Facility on Support to Operational Hydrology and Water Management (H-SAF). SM-OBS-1 has a spatial resolution of 25 km on a 12.5 km grid. It is generated by means of an algorithm originally conceived, at the Vienna University of Technology, for the ERS scatterometer [3]. The algorithm is based on a change detection approach which assumes that surface soil moisture is linearly related to backscattering (in dB units) and that the temporal changes of surface roughness, canopy structure and vegetation biomass occur at longer temporal scales than soil moisture changes, so that soil moisture variations in time can be detected. Consequently, for each SM-OBS-1 map, a pixel value represents a relative measure, i.e., an index between 0% and 100%, of moisture with respect to the driest and wettest conditions registered for that pixel during the calibration phase of the algorithm. Assuming that these conditions represent completely dry and wet soils, respectively, this index is equal to the degree of saturation (SD_{ASCAT}). SM-OBS-2 results from disaggregating the SM-OBS-1 product and re-sampling at 1 km with the help of long-term ENVISAT ASAR backscattering properties to better fit the hydrological requirements for higher spatial resolution. SM-DAS-2 (Root zone soil moisture index in the root zone by scatterometer data assimilation) is a modeling product that results from assimilating, by using a Simplified Extended Kalman Filter (EKF), the SM-OBS-1 product in the ECMWF Land Data Assimilation System (LDAS). In the soil moisture assimilation system, the surface observation from ASCAT is propagated towards the roots region down to 2.89 m below surface, providing estimates for 4 layers (thicknesses 0-7 cm, 7-28 cm, 28-100 cm and 100-289 cm) of a soil moisture index ranging from 0 to 1. SM-DAS- 2 is available at a 24 hour time step, with a global daily coverage at 00:00 UTC. This study considers only the second level of this product (7-28 cm) because it is considered to be more representative of the soil moisture in the root zone.

As for SMOS, the reprocessed L2 product that provides actual volumetric moisture content (SMC: ratio between the actual water volume and the total volume of the terrain), in the surface layer, is used; the version number of the processor is 551. L2 data are sampled over the ISEA4h9 grid, which has spacing in the order of 15 km.

3. DATA ELABORATION AND ASSIMILATION SCHEME

Before the assimilation into the model, all the satellite data have been resampled to the model resolution (100 m) using the nearest neighbor method. H07 data which presented a quality flag (provided with the product) greater than 15 were discarded; SMOS data were not considered in presence of quality index (dqx) greater than 0.045 and Radio Frequency Interference probability (RFI) greater than 1%. The model outputs, as well as the in situ discharge data, temporarily closest to the satellite overpasses of the Orba basin have been selected and only satellite morning passes have been considered. All the satellite-derived products have been firstly normalized using their minimum and maximum values in order to obtain a SD between 0 and 1. Regarding SMOS data, this normalization allow to obtain a SD_{SMOS} from the volumetric soil moisture content SMC_{SMOS} in order to be comparable with SD_{MODEL}. In a previous work (e.g. [4]), in the same way, SD_{ASCAT} has been converted into SMC_{ASCAT} to be compared with SMC_{SMOS}.

Then, since the ASCAT SM-OBS-1 and SM-OBS-2 products, as well as the SMOS L2 product, are referred to the first centimeters of soil, an exponential filter, developed in [3], has been applied to these normalized data to obtain an estimate of the soil moisture in the root zone (SWI), which is comparable with SD_{MODEL}.

The exponential filter has the effect of smoothing the satellite-based surface SD and this implies that that the root zone SD range in an interval that is smaller than [0-1] (see [5]). For this reason, the SWI data have been finally rescaled. For the H07 and H08 data (SWI_{ASCAT}), this rescaling has been carried out by using a Min Max correction:

$$SWI^*_{ASCAT} = \frac{SWI_{ASCAT} - \min(SWI_{ASCAT})}{[\max(SWI_{ASCAT}) - \min(SWI_{ASCAT})]} \times [\max(SD_{MODEL}) - \min(SD_{MODEL})] + \min(SD_{MODEL}) \quad (1)$$

While the SD from H14 and SWI from SMOS, indicated as SAT in the following formula (2), have been rescaled by using a linear rescaling technique (e.g. [6]).

$$SAT^* = \frac{SAT - \mu(SAT)}{\sigma(SAT)} \cdot \sigma(SD_{\mathrm{mod}}) + \mu(SD_{\mathrm{mod}}) \quad (2)$$

Rescaled satellite saturation degree (X_{OBS}) are then assimilated into the Continuum hydrological model by using a Nudging scheme [7]:

$$X_a(t) = X_{MODEL}(t) + G \cdot [X_{OBS}(t) - X_{MODEL}(t)] \quad (3)$$

The gain matrix (*G*) takes into account the uncertainties of both the model and the satellite observations. It is estimated using the root mean square difference of both modeled ($RMSD_{MODEL}$) and observed variables ($RMSD_{OBS}$):

$$G = \frac{RMSD_{MODEL}}{RMSD_{MODEL} + RMSD_{OBS}} \quad (4)$$

If G = 1 observations are assumed as very reliable, so that modeled SD are replaced by the observed SD (direct insertion); on the contrary, when G = 0 the model is assumed to be correct and no update is done. RMSDMODEL, in terms of saturation degree, has been assumed equal to 0.092 after performing a validation test in which model outputs have been compared with real soil moisture measurements (in a different basin). As for RMSDOBS it has been considered equal to 0.22 for H14, 0.12 for H07 and H08 and 0.24 for SMOS. These values have been derived from literature studies (e.g. [8], [9]).

4. RESULTS

At first the saturation degrees derived from satellite data have been compared with those simulated by the model (Fig. 1). The correlation between modeled and satellite data are very good especially for H14 whose temporal trend is very similar to that predicted by the model (Fig.1).

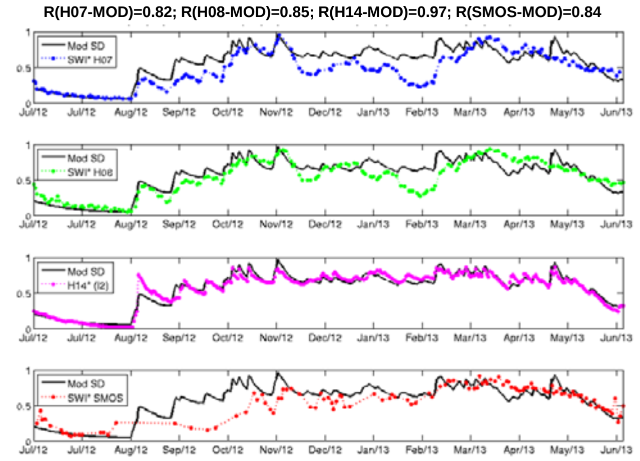

Fig. 1. Comparison between model derived (black line) and satellite-derived soil moisture data (blue for SWI^*_{H07}, green for SWI^*_{H08}, magenta for $H14^*$ and red form SWI^*_{SMOS}) temporal trends of the saturation degree. In the top of the graph the correlation coefficients are reported

The impact of the assimilation of satellite products in the Continuum model has been evaluated by comparing the simulated discharges in open loop (without assimilation) and assimilation configurations with the observed one. The Nash-Sutcliffe efficiency coefficient (E) and the root mean square error (RMSE) have been calculated. Nash-Sutcliffe is defined as

$$E = 1 - \sum_{i=1}^{n} (Q_{oi} - Q_{si})^2 / \sum_{i=1}^{n} (Q_{oi} - \overline{Q}_o)^2 \quad (5)$$

where Q_o and Q_s are observed and simulated discharges respectively. E=1 means perfect match between observations and simulations; E>0 indicates that simulations are close to observations; E=0 means that model prediction are as accurate as the mean of observation data, while E<0 means that the model is not able to reproduce the observations. The aforementioned scores are reported in Table I. An improvement with respect to the Open Loop (OL) case (i.e., without assimilation) occurs with the assimilation of quite all the satellite data.

Table II reports the various efficiencies in the different seasons of the period considered in this study (July 2012 – June 2013). It can be noted that in summer the model does not behave well, but this could be expected since the model has been designed for civil protection purposes and so it aims at reliable prediction of high discharges; in summer 2012 the discharge values were very small (a few m3/s). Nonetheless, in this season the improvement provided by the assimilation is significant, especially for H07 and H08 and except for SMOS that generally yields the worst results. The assimilation of H07 and H08 does not improve the behavior of the model in winter and spring, this because of ASCAT problems in soil moisture estimation due to snow or frozen soil. Note that in autumn, when Q values are generally high, the assimilation of ASCAT data produces fairly high values of E (in the order of 0.7, see Table II).

Fig. 2 shows the improvement of the accuracy of estimated Q obtained by assimilating satellite data with respect to OL. As previously underlined, despite of the overall poor performances in summer, the improvement achieved in this season by using H-SAF products is relevant.

TABLE I
COMPARISON BETWEEN PREDICTED AND SIMULATED DISCHARGES EVALUATED IN TERMS OF EFFICIENCY AND ROOT MEAN SQUARE ERROR.

JULY 2012 – JUNE 2013	**RMSE**	**E**
OL	25.3	0.63
ASSIM H07	24.7	0.65
ASSIM H08	25.4	0.63
ASSIM H14	22.5	0.71
ASSIM SMOS	24.6	0.65

TABLE II
COMPARISON BETWEEN PREDICTED AND SIMULATED DISCHARGES EVALUATED IN TERMS OF EFFICIENCY IN DIFFERENT SEASONS.

E	***SUMMER***	***AUTUMN***	***WINTER***	***SPRING***
OL	-2.64	0.57	0.52	0.78
ASSIM H07	-0.28	0.70	0.39	0.75
ASSIM H08	-0.13	0.68	0.44	0.66
ASSIM H14	-1.14	0.69	0.54	0.83
ASSIM SMOS	-2.65	0.61	0.54	0.78

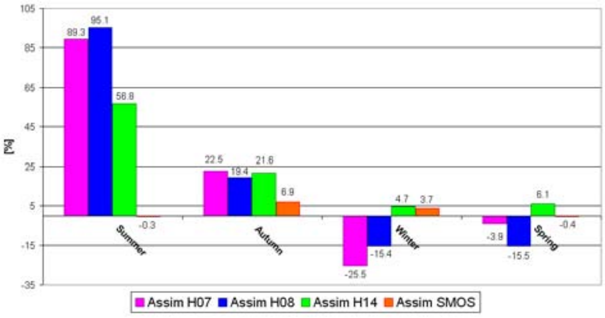

Fig. 2. Improvements of the efficiency of the Continuum model obtained by assimilating satellite products grouped by season.

5. CONCLUSIONS

In this work we assimilated four different satellite-derived soil moisture products from ASCAT and SMOS into a distributed physically based hydrological model. All products well reproduce soil moisture saturation degree at basin scale with particularly good results for the SM-DAS-2. Moreover, in the studied period (July 2012 – June 2013), the use of the soil moisture satellite products has improved the model performances in reproducing observed discharge.

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6. REFERENCES

[1] N. Pierdicca, L. Pulvirenti, G. Pace, “A Prototype Software Package to Retrieve Soil Moisture from Sentinel 1 Data by Using a Bayesian Multitemporal Algorithm,” IEEE J. Sel. Topics Appl.Earth Observ. Remote Sens. (JSTARS), vol. 7, no. 1, pp., 153-166, Jan.2014.

[2] F. Silvestro, S. Gabellani, F. Delogu, R. Rudari, and G. Boni, “Exploiting remote sensing land surface temperature in distributed hydrological modelling: the example of the Continuum model,” *Hydrol. Earth Syst. Sci*., vol. 17, pp. 39–62, 2013.

[3] W. Wagner, G. Lemoine, and H. Rott, “A method for estimating soil moisture from ERS scatterometer and soil data—Empirical data and model results,” *Remote Sens. Environ*., vol. 70, no. 2, pp. 191–207, Nov. 1999.

[4] N. Pierdicca, L. Pulvirenti, F. Fascetti, R. Crapolicchio and M. Talone, “Analysis of two years of ASCAT- and SMOS-derived soil moisture estimates over Europe and North Africa,” European Journal of Remote Sensing, vol. 46, pp. 759-773, 2013.

[5] L. Brocca, F. Melone, T. Moramarco, W. Wagner, and C. Albergel, “ Scaling and filtering approaches for the use of satellite soil moisture observations,” *Remote Sensing of Land Surface Turbulent Fluxes and Soil Surface moisture Content: State of the Art*., Taylor & Francis Ed, Chapter 17, 415-430.

[6] C. Draper, J. P. Walker, P. Steinle, R.A.M. De Jeu, and T.R.H Holmes, “An evaluation of AMSR-E derived soil moisture over Australia,” *Remote Sens. Environ*, vol. 13, no. 4, pp. 703-710, 2009.

[7] P.R. Houser, G.J.M. De Lannoy and J. P. Walker “Hydrologic Data Assimilation”, Approaches to Managing Disaster - Assessing Hazards, Emergencies and Disaster Impacts, Prof. John Tiefenbacher (Ed.), ISBN: 978-953-51-0294-6, InTech, 2012. Available from: http://www.intechopen.com/books/approaches-to-managing-disaster-assessing-hazards-emergencies-anddisaster-impacts/land-surface-data-assimilation

[8] L. Brocca, S. Hasenauer, T. Lacava, F. Melone, T. Moramarco, W. Wagner, W. Dorigo, P. Matgen, J. Martínez-Fernández, P. Llorens, J. Latron, C. Martin, and M. Bittelli, “Soil moisture estimation through ASCAT and AMSR-E sensors: An intercomparison and validation study across Europe,” *Remote Sens. Environ*, vol. 115, pp. 3390-3408, 2011.

[9] C. Albergel, P. de Rosnay, C. Gruhier, J. Muñoz-Sabater, S. Hasenauer, L. Isaksen, Y. Kerr, and W. Wagner, “Evaluation of remotely sensed and modelled soil moisture products using global ground-based in situ observations,” *Remote Sens. Environ*, vol. 118, pp. 215-226, 2012.