

PRODUCTION OF A 5-YEARS DATASET OF SOIL MOISTURE MAPS ON ITALIAN TERRITORY WITH AN OPERATIONAL ALGORITHM

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ABSTRACT

The knowledge of the soil moisture state is fundamental in water resources management, agricultural application and drought and flood events prediction. The evaluation of such variable at watershed scale can be achieved by mean of remote sensing techniques. In this work maps of Land Surface Temperature retrieved by satellite imagery have been used in a variational assimilation framework named ACHAB (Assimilation Code for Hydrologic and Atmospheric Budget) in order to provide optimal estimates of the land surface energy balance components and daily maps of soil moisture saturation index (SMSI). The assimilation procedure is able to discern the soil and the vegetation components, and requires ground observations of air temperature and humidity, solar radiation and wind velocity. ACHAB utilizes LST maps from different sensors, in this work images from MSG-SEVIRI and Terra-MODIS have been used. The simulation has been performed over the whole Italian territory for five years (2005-2009) with about 4 km of spatial resolution. A climatology of the SMSI maps has been computed and reliability index maps have been provided for the period of analysis. This study has been realized in the framework of "OPERA – Protezione Civile dalle Alluvioni, a project of the Italian Civil Protection aimed to the operational use of satellite data for floods prediction and water resources management.

1 INTRODUCTION

The importance of the soil moisture state in hydrological, meteorological and agricultural applications is well known. However, direct measurements of this variable at spatial and temporal scale significant for the characterization of the water balance is not possible. Due to such operational difficulties, indirect methods are employed in which the soil saturation is estimated as variable related the energy and mass fluxes exchanged between the land surface and the atmosphere. In order to estimate such fluxes a largely utilized tool is constituted by remote sensing, if necessary in conjunction with ground observed data. Spectral measurements from space borne sensors are not directly linked to heat and moisture fluxes, but they can be used to infer physical conditions at the land surface that are intimately related to the energy balance.

Among these conditions the land surface temperature is the prognostic variable for the indirect estimation of surface fluxes (Schulz et al. (1998)). Data assimilation techniques applied to satellite-derived LST maps can be employed in order to extract information about the surface energy budget.

In this study a data assimilation scheme has been employed in order to retrieve optimal surface states and parameters that describe the energy balance at the land surface. The main input were sequences of radiometric surface temperature measurements obtained by sensors on satellite platform: SEVIRI (aboard the Meteosat Second Generation, MSG) and MODIS sensors (aboard Terra satellite) have been used as LST input at different spatial and temporal resolutions. A parsimonious 1-D multiscale variational assimilation model, ACHAB (Caparrini et al. (2004)) has been followed, based on a simplified description of the LST dynamics. This model requires, together with the LST information, micrometeorological standard observations such as air temperature and humidity, wind velocity and solar radiation, that have been obtained by a ground sensors network. The model has been applied to a five year-long period (2005-2009) on the whole Italian territory at an horizontal resolution of about 5 km (approximately the MSG-SEVIRI resolution). The model is able to retrieve maps of sensible and latent heat fluxes and parameters that regulate the energy balance such as the coefficient of turbulent transfer and the evaporative fraction.

Such data have been used in order to estimate daily maps of soil moisture saturation index (SMSI) on Italian territory in regions in which cloud cover was not present. A climatology of the SMSI maps has been computed for the period of study, together with reliability index maps. The daily maps of SMSI are currently operationally produced in the framework of the “OPERA – Protezione Civile dalle Alluvioni” Project (Boni et al. (2009)).

2 ACHAB MODEL DESCRIPTION

ACHAB (Assimilation Code for Hydrologic and Atmospheric Budget, Caparrini et al. (2004)) is an LST variational assimilation scheme able to retrieve optimal estimates of the land surface energy budget discerning the soil and the vegetation components. The algorithm is based on a simplified description of the LST dynamics given by the Force-Restore Equation (Dickinson (1988)) and requires ground observations of air temperature and humidity, solar radiation and wind velocity. The model is able to assimilate LST estimates maps from sensors on different satellite platforms, either geostationary (MSG-SEVIRI, in this work the LSA-SAF products have been used, see LSA-SAF PROJECT TEAM (2006)) and polar-orbit (Terra-MODIS).

ACHAB allows the estimation of the various components and parameters of the energy balance: sensible and latent heat fluxes, soil and vegetation temperature and humidity, bulk transfer coefficient and evaporative fraction EF.

Given a sequence of land surface temperature observations, the estimation of heat fluxes that characterize the energy budget at the surface can be formulated with an inverse approach. According to the bulk parameterisation of surface exchanges (Stull (1988)), latent and sensible heat fluxes from land to the atmosphere can be calculated using surface temperature measurements and standard micrometeorological observations (air temperature, humidity, wind speed):

$$H = \rho c_p C_B |U| (T_s - T_a) \quad (1)$$

$$LE = \rho L C_B |U| (q_s - q_a) \quad (2)$$

where ρ is the air density, c_p is the specific heat at constant pressure of the air, C_B is the bulk coefficient of turbulent transfer, U is the wind velocity, L is the latent heat of evaporation T_s and q_s are the soil surface temperature and humidity, T_a and q_a are the air temperature and humidity.

The parameters that regulate such process and that are estimated in the assimilation scheme are (Caparrini et al. (2004)) the bulk transfer coefficient C_B (that characterize the scale of surface heat fluxes) and the evaporative fraction, $EF (= LE/(H + LE))$ which is related to soil moisture content and gives the partition of fluxes between latent and sensible heat.

The physical constraint of the model is constituted by the Force-Restore Equation (Dickinson (1988)) that describes the evolution of the soil surface temperature:

$$\frac{dT_s}{dt} = 2\sqrt{\pi\omega} \frac{R_n - H - LE}{P} - 2\pi\omega(T_s - T_{deep}) \quad (4)$$

where H and LE are positive upward, R_n is net surface radiation, positive downward, P is thermal inertia, T_{deep} is the deep ground temperature and it is assumed that the forcing has a dominant frequency ω (i.e. diurnal).

The assimilation scheme used in ACHAB follows the dual-source formulation in (Caparrini et al. (2004)). The soil-vegetation system is represented as a resistance network that includes nodes at the soil, the canopy leaves, the within canopy air and air above the canopy, as shown in Figure 1. In this way separated values for the different variables have been considered for soil and vegetation.

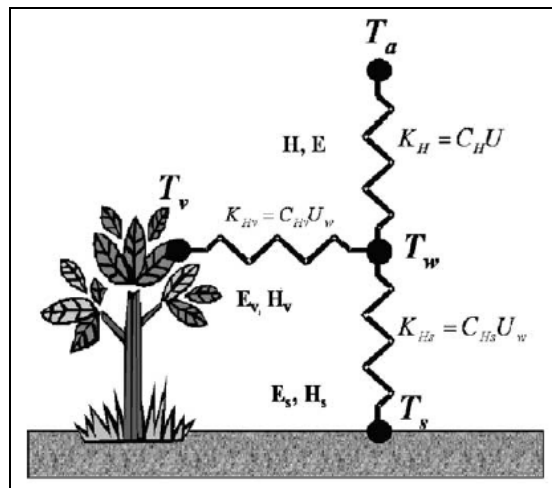


Figure 1. Schematics of dual-source (soil and vegetation) energy balance at the surface (Caparrini et al. (2004)).

The Force-Restore governing equation is adjoint, through Lagrange multipliers, to a quadratic penalty function J which measures the misfit between the observed LST (from satellite) and the estimated LST maps (by the model). The functional also includes the parameters C_B and EF , considering separately the soil and vegetation. The correct values for the parameters can be found minimizing J , thus imposing the vanishing of its first variation ($\delta J = 0$). Imposing that all the variations independently go to zero we obtain the Euler-Lagrange update equations.

The ACHAB model solves the Euler-Lagrange equations through an iterative procedure on monthly basis. The model worked, for each day of the period of interest, inside the diurnal temporal window at an hour timestep. Together with parameters, maps for each timestep (inside the diurnal assimilation window) and for each day have been produced for surface states (temperature and humidity) and fluxes (sensible and latent heat) for both soil and vegetation.

In particular, daily maps of evaporative fractions and monthly maps of coefficient of turbulent transfer have been produced. Given the sequence of EF daily maps, the corresponding soil moisture maps have been computed on a daily basis by mean of the relation:

$$SMSI = \frac{EF - EF_{min}}{EF_{max} - EF_{min}} \quad (5)$$

where EF_{max} and EF_{min} are the extreme values, for each pixel and for each month, in order to take into account the seasonality effects. Together with the daily maps of soil saturation, the algorithm also provides quality maps based on the comparison between the land surface temperature maps obtained by the model and the satellite observations.

The temperatures maps have been de-trended and an error has been computed:

$$E = \frac{(((T_s - T_{s,o}) - \overline{(T_s - T_{s,o})})^2)}{n} \quad (6)$$

where T_s is the LST estimated by the algorithm, while $T_{s,o}$ is the corresponding observation. The E error is then compared with the quantiles of an opportune Gamma probability distribution, fitted on the five year-period of the study.

The cells for which the error is between 10% and 90% quantiles are classified as *high* quality pixel, if the error is between the 5% and the 10% quantiles or between the 90% and the 95% the quality is *medium*, otherwise (below 5% of above 95% quantiles) the quality is considered to be *low*.

3 CASE OF STUDY AND RESULTS

The domain of the study was the whole Italian territory for the period 2005-2009 at about 5 km of spatial resolution (approximately the MSG-SEVIRI resolution).

The simulation has been performed on a monthly basis, in order to take into account the intra annual variation of the turbulent transfer coefficient. Daily maps of soil moisture state have been for the five-years long period. Due to the employed assimilation algorithm, only pixels in which at least three values per day of satellite-observed LST were available (in three time window, morning, midday, afternoon) have

been processed. Thus, SMSI values during periods of intense, persistent cloud cover were not computed; for this reason, a large part of the produce maps present consistently extended regions of no-data, essentially in correspondence with the main cloud system present in those days.

In Figures 2 the soil saturation map for 31 Jul 2005, during a quite dry period, is shown (left panel) with the corresponding quality map (right panel). In Figure 3 analogous maps are presented, for the autumn period, for 13 October 2009, after severe precipitation events.

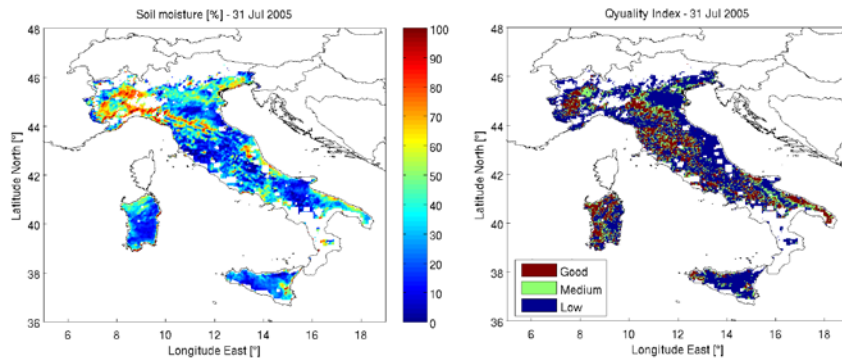


Figure 2. Soil Moisture Saturation Index map for 31 July 2005 (left panel) and corresponding quality index map (right panel).

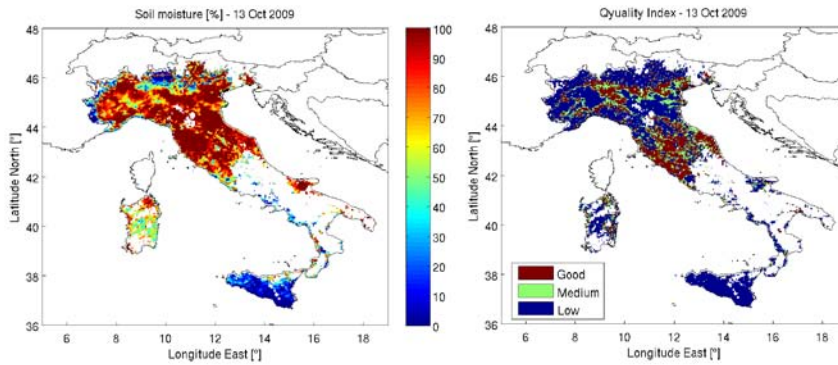


Figure 3. Soil Moisture Saturation Index map for 13 October 2009 (left panel) and corresponding quality index map (right panel).

A climatology of the soil moisture maps has been produced considering average and quartiles maps for each month and for the whole period.

In Figure 4 and 5 the mean monthly maps of SMSI are shown for first and second part of the year, respectively. In Figure 6 a statistics is represented concerning the quality index. For the whole period of analysis it is reported the monthly average of the percentages of pixels classified in the three quality levels.

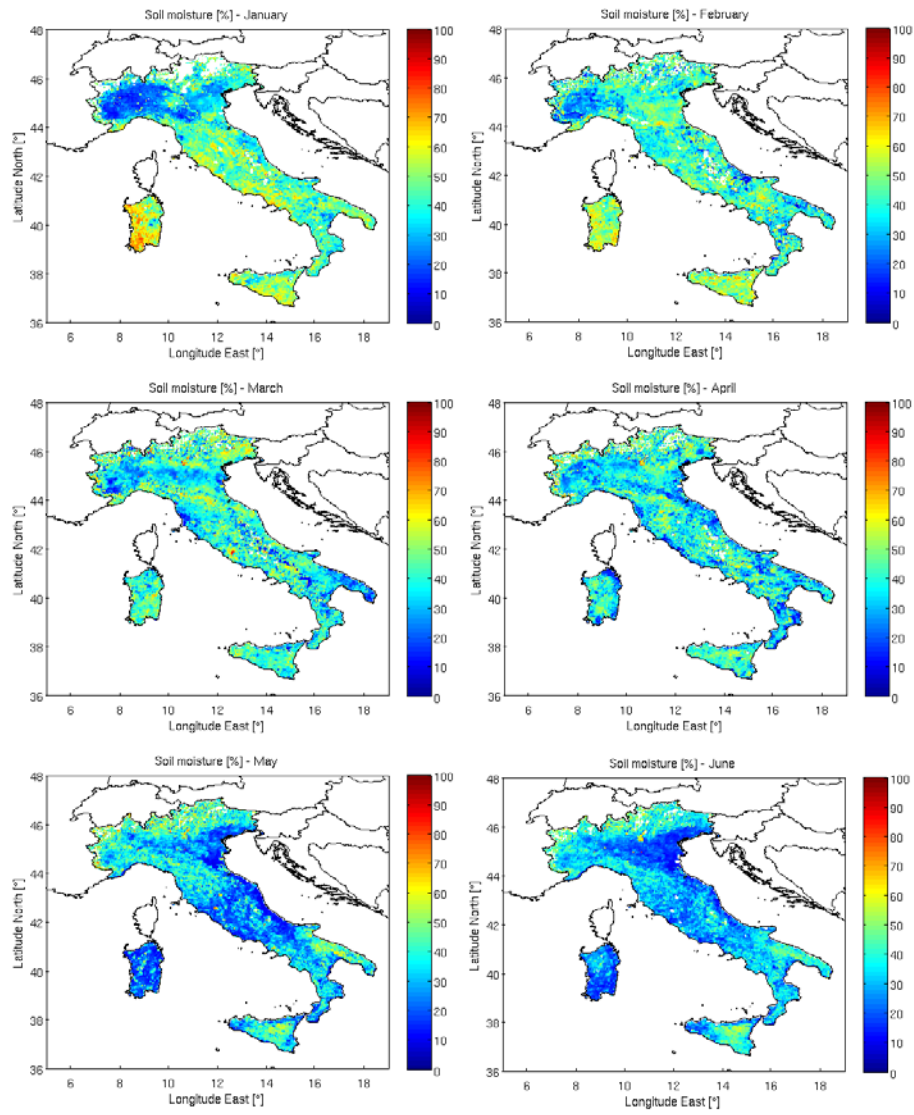


Figure 4. Soil Moisture Saturation Index climatic monthly maps from January to June.

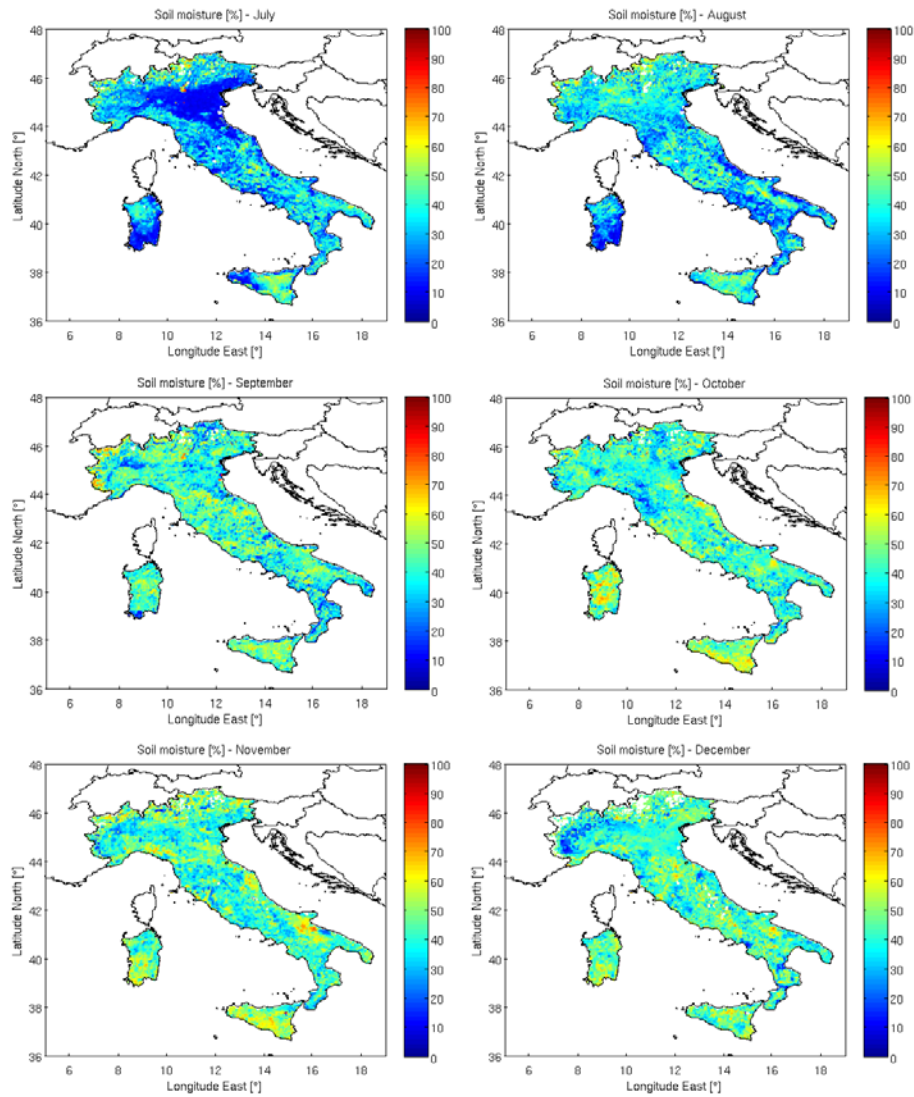


Figure 5. Soil Moisture Saturation Index climatic monthly maps from July to December.

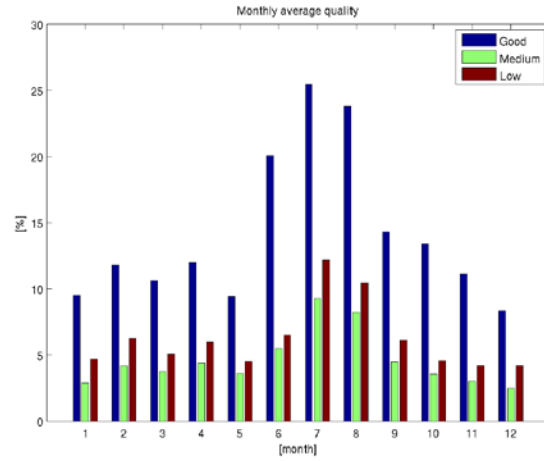


Figure 6. Monthly average percentage of pixels classified in the three quality class.

As it is possible to observe from the bar chart, the quality follows a seasonal trend, related essentially with the cloud occurrence in the different part of the year. The lower quality pixels, in fact, are found in proximity of the cloudy regions, that are generally more extended and frequent during cold months.

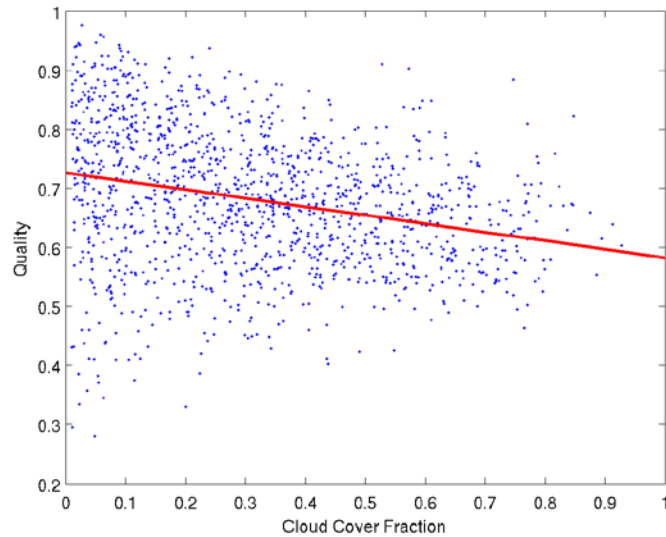


Figure 7. Scatterplot between the mean daily cloud cover and the mean daily quality level. R^2 is 0.25.

As further characterization of such relation, in Figure 7 a scatterplot is shown in Figure 7 between the daily average cloud cover and the daily average quality, in which

a slight correlation is observed.

The relation between the quality class and the cloud cover is explainable mainly with the lower efficiency in the SAF LST retrieval algorithm (LSA-SAF PROJECT TEAM (2006)) that provides worse estimates in pixel partially contaminated by the presence of clouds or erroneously classified as free sky.

4 CONCLUSIONS

The knowledge about the soil saturation state on large areas is required in many applications, like water resources management or flood prediction. However, the direct measurements of this variable presents several operational difficulties at large spatial scales. For this reason one of the main approach to this problem is constituted by the remote sensing of indirectly related variables like the Land Surface Temperature.

In this work a parsimonious 1-D variational assimilation scheme has been applied on the whole Italian territory for a five year-long period in order to estimate the energy budget at the interface between the land surface and the atmosphere.

The retrieved maps of land surface fluxes (sensible heat and evapotranspiration), states and parameters (turbulent transfer coefficient and evaporative fraction) have been used to produce daily maps of soil saturation index at about 5 km of horizontal resolution. Corresponding quality index maps were computed basing on the comparison between the observed and the estimated LST maps.

A climatology of these maps has been computed, providing monthly averages and quartiles based on the whole period of analysis, together with statistics on the quality classes in which the pixels of each daily SMSI map have been classified.

The Italy soil saturation maps are operationally produced in the framework of the “OPERA – Protezione Civile dalle Alluvioni” Project (Boni et al., 2009) and are utilized in the hydrological model chain for flood prediction.

REFERENCES

- Boni, G., Candela, L., Castelli, F., Dellepiane, S., Pelandri, M., Persi, D., Pierdicca, N., Rudari, R., Serpico, S., Siccardi, F. & Versace, C. (2009) The Opera project: EO-based flood risk management in Italy, *Proceedings of 2009 IEEE International Geoscience and Remote Sensing Symposium*, 1180-1183.
- Caparrini, F., Castelli, F. & Entekhabi, D. (2004) Variational estimation of soil and vegetation turbulent transfer and heat flux parameters from sequences of multisensor imagery, *Water Resources Research*, vol. 60, W12515, doi:10.1029/2004WR003358, 2004.
- Dickinson, R. E. (1988) The force-restore model for surface temperatures and its generalizations, *Journal of Climate*, 1, 1086-1097.
- LSA-SAF PROJECT TEAM (2006) Product User Manual LAND SURFACE TEMPERATURE, <http://landsaf.meteo.pt.2006>.
- Schulz, J.-P., Dumenil, L., Polcher, J., Schlosser, C. A. & Xue, Y. (1998) Land surface energy and moisture fluxes: Comparing three models, *Journal of Applied Meteorology*, 37(3), 288–307.
- Stull, R. N. (1988) An introduction to Boundary Layer Meteorology, Kluwer Academic Publisher, Dordrecht, The Netherlands.