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LAND SURFACE TEMPERATURE FROM REMOTE SENSING AND FROM A DISTRIBUTED ENERGY – WATER BALANCE MODEL FOR WATER MANAGEMENT

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ABSTRACT

The present work investigates the potentiality to control surface soil moisture and its spatial and temporal variability through the detection of land surface temperature from the synergic us of operative satellite remote sensing (MODIS) data, ground observations and the thermodynamic equilibrium temperature of the modelled energy water balance. Analysis is performed at basin scale as well at field scale.
At field scale the energy water balance is monitored through the eddy covariance technique and a comparison with in situ modelling simulations is provided to check the model performances.
At basin scale LST from operative remote sensing is used for the validation of the distributed hydrological model in addition to the traditional validation with discharge measurements along the river streams.
The case studies are the experimental maize field of Landriano and the Po river basin at Ponte della Becca cross section in Italy.

1 INTRODUCTION

Soil Moisture is recognized as the key variable in the hydrologic water balance for operational purpose as for flash flood forecast system as well as for irrigation management (*Montaldo & Albertson*, 2003b). Respect to this role, it is most of the time confined to an internal numerical model variable (*Dooge*, 1986). This is mainly due to its intrinsic space and time variability and to the well known difficulties in assessing its value from remote sensing as from in situ measurements (*Engman & Chauhan*, 1995). These problems drove the scientific community to the use of hydrologic modelling in conjunction with remote sensing data for water content estimation at basin and field scale through connected variables to soil moisture such as land surface temperature.

Land surface temperature (LST) is the parameter that links the energy fluxes between the atmosphere and the surface and so it becomes fundamental in the energy balance modelling to estimate the net radiation and the soil, sensible and latent heat fluxes (*Noilhan & Planton*, 1989; *Famiglietti & Wood*, 1994). The availability of satellite remote sensing information makes easy to retrieve LST in raster format, mainly suited for the use in conjunction to distributed model. However, some uncertainties have to be addressed, such as the definition of satellite LST over an heterogeneous area that is a function of the surface temperature of each component of the area (bare soil or vegetation), of the occupied percentage by each type of soil and of the scan angle of view of the satellite (*Norman et al*., 1995).

The potentiality of a “representative surface temperature” in an energy mass balance model as a tool to monitor soil moisture dynamic from operative satellites such as TERRA with on board MODIS sensor is discussed. At local scale the paper tries to asses soil moisture values and its spatial and temporal dynamic developing an energy water balance model (FEST-EWB) tested at field scale with fluxes measured from an eddy tower. Modelled land surface temperature values are compared with operative satellite data (MODIS) and in situ ground measurements to improve irrigation management for the year 2006 in the Landriano agricultural test area.

The goodness of the measured ground data is evaluated testing the energy budget closure considering the additional terms of the energy storage such as the photosynthesis flux, the crop and air enthalpy changes and the soil surface layer heat storage. In fact the traditional energy budget is typically not closed when measuring energy with an eddy correlation station and the available energy is usually bigger than the sum of the turbulent vertical fluxes with a ratio that ranges between 70 and 90% *(Jacobs et al.,* 2008; *Meyers & Hollinger*, 2004). This is mainly due to instrumental errors, especially those of the eddy covariance technique, to the problem of heterogeneities in the area and to the energy storage.

At basin scale this work tries to evaluate the use of LST retrieved from satellite images for the validation of a distributed hydrological model as a complementary method to the traditional calibration with discharge measurements. The energy balance gives the opportunity to increase the fluxes control points and so to improve the mass balance accuracy.

2 THE ENERGY BALANCE MODEL

FEST-EWB is a distributed hydrological energy water balance model (*Corbari et al.,* 2008) and it is developed starting from the FEST-WB and the event based models FEST98 and FEST04 (*Mancini*, 1990; *Ravazzani et al*., 2008). FEST-WB computes the main processes of the hydrological cycle: evapotranspiration, infiltration, surface runoff, flow routing, subsurface flow and snow dynamic. In the FEST-EWB the energy balance module is introduced where land surface temperature is the key parameter that links the energy fluxes between the low atmosphere and the ground surface.

At the ground surface, the complete energy balance equation is expressed as:

$$R_n - G - (H_s + H_c) - (LE_s + LE_c) = F_{CO2} + S_c + S_{air} + S_s \quad (1)$$

where all the terms depend on LST: Rn (Wm^{-2}) is the net radiation, G (Wm^{-2}) is the soil heat flux, H_s and H_c (Wm^{-2}) and LE_s and LE_c (Wm^{-2}) are respectively the sensible heat and latent heat fluxes for bare soil (s) and for canopy (c), and the energy storage terms: the photosynthesis flux (F_CO_2), the crop and air enthalpy changes (S_{canopy} and S_{air}) and the soil surface layer heat flux (S_{soil}) (Wm^{-2}). These terms are often negligible, especially at basin scale with a low spatial resolution; instead at local scale the contribution of these terms could be significant (*Jacobs et al.*, 2008*).*

All the terms of the energy balance depend on the land surface temperature and so the energy balance equation can be solved with the well known Newton-Rhapson method:

$$LST_n = LST_{n-1} + \frac{f_t(LST_{n-1})}{f_t'(LST_{n-1})} \tag{2}$$

where LST_n is the actual value, LST_{n-1} is the value at the previous iteration, $f_t(LST_{n-1})$ is the energy balance function and $f_t'(LST_{n-1})$ is its derivative. The solution is acceptable when:

$\left|\frac{f_t(LST)}{f_t'(LST)}\right| < tolerance$ and $f_t(LST) < tolerance$, with tolerance equal to 0.001.

The terms of the energy balance equation are described in the following.

The net radiation is the algebraic sum of the incoming and outgoing short wave and long wave radiation, strictly correlated with albedo, soil and atmosphere emissivity.

The soil heat flux is the heat changed for conduction with the sub-surface soil and it is evaluated as the difference between LST and the temperature below the first layer of soil and considers the soil thermal conductivity (*McCumber & Pielke*, 1981).

The sensible heat flux is considered for the situations of bare soil, H_s, and of canopy presence, H_c. The cell of the computational domain is characterized by a vegetation fraction, f_v, to discriminate the percentage of vegetation coverage. This vertical flux is computed as:

$$Hs + Hc = (1 - fv)\frac{\rho_a c_p}{r_a}(LST - T_a) + fv\frac{\rho_a c_p}{r_a}(LST - T_a) \tag{5}$$

where ρ_a is the air density (Kgm^{-3}), c_p is the specific heat of humid air ($MJkg^{-1}K^{-1}$). Correction functions for atmospheric stability or instability are included in the aerodynamic resistance, r_a (sm^{-1}), using the Thom model (*Thom*, 1975).

The latent heat fluxes for bare soil, LEs, and of canopy, LEc. are:

$$LEc + LEs = f_v(\frac{\rho_a c_p}{\gamma(r_a + r_c)})\left(e^* - e_a\right) + (1 - f_v)\frac{\rho_a c_p}{\gamma(r_a + r_s)}\left(e^* - e_a\right) \tag{7}$$

where γ is psychrometric constant (Pa°C^{-1}), e*is the saturation vapour pressure (Pa) computed as function of the LST and e_a is the vapour pressure (Pa), r_c (sm^{-1}) the canopy resistance (*Jarvis*, 1976) and r_S (sm^{-1}) the soil resistance (*Sun*, 1982).

The photosynthesis flux, that is the change in the Gibbs free energy, is calculated with the conversion from the measured flux of 1 mg CO_2 m^{-2} s^{-1} to 11 Wm^{-2} (*Nobel*, 1974). The air enthalpy is evaluated as:

$$S_{air} = \frac{\Delta T_a \rho_a c_p}{\Delta t}\Delta z_{air} \tag{12}$$

where ΔT_a is the difference of air temperature (°C), Δt is the time step (s) and Δz_{air} is the height of the measurement instrument (m). The canopy enthalpy is computed only over a fixed vegetation height:

$$S_{canopy} = \frac{\Delta LST\,(m_w c_w + m_b c_b)}{\Delta t} \tag{13}$$

where m_w and m_b (Kgm^{-2}) are respectively the masses of water and biomass, c_w and c_b ($JKg^{-1}K^{-1}$) are the specific heat capacities of water and biomass.

A similar approach is used for the heat flux in the soil surface layer:

$$S_{soil} = \frac{\Delta T_{soil}\,(SMm_w c_w + \rho_s c_s)}{\Delta t}\,\Delta z_{soil} \tag{14}$$

where T_{soil} is the soil temperature (K) at the soil heat flux plate depth (Δz_{soil}), ρ_s (Kgm^{-3}) is the soil density and c_s ($JKg^{-1}K^{-1}$) is the specific heat of soil capacity.

For water bodies, such as lake or paddy, the energy water balance equation is introduced and is solved, as for the soil surface energy budget, with the well known Newton-Rhapson method:

$$Rn - Hw - LEw = S_{water} \tag{15}$$

where: H_w (Wm^{-2}) is the sensible heat flux, LE_w (Wm^{-2}) is the latent heat flux, which is considered in its potential form, and S_w (Wm^{-2}) is the storage term of water. G (Wm^{-2}) is often negligible. The additional flux term (Wm^{-2}) considered in the energy balance equation is the water heat flux that is computed as:

$$Sw = \frac{(LST - LSTprof\,)\rho_w c_w}{\Delta t}\,\Delta z \tag{18}$$

where LSTprof is the water temperature (K) at a fixed depth (Δz), ρ_s (Kgm^{-3}) is the soil density and c_w ($JKg^{-1}K^{-1}$) is the specific heat of water capacity.

3 THE ENERGY BUDGET MEASUREMENT AT LOCAL SCALE

3.1 Study site at local scale

Landriano eddy correlation station (45.19 N, 9.15 E) is located in the Po river plain (Northern Italy) operated by the Politecnico of Milano where the data were gathered during year 2006 from 13th of March to 11th of October at. The site is an experimental field of maize, that was planted 1st of June and harvest 11th of October at a reached height of 224 cm. Maize reached is full grown stage at the end of August, with a maximum value of LAI of 4.3. The station acquires data averaged on half an hour basis, 24 hours a day (*Horeschi et al.*, 2008).

3.2 Energy budget closure

The energy balance closure is studied to evaluated the reliability of the measured ground data and the implication that has on the interpretation of the energy fluxes.

The closure of the energy balance with the raw data shows a linear regression forced through the origin equal to y=0.824x. Instead if the energy storage terms are considered, such as the photosynthesis flux, the enthalpy changes of crop and air and the soil surface layer heat flux, an improvement in the energy balance closure is reached (*Meyers & Hollinger*, 2004). In fact the linear regression forced through the origin goes up to y=0.897x (Figure 1). The total percentage of the improvement is of 8 %, that it is not negligible even if the single component gives a low contribution.

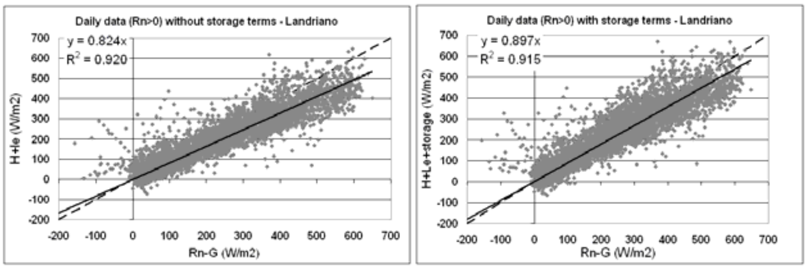

Figure 1. Energy budget closure for measured fluxes (left) and with the additional fluxes (right).

4 MODEL VALIDATION WITH GROUND AND SATELLITE DATA AT LOCAL SCALE

4.1 Energy fluxes

The measured and simulated principal fluxes of the energy budget, such as the net radiation, the latent and sensible heat fluxes and the soil heat flux, are compared (Figure 2) and a good accuracy is reached.

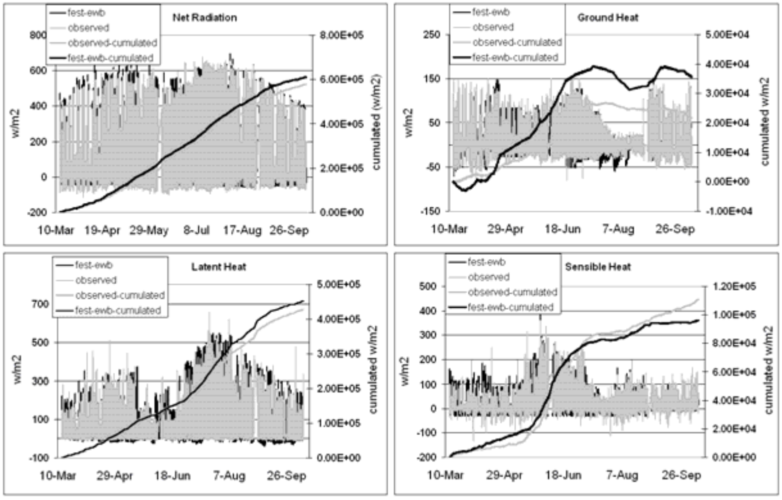

Figure 2. The comparison of the simulated and measured energy fluxes

These results are confirmed from a statistical analysis looking for the minimization of the root mean square error (RMSE) and the maximization of the efficiency of the Nash and Sutcliffe index (Nash and Sutcliffe, 1970). The RMSE has low values for each flux in regard to its maximum value (Table 1).

	η	**RMSE (Wm^{-2})**
Net Radiation	0.96	38.3
Latent Heat	0.75	54.8
Sensible Heat	0.71	29.6
Ground Heat	0.68	22.5

Table 1. RMSE and the Nash and Sutcliffe index for the energy fluxes.

4.2 Land surface temperature

Land surface temperature is the key parameter in the energy balance modelling that links the energy fluxes between atmosphere and surface because it drives heat exchange. Satellite images are an important instrument for the use in conjunction to distributed model, even if some uncertainties have to be addressed, such as the definition of satellite LST of an heterogeneous area. For this study we use 104 daily and nocturne LST product from MODIS radiometer on board satellite TERRA, (http://ladsweb.nascom.nasa.gov/index.html) for the simulation period from 13th of March to 11th of October 2006 for Landriano station. This area can be considered homogenous permitting to avoid the problem of MODIS spatial resolution of 1 Km.

LST from MODIS and LST measured from the radiometer of the eddy station are compared with the land surface temperature simulated from FEST-EWB. In Figure 3, the linear regression forced through the origin for the LST from FEST-EWB against LST form the station is y = 0.97 x, showing a good behaviour of the model in representing the observed data. When the modelled values are compared with the satellite ones, a slope of 0.9 is reached. Also the rout mean square error (RMSE) and the Nash and Sutcliffe index (η) confirm the results of the modelling simulation according to the ground measured data and to the LST retrieved from MODIS images.

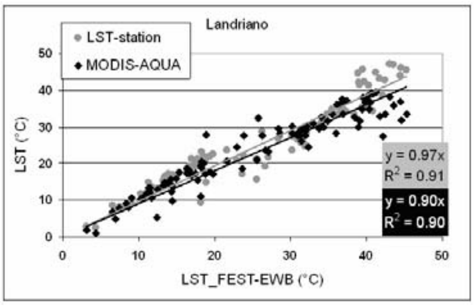

Figure 3. The comparison between modelled LST (K), LST-MODIS and LST from the station

5 SOIL MOISTURE VARIABILITY AT LOCAL SCALE

Soil Moisture from modelling results and in situ data are compared for the Landriano agricultural field (9 ha). Soil moisture field data are acquired using a TDR sensor (5 cm) after each irrigation in 37 points, while local vertical profile is detected continuously in time at the station (*Horeschi*, 2008). The field is irrigated with farrow irrigation that causes a non homogeneous spatial variability.

The FEST-EWB model seems to well reproduce also soil moisture temporal dynamic at the station considering both precipitation and irrigation (Figure 5).

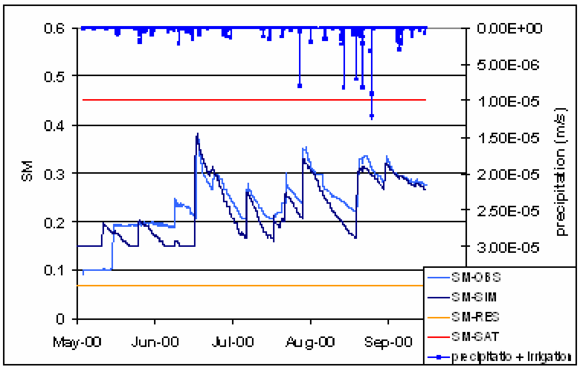

Figure 5. Simulated and observed soil moisture temporal dynamics.

6 MODEL VALIDATION AT BASIN SCALE

6.1 Study site at basin scale

The study domain is the upper Po river basin, in the north-west of Italy, a predominantly alpine region covering 38 000 km^2. It is located in the Padana plain and bounded on three sides by mountain chains covering 73% of its territory. For this study, meteorological and hydrologic ground measured data were collected by the telemetric monitoring system of the Regione Piemonte, Regione Lombardia and Switzerland. Data of rainfall, air temperature, incident short wave solar radiation and air relative humidity are available from 1st January 2000 to 31st December 2004 at hourly or sub-hourly time step (*Rabuffetti at al.*, 2008).

6.2 Land surface temperature

At basin scale LST retrieved from satellite images gave a relevant opportunity to validate the distributed hydrological model as a complementary method to the traditional calibration with discharge measurements.

130 daily and nocturne LST MODIS products are compared with the FEST-EWB land surface temperature over the 4 years of simulation. In particular only images with cloud cover below 20 % over the all area were selected.

Particular attention has been paid to paddies which occupies an area of 2300 Km^2 in the river Po plain, equal to 6 % of the total basin area. This cultivation is characterized by a 4 months period, from May to October, of flood field when they can be considered as lakes with a deepness of 20 cm, while during the other months they are simulated as bare soil. Also the Maggiore lake was simulated with the water energy balance and good results are found with LST MODIS products. So LST from modelling simulation and LST-MODIS products are compared for the entire basin for the 4 years of simulation and a good correlation is found. In Figure 6, two LST maps of FEST-EWB and MODIS are reported for 29th January 2003 at 11 am and 29th June 2003 at 1 pm where paddies are evident in the plain area with lower LST values than the surrounding fields.

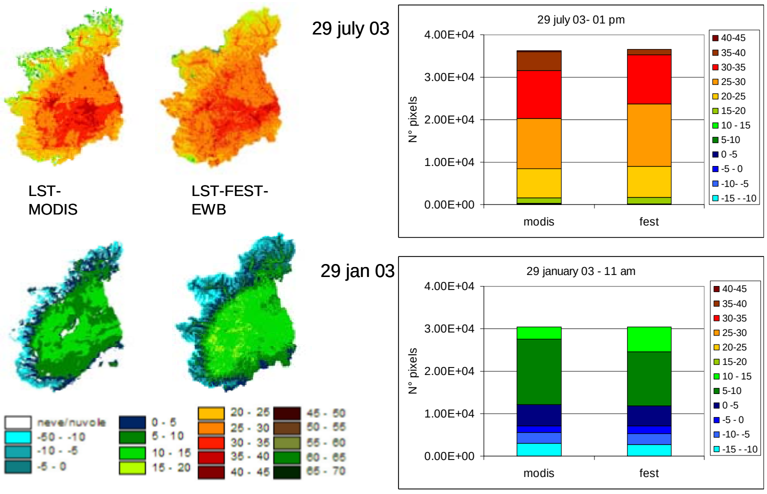

Figure 7. LST form FEST-EWB and from MODIS

In Figure 8 the differences between LST form FEST-EWB and form MODIS are reported.

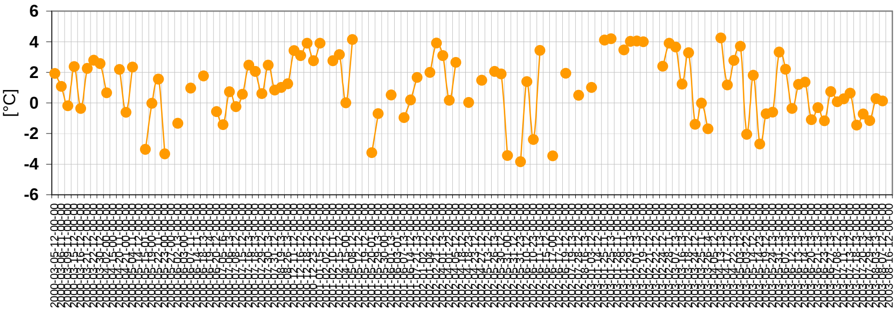

Figure 8. Difference between LST form FEST-EWB and form MODIS

Model LSTs are on average 3 °C higher then satellite ones, but with good accuracy in the mountains area when there is no snow; while agricultural plain shows bigger errors due to the difficulty to exactly represent the vegetation period of cultivation that is characterized by a strong heterogeneity and only LAI, from MODIS 8-days compositing products, and CORINE land cover maps are available. Moreover in the entire basin only 80 solar radiation stations are available and with a non homogenous spatial distribution, in fact there are few stations in the mountains area. Another problem, as said before, as to be addressed to the LST retrieval from satellite images for heterogeneous area that is affected by uncertainty.

7 CONCLUSIONS

The present paper investigated the possibility to control surface soil moisture into a distributed hydrologic model through the detection of land surface temperature from satellite remote sensing due to the simpler information and availability of infrared satellite images respect to the microwave ones. Closing the energy budget on the land surface temperature seems to be promising for the use of ground and satellite data. Moreover the use of satellite LTS seems to be an affordable way to increase the fluxes control points so to improve the mass balance accuracy.

At local scale the energy water balance model (FEST-EWB) reproduces soil moisture values and its spatial and temporal dynamic in agreement with observed data. Modelled land surface temperature values are also compared with operative satellite data (MODIS) and with in situ ground measurements. The goodness of the measured ground data has been evaluated testing the energy budget closure considering the additional terms of the energy balance that allow an improvement in the energy budget closure of 7.5 %. FEST-EWB is developed considering these additional terms and the energy fluxes from field data and modeling are in good agreement.

It is show that in any case the local scale analysis is a necessary passage to basin scale applications. For the considered basin the use of effective LST from operative satellite seems be comparable with modelled LTS considering the heterogeneity of the area.

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REFERENCES

Dooge, J.C.I.. Looking for hydrologic laws, *Water Resour Res*, 1986, 22(9) 46S-58S.

Engman, E.T. & Chauhan, N.. Status of microwave soil moisture measurements with remote sensing, *Remote Sens. Environ.*, 1995, 51, 189-198.

Famiglietti, J. S. & Wood, E. F. Multiscale modelling of spatially variable water and energy balance processes, *Water Resour. Res.*, 1994, 30, 3061-3078.

Horeschi, D. Misure sperimentali per la determinazione del bilancio idrologico, PhD dissertation, Politecnico di Milano, Milan, Italy (in italian), 2008.

Jacobs, A.F.G., Heusinlveld, B.G. & Holtslag, A.A.M. Towards closing the energy surface budget of a mid-latitude grassland, *Boundary Layer Meteorol*, 2008, 126, 125-136.

Jarvis, P.G. The interpretation of the variations in leaf water potential and stomatal conductance found in canopies in the field, *Philos. Trans. Roy. Soc.*, 1976, B. 273, 593-610.

Mancini, M. La modellazione distribuita della risposta idrologica: effetti della variabilità spaziale e della scala di rappresentazione del fenomeno dell’assorbimento, PhD dissertation, Politecnico di Milano, Milan, Italy (in italian), 1990.

McCumber, M. C. & Pielke, R. A. Simulation of the effects of surface fluxes of heat and moisture in a mesoscale numerical model, *J. Geophys. Res.*, 1981, 86(C10), 9929–9938.

Meyers, T.P. & Hollinger, S.E. An assessment of storage terms in the surface energy balance of maize and soybean, *Agr. Forest Meteorol.*, 2004, 125, 105-115.

Montaldo, N. & Albertson J. D. Temporal dynamics of soil moisture variability: 2. Implications for land surface models, *Water Resour. Res.*, 2003b, 39 (10), SWC 3-1: 3-13.

Nash, J. E. & Sutcliffe J. V. River flow forecasting through the conceptual models, Part 1: A discussion of principles, *J. Hydrol.*, 197, 010 (3), 282-290.

Nobel, P.S. Introduction to biophysical plant physiology. New York: Freeman, 1974, 260pp.

Noihlan, J. & Planton, S. A Simple parameterization of Land Surface Processes for Meteorological Models, *Mon. Wea. Rev.*, 1989, 117, 536-549.

Norman, J.M., Kustas, W. P. & Humes, K. S. Source approach for estimating soil and vegetation energy fluxes in observations of directional radiometric surface temperature, *Agr. Forest Meteorol.*, 1995, 77, 263-293.

Rabuffetti D. Ravazzani, G. Corbari, C. and Mancini, M. Verification of operational Quantitative Discharge Forecast (QDF) for a regional warning system - the AMPHORE case studies in the upper Po River, *Nat. Hazards Earth Syst. Sci.*, 2008, 8, 1-13.

Ravazzani, G., Rabuffetti, D., Corbari, C. and Mancini, M. Validation of FEST-WB, a continuous water balance distributed model for flood simulation, *Procedings of XXXI Italian Hydraulic and Hydraulic Construction Symposium*, Perugia, Italy, 2008.

Sun, S.F. Moisture and heat transport in a soil layer forced by atmospheric conditions. M.Sc. dissertation, University of Connecticut, Storrs, CT., 1982.

Thom, A.S., Momentum, mass and heat exchange of plant communities, Monteith, J.L., (Ed.), Vegetation and Atmosphere. London: Academic Press, 1975, 57–110 pp.