CALIBRATION OF A DISTRIBUTED HYDROLOGICAL MODEL USING SATELLITE DATA OF LST AND GROUND DISCHARGE MEASUREMENTS

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ABSTRACT

Calibration and validation of distributed models at basin scale generally refer to external variables, which are integrated catchment model outputs, and usually depend on the comparison between simulated and observed discharges at the available rivers cross sections, which are usually very few. However distributed models allow an internal validation due to their intrinsic structure, so that internal processes and variables of the model can be controlled in each cell of the domain. In particular this work investigates the potentiality to control evapotranspiration and its spatial and temporal variability through the detection of land surface temperature from satellite remote sensing. This study proposes a methodology for the calibration of distributed hydrological models at basin scale through the constraints on an internal model variable using remote sensing data of land surface temperature. The model (FEST-EWB) algorithm solves the system of energy and mass balances in term of the equilibrium pixel temperature or representative equilibrium temperature that governs the fluxes of energy and mass over the basin domain. This equilibrium surface temperature, which is a critical model state variable, is compared to land surface temperature from MODIS and AATSR. So soil hydraulic parameters and vegetation variables will be calibrated according to the comparison between observed and simulated land surface temperature minimizing the errors. A similar procedure will also be applied performing the traditional calibration using only discharge measurements. These analyses are performed for Upper Yangtze River basin (China) in framework of DRAGON-2 and DRAGON-3 Programme funded by NRSCC and ESA.

1 . INTRODUCTION

Hydrological models can give an important contribute to quantify mass and energy fluxes at the basin and irrigation district scale, as quoted in literature over the last decades [1] [2] [3] [4] [5]. Nevertheless, their application, both in operative and scientific research, is limited by the difficulties to verify evapotranspiration (ET) and soil water content at the basin scale. In fact, calibration and validation of distributed models generally depend on comparison between simulated and observed discharges at the available rivers cross sections. Soil moisture (SM), which is recognized as the key variable in these hydrologic energy water balance models, respect to this role is most of the time confined to an internal numerical model variable and it seems that the link between internal and external variables [6] is not resolved yet. These problems drove the scientific community to the use of hydrologic modelling in conjunction with remote sensing data, in particular land surface temperature (LST). This approach seems to solve many limitations and difficulties of the previous technology based on micro-wave satellite images. In fact, promising results are now coming using both hydrological modelling and thermal infrared satellite images available from sensors [7] [8] [9].

A continuous distributed hydrologic energy water balance model, (FEST-EWB - Flash–flood Event–based Spatially–distributed rainfall–runoff Transformation- Energy Water Balance), will be used. FEST-EWB model has been already calibrated and validated at different scales, from local to agricultural area [10] [11]. The model algorithm solves the system of energy and mass balances in terms of a representative equilibrium temperature (RET) that is the land surface temperature that closes the energy balance equation and so governs the fluxes of energy and mass over the basin domain. This equilibrium surface temperature, which is a cr itical model state variable, is comparable to LST as retrieved from operational remote sensing data. So a new methodology for the calibration of distributed hydrological models at basin scale is proposed by constraining an internal model variable. Soil hydraulic and vegetation parameters are then calibrated in each pixel of the domain according to the comparison between observed and simulated land surface temperature minimizing the differences. A traditional "trial and error" calibration procedure is also applied by comparing only discharge measurements in the available cross section. The FEST-EWB model has been implemented for the Upper Yangtze River basin with an extent of about 1,000,000 Km^2 at spatial resolution of 5km and temporal resolution of 1 hour. Results are provided in terms of hourly evapotranspiration, soil moisture and land surface temperature maps for the period between 2000 to 2009 where ground and satellite data are available for engineering and environmental applications as parsimonious irrigation, real time flood forecast, and quantitative water resources availability. The model accuracy will be controlled from the comparison with

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traditional discharge daily data series and also from the comparison between model and satellite land surface temperature used as a proxy of evapotranspiration fluxes.

2. HYDROLOGIC MODEL: FEST-EWB

FEST-EWB is a distributed hydrological energy water balance model [12] and it is developed starting from the FEST-WB and the event based models FEST98 and FEST04 [13]. FEST-EWB computes the main processes of the hydrological cycle: evapotranspiration, infiltration, surface runoff, flow routing, subsurface flow and snow dynamic. In particular the energy budget is solved looking for the representative thermodynamic equilibrium temperature (RET) defined as the land surface temperature that closes the energy balance equation considering also the storage terms such as the photosynthesis flux, the air and crop enthalpy changes and the surface soil heat flux.
So using this approach, soil moisture is linked to the latent heat flux and then to LST. The RET thermodynamic approach solves most of the problems of the actual evapotranspiration and soil moisture computation. In fact it permits to avoid computing the effective evapotranspiration as an empirical fraction of the potential one.
Soil moisture evolution for a generic cell at position i,j, is described by the system between energy and water balance equations:

$$\begin{cases} \frac{\partial SM_{i,j}}{\partial t} = \frac{1}{dz_{i,j}}\left(P_{i,j} - R_{i,j} - PE_{i,j} - ET_{i,j}\right) \\ Rn_{i,j} - G_{i,j} - H_{i,j} - LE_{i,j} = \frac{\Delta W}{\Delta t}_{i,j} \end{cases} \qquad (1)$$

where P is precipitation rate (mm h^{-1}), R is runoff flux (mm h^{-1}), D is drainage flux (mm h^{-1}), ET is evapotranspiration rate (mm h^{-1}), z is the soil depth (m), Rn (Wm^{-2}) is the net radiation, G (Wm^{-2}) is the soil heat flux, H (Wm^{-2}) and LE (Wm^{-2}) are respectively the sensible heat and latent heat fluxes, and $\Delta W/\Delta t$ (Wm^{-2}) encloses the energy storage terms.
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:

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

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.

In particular the input parameters of the model are: 1) meteorological variables, such as air temperature, incoming shortwave radiation, wind velocity, precipitation, air humidity; 2) the soil parameters in distributed maps, such as the saturated hydraulic conductivity (ksat), the field capacity (fc), wilting point (wp), residual (θr) and saturated (θs) soil water content, Brooks-Corey index (BC), bubbling pressure (bp) and soil depth (depth) and 3) the vegetation parameters, such as leaf area index (LAI), vegetation height (hv) and minimum stomatal resistance (rsmin); 4) the digital elevation model (DEM) and land use/cover map.

3. STUDY SITE

The test area is the Upper Yangtze River basin in China gauged at Yichang where the three gorges dam is located. The basin is delimited by a red line in Fig.1. The total area is of about 1005500 km2. The main river length is equal to 2400 km with an average discharge of 13’200 m^{3}s^{-1} and a mean annual precipitation of about 800 mm concentrated during the Monsoon period when flood events are frequent. This catchment drains a region characterized for 60 % of mountains and for 40 % an agricultural plain [14].

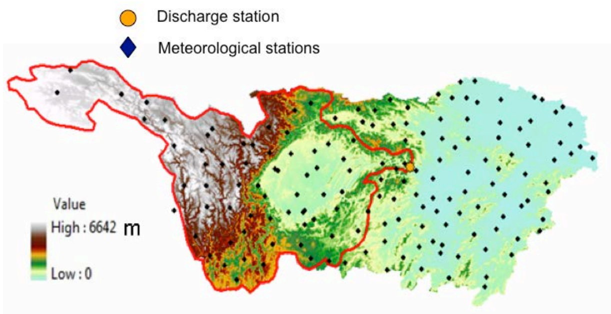

Figure 1. Study area and available meteorological data and discharge station

3.1. Meteorological ground station

Meteorological data of rainfall, air temperature, relative air humidity and horizontal wind velocity are available from 1 January 2000 to 31 December 2009 at daily scale from the NDCD database (http://www.ncdc.noaa.gov/oa/ncdc.html). Instead daily incident short wave solar radiation, which is needed for energy balance computation, is computed using the [15] equation based on maximum and minimum daily air temperature and the extraterrestrial radiation.
However FEST-EWB hydrological model should be run at hourly scale due to the basic idea of the paper for calibrating the soil and vegetation parameters using instantaneous satellite data of land surface temperature. So these daily meteorological data are rescaled at hourly scale. In particular for air temperature estimate

the method proposed by [16] is used, which is based on a sinusoidal algorithm considering sunrise and sunset hours. The [17] model is used for incoming shortwave radiation computation based on a Gaussian curve. Rainfall, wind velocity and relative air humidity are assumed constant during the day.
Only 71 stations are available for such a big basin with a very low spatial density if compared to European or US river basins (Fig..1).
Discharge measurements are available from 1 January 2000 to 31 December 2004 at Yichang station (30.66 N, 111.23 E) where the three gorges dam is located.

3.2. Soil database and hydraulic properties

Available digital cartographic data includes the Digital Elevation Model (DEM) which has been developed at the U.S. Geological Survey's (USGS) EROS Data Center at 30 arc-second digital elevation model of the world (GTOPO30). Flow directions, slope and aspect have been computed starting from the DEM resampled at a spatial resolution of 5000 m x 5000 m.
The pedologic characteristics for soils are available from the Harmonized World Soil Database (HWSD) [18]. For the Yangtze River basin only three main classes can be identified: the soil texture is predominantly for 94.5 % in the sandy clay loam class, while only 2 % of sand and 3.5 % of clay. From this available basic thematic layer, hydraulic soil parameters required for the application of the hydrological model have been derived using the well known database of [19]. These include: saturated hydraulic conductivity, residual and saturated soil moisture, pore size distribution index, wilting point, field capacity and Brooks-Corey index.

3.3. Vegetation information

The land cover map for the Yangtze River basin has been derived from the ESA Globcover Land Cover which is generated from the 300m MERIS time series for the period between 2005 and June 2006 [20], with 22 land cover types defined according to the UN Land Cover Classification System. Leaf area index (LAI) maps have been retrieved from the MODIS LAI products generated over an 8-days compositing period with a spatial resolution of 1 Km resampled at 5km (http://ladsweb.nascom.nasa.gov/index.html). Images have been taken every sixteen days.

3.4. LST retrieved from satellite images

Land surface temperature is retrieved from MODIS LST daily L3 global 1km sin grid v005. In particular land surface temperature is retrieved from MODIS on board the operative satellites TERRA and AQUA with a spatial resolution of 1 Km in the thermal infrared bands [21]. 170 daytime and nocturnal images of MODIS11 LST products are selected for the whole simulation period from January 2000 to December 2004. The images have been aggregated at the same spatial resolution of FEST-EWB model simulations equal to 5 km.
AATSR data (ATS_NR__2P product) on board ENVISAT have also been used for land surface temperature analysis at the spatial resolution of 1 km. Data have been collected from July 2002 to December 2004, analysing 150 images. ENVISAT images are insufficient to cover the entire period of interest and they have a swath not able to cover the entire basin. The model has than been calibrated with MODIS data.

4. MODEL CALIBRATION ON SATELLITE LAND SURFACE TEMPERATURE

At basin scale satellite images of land surface temperature can give a relevant opportunity to calibrate distributed hydrological model in each pixel of the domain as a complementary method to the traditional calibration with discharge measurements at the few available control cross sections. The methodology for the calibration of soil hydraulic parameters is based on a “trial and error” approach. The procedure can be divided in six steps: 1) FEST-EWB model is run with the configuration with the original soil-vegetation parameters (O-SoVeg), 2) RET is compared with LST from MODIS and statistical parameters, histograms and spatial autocorrelation functions are computed, 3) soil and/or vegetation parameters are modified in order to minimize errors between observed and modelled land surface temperature, 4) simulated and observed cumulated volumes of discharge are compared at available river cross sections and statistical parameters are calculated 5) subsurface flow parameters are modified according to the evaluation parameters 6) FEST-EWB model is run with the new configuration. The procedure is then repeated from Step 2).
The parameters subjected to calibration are: soil hydraulic conductivity, Brooks-Corey index, soil depth, minimum stomatal resistance and kprof.
For the Upper Yangtze River basin, FEST-EWB model is run at hourly time step and with a spatial resolution of 5 km. Among the simulation period from 2000 to 2004, the period from 1 January to 31 July 2000 is considered as a start-up period, due to the fact that initial snow cover condition in the mountains is equal to zero. So the comparison between observed and simulated land surface temperature images and cumulated volumes starts from August 2000.

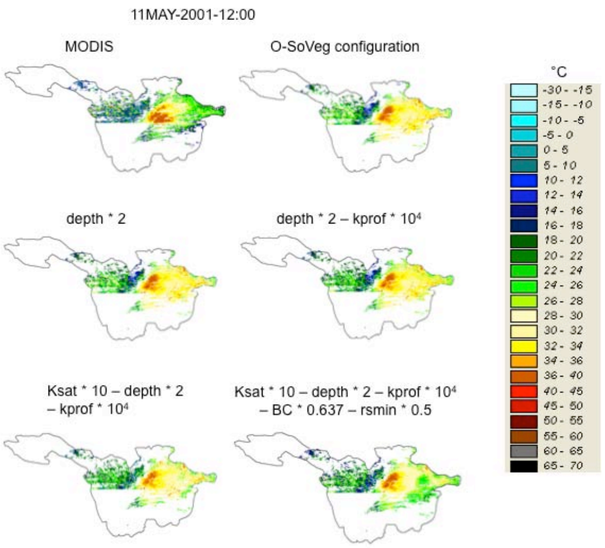

Figure 2. Comparison between LST from FEST-EWB with different parameters calibration and from MODIS

In Fig.2, as example, the RET image for 11 May 2001 at 12:00 is reported for the O-SoVeg configuration as well as LST image from MODIS. The hydrological model clearly overestimates the observed values. In fact if histograms are computed (Fig.3), a discordant distribution of pixels number is found between RET and MODIS LST in each class of temperature. The classes are composed of temperature ranges of 2 °C. MBE and AMBE denote a mean overestimation respectively of 0.4 ° C and 4.5 °C for the entire datasets of 170 images, RMSE is equal to 5.3 °C and the relative error is equal to 18.4 %.

So according to the calibration methodology, the soil hydraulic and vegetation parameters are now modified in order to minimize RMSE, mean difference (MBE) and the mean absolute difference (AMBE) and to maximize the Nash and Sutcliffe index. More than 30 simulations with different configurations have been performed. In particular ksat has been changed multiplying its original valor of O-SoVeg configuration by values between 10^{-2} and 10^{2} m s^{-1}, kprof between 10 and 10^{6}, Brooks and Corey index between 0.1 to 0.8, soil depth between 1.5 and 3 m, rsmin between 0.5 and 2 s m^{-1}.

In Fig.2 and Fig.3, RET images for 11 May 2001 at 12:00 are also reported for some significant simulations showing how land surface temperature is affected by the changes in soil hydraulic and/or vegetation parameters changes. In fact the number of pixels in the different classes changes between the different simulations.

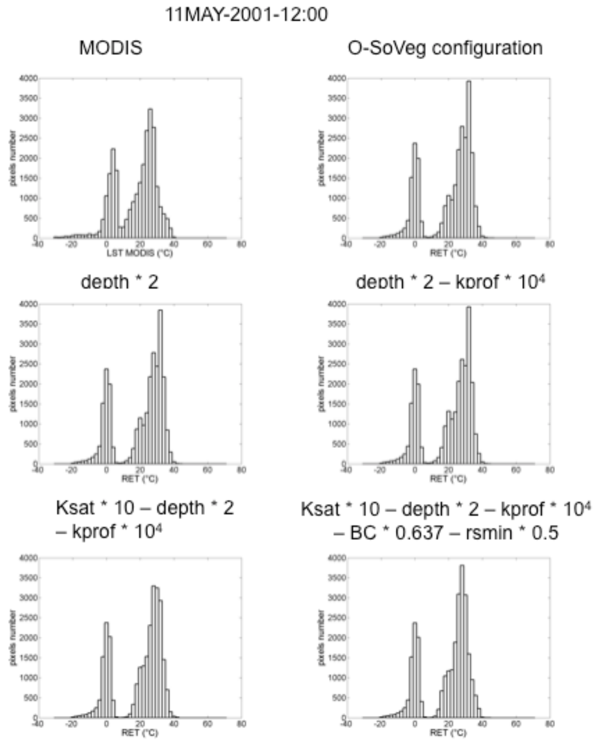

Figure 3. Comparison between LST histograms from FEST-EWB with different parameters calibration and from MODIS

From these analysis performed considering the entire database of satellite images, the parameters that minimize AMBE (0.2 °C), MBE (2.5 °C), RMSE (3.4 °C), RE (8.2 %) and that maximize the Nash-Sutcliffe index (0.63) are: ksat is multiplied by 10^{1}, depth by 2, BC by 0.5, rsmin by 0.5 and kprof by 10^{4}.

4.1. LST comparison with AATSR

LST from MODIS and from the calibrated FEST-EWB model have then be compared to LST from AATSR. In Fig.4 the comparison between LST from MODIS, AATSR and RET is reported for 18 August 2002 at 11:12am. LST from FEST-EWB has a mean temperature of 24.1 °C, with a standard deviation of 5.1 °C; while MODIS LST is on average 2 °C below and LST from AATSR is 2°C higher.

When considering all the 150 selected AATSR images, the mean difference between AATSR and RET is equal to 5.0 °C with a standard deviation of 2.9 °C.

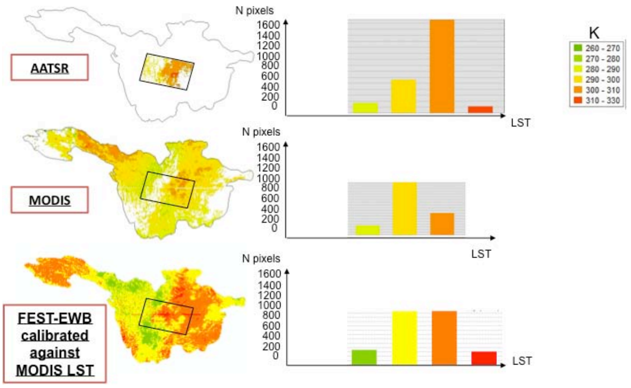

Figure 4. Comparison between LST from MODIS, AATSR and calibrated FEST-EWB model for 18 August 2002 at 1:12am

5. MODEL CALIBRATION ON GROUND MEASURED DISCHARGE

FEST-EWB model has also been calibrated following the traditional methodology well assessed in the scientific community based on the comparison between observed and simulated discharge cumulated volume in river cross section [22]. In particular for the Yangtze River basin the Yichang station has been selected due to availability of observed data only in that cross section.

The main calibration activity is based on the “trial and error” approach which has been used also for the calibration performed with land surface temperature images. The parameters subjected to calibration are the soil hydraulic conductivity, soil depth and kprof. Each simulation is then compared with the observed cumulated volume calculating the quality indices to classify the model reliability. In this framework, negative relative error values for discharge volumes show the model tend to underestimate. Before calibration, the FEST-EWB model tends to underestimate cumulated volume over 4 years and a model improvement can be appreciated along the calibration process. In fact the calibration activity produced a generalised improvement of the model performance in terms of flood volume errors ranging from -77.9 % to -8.7 %. The simulation which minimizes the error on cumulated volume is characterized by the modified soil parameters: ksat multiplied by 10, soil depth by 2 and kprof by 10^4.

These values of ksat, depth and kprof are the same as those reached with the internal calibration performed using LST data from remote sensing. The error on cumulated volume is also computed for the selected simulation after the calibration process performed with LST from MODIS: ksat* 10 – BC * 0. 637 – rsmin / 2 – depth * 2 – kprof * 10^4 and the smaller errors are shown, equal to 3.8 %.

In Fig.7 the observed cumulated volume is shown together with the selected FEST-EWB simulations after the calibrations performed against cumulated volume and against satellite land surface temperature images. The simulation period from 1 January to 31 July 2000 is considered a start-up period, due to the fact the initial snow cover condition is zero; so that statistical parameters are computed starting from 1 August 2000.

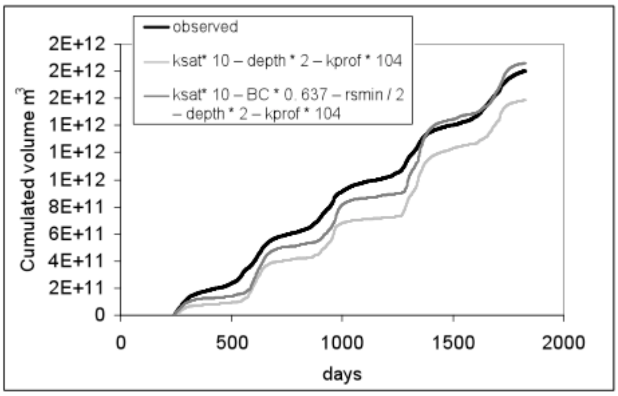

Figure 7. Comparison between observed discharge and simulated from FEST-EWB after the calibration against discharge and LST

7. CONCLUSIONS

A procedure for the internal calibration of a distributed energy water balance model has been presented so that soil hydraulic parameters and vegetation variables are calibrated according to the comparison between observed LST from MODIS and simulated RET minimizing the errors.

For the specific test case of the Upper Yangtze River basin the parameters that minimize AMBE (0.2 °C), MBE (2.5 °C), RMSE (3.4 °C), RE (8.2 %) and that maximize the Nash-Sutcliffe index (0.63) are: ksat is multiplied by 10^1, depth by 2, BC by 0.637, rsmin by 0.5 and kprof by 10^4.

A similar calibration procedure based on a “trial and error” approach between observed and simulated discharges has been tested, leading to different values of soil and vegetation parameters: ksat multiplied by 10^1, soil depth by 2 and kprof by 10^4.

8. REFERENCES

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