An integrated modelling and remote sensing approach for hydrological study in arid and semi-arid regions : the SUDMED programme

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Abstract. Recent efforts have been concentrated in the development of models to understand and predict the impact of environmental changes on hydrological cycle and water resources in arid and semi-arid regions. In this context, remote sensing data have been widely used to initialize, to force or to control the simulations of these models. However, for several reasons, including the difficulty in establishing relationships between observational and model variables, the potential offered by satellite data has not been fully used. As a matter of fact, a few hydrological studies that use remote sensing data emanating from different sources (sensors, platforms) have been performed. In this context, the SUDMED program has been designed in 2002 to address the issue of improving our understanding about the hydrological functioning of the Tensift basin which is a semi-arid basin situated in central Morocco. The first goal is model development and/or refinement, for investigating the hydrological responses to future scenario about climate change and human pressure. The second aim is the effective use of remote sensing observations in conjunction with process models, to provide operational prognostics for improving water resource management. The objective of this paper is to present the SUDMED program, its objectives and its thrust areas, and to provide an overview of the results obtained in the first phase of the program (2002-2006). Finally, the lessons learned, future objectives and the unsolved issues are presented.

Key words: Semi-arid, land-surface interactions, remote sensing, disaggregation, aggregation, snow processes, surface hydrology, ground water hydrology, soil-vegetation-atmosphere model, vegetation growth, irrigation.

1. Introduction

Population growth has resulted in intense demands on the quantity and quality of worldwide water resources. Water shortage is likely to be one of the main pressing problems, resulting from combined effects of alterations in the hydrological cycle, anticipated under climate change, and of increase in water demands for agriculture, urban and industries (IPCC 1998, 2007). The impact of climate change on water resources is potentially greater in worldwide arid and semi-arid regions, where climatic variability has already a determinant effect on water availability, and where competition over water allocation for the needs of growing populations is already acute (USGCRP 1997; WMO 1998; IGBP 1998).

In Southern Mediterranean regions as well as other arid and semi-arid regions in the world, water consumption has significantly increased over the last decades while available water resources are becoming increasingly scarce. The conflict for water in arid and semi-arid regions has led several groups to offer solutions to this problem. Most of them correspond to methods that supposedly enhance precipitation without a solid scientific justification. All of which might be considered examples of inefficiency since they rarely solve the problem while having an elevated economic cost (IRI: http://iri.columbia.edu).

There is a need for developing Climate Change Adaptation strategies that reduces vulnerability to the expected impact on water resources. In this regard, the first step towards developing such strategy is to understand the critical hydrological processes at the basin scale and more importantly to address them in an integrated manner. The development of improved management strategies and viable interventions to meet these challenges that will be accepted by the managers, the policy makers and the public should entail unprecedented coordination and integration across a broad range of disciplines and actors. However, due to the combined effect of shortage of expertise and funding, and lack of a common "culture" between the scientist and the manager/policy making communities, little has been attempted toward the understanding of a basin-wide hydrological functioning, i.e. natural and/or human induced stresses and the consequent hydrological responses to those stresses.

In this regard, a close integration of the individual components of hydrological cycle, i.e., vegetation functioning, surface-water/ground-water interaction, surface/atmosphere interaction is required. Such integration is made difficult by the discrepancy of time-space scales at which each of these processes is pertinent and thus need to be addressed. Further complications are induced by the specificity of the space representation required for each component (Grid versus Hydrological Response Units and Geomorphologic Units for example). Additionally the issue of the degree of complexity required to accurately describe some of the individual processes is scale dependent and varies according to individual processes. Last - but not least-, the hydrology research community is usually structured around individual processes (surface hydrologist, ground water hydrologist, land surface hydrologist, agronomist) which strongly limits the much needed integration.

Remote sensing data have been widely used to initialize, to force or to control hydrological model simulations. However, due to the complexity of the earth-surface system which involved various and interconnected processes, no single waveband can effectively characterise or constraint them. It is thus crucial to use information emanating from several sources (sensors, platforms) in order to achieve an effective control of hydrological models. However, information emanating from different remote sensing sources involves different space-time resolutions. This requires developing and using aggregation-disaggregation algorithms, which is not a trivial task. As for hydrologist, remote sensing community is often structured around a given spectral band (Solar, thermal infrared and microwave specialists). This might explain why the potential offered by satellite data has not been fully used in hydrological science.

Additionally to the use of remote sensing observations, understanding basin-wide hydrological functioning cannot be fulfilled without making a full use of historical data and newly developed technology: Geographic Information System, ground instruments such as scintillometers and isotopic analysis, numerical modelling, and data assimilation. Fortunately, several multi-disciplinary and multi-institutional programs have recently made substantial progresses in pulling together the right combination of expertise and strategy: SALSA (www.ars.usda.gov/salsa/salsahome.html, see Goodrich *et al.* 2000 and Chehbouni *et al.* 2000a for details) and SAHRA (www.sahra.arizona.edu/).
As a follow up to SALSA in the Mediterranean region, the SUDMED program has been designed in central Morocco to help answer the following critical question: how to develop a policy that ensures economic growth and manage water resources in a sustainable manner?

The objective of the present paper is to provide an overview of the SUDMED Program, its general and specific objectives, and the preliminary results obtained during the first phase (2002-2006). The paper is organized as follow. First we present the objectives of the program, as well as the general structure and the thrust areas. Second we present the study site, followed by an overview of the initial results, ongoing and future investigations.

2. Objectives and structure of the SUDMED program

The SUDMED program (Chehbouni *et al.*, 2003 and 2005) was conceived in 2002 by investigators from CESBIO/IRD (Centre d'Etudes Spatiales de la Biosphere/ Institut de Recherche pour le Développement) in a close connection with Moroccan scientists from the University of Marrakech, as well as with local managers, decision makers and other stake holders. The objectives were to understand the integrated hydrological functioning of the Tensift semi-arid basin in Morocco, and to provide guidance to policy makers / stake holders, and tools to mangers for sustainable management of water resources in the basin. The consortium has been enlarged to other include French and other Europeans scientists through two E.U. funded projects (WATERMED AND IRRIMED). The specific objectives of the program are:

- Documenting changes that occurred within the basin during the past 30 years, identifying the different drivers and assess the impact of these changes on water resources in the basin.
- Describing, in an integrated manner, the dominant processes that control the overall hydrological functioning of the basin, by making full use of recent technological and scientific developments (Modelling, Remote Sensing, Geographic Information System (GIS), and Assimilation).
- Providing operational tools to managers while assuring compatibility between levels of technology and the user's ability to operate them.

To achieve the above objectives, the program has been structured into the following thrust areas:

1. Basin characterisation and Geographic Information System development.
2. Snow dynamics, Rainfall – runoff modelling, and surface water – ground water interaction.
3. Basin scale evapotranspiration and vegetation functioning.
4. Aggregation, disaggregation, and data assimilation
5. Education, capacity building and knowledge sharing.

It is worth noting these thrust areas are intimately linked in the context of an integrated hydrological modelling effort: basin characterization is used to document models, remote sensing to drive hydrological simulations, surface and subsurface water flows are connected to evapotranspiration and crop water needs and requirements. Therefore the structure of the program should not be interpreted as a sign of disciplinary border. Integrating processes and individuals were rather a major component of the program's vision.

3. Site description and experimental setup

3.1. Site Description

The study region of the SUDMED program is the Tensift basin in central Morocco (see Fig. 1 for the site location). The size of the basin is 20450 km^2. The basin originates in the High-Atlas mountains and flows west to the Atlantic Ocean. The basin embodies nine sub-watersheds located in the High-Atlas range and the Haouz plain where intensive irrigated districts are located. The altitudes of the sub-watersheds range from 1084 to 4167m. The annual rainfall ranges from around 150 mm in the driest part of the plain to about 1000 mm in the mountains (Fig. 2), while annual potential evapotranspiration in the plain is about 1800 mm. The majority of precipitation occurs during the winter season (November to April). Precipitations may occur as snow on the upper parts of the basin (above 1400m) with more snowfall over northern than southern side. Both precipitation and snowfall patterns depict strong annual to inter-annual variability.

In the plain about 85% of available water is used by agriculture. Major irrigated vegetation types include olive (40% of national production), oranges and wheat. Due to a tremendous expansion of the main city (i.e. Marrakech, which expanded of about 35 % during the past 30 years, Fig.3) as well as of the surface of irrigated zones (increase of about 40% during the past 30 years: Fig. 4), water resource is facing an enormous pressure. This has been translated to an over-exploitation of ground-water (Fig. 5), its level decreases of about 0.5 to 1.5 m a year (Abourida *et al.*, 2003 and 2004). The basin is characterized by a significant topographic and vegetation variation, and a highly variable climate.

Thus, the Tensift basin presents a number of characteristics which make it an exceptional outdoor laboratory for addressing a large number of scientific challenges over arid and semi-arid regions: hydrology, meteorology, ecology, social and policy sciences.

3.2. Experimental setup

To achieve the program's objectives, a comprehensive experimental setup was designed. It includes a basin-wide meteorological network made up of 13 automatic stations that measure incoming radiation, wind speed/direction, air temperature/humidity, and rainfall. In the mountain site a relatively dense network of rain gauges was deployed to capture the spatial variability of the rainfall. Additionally measurements of snow fall and depth, surface runoff were made. Geochemical samplings were performed to provide insight on the interaction between surface water and ground water.

In the plain part of the basin, 8 flux stations (eddy correlation) were deployed over the dominant vegetation types (olives, oranges and wheat) and under different irrigation methods (drip and flooding). A large aperture scintillometer (LAS) measuring sensible heat flux over large surfaces (up to 5 km) was also deployed over transects including olive (2002-2003), wheat (2003 and 2006) and orange (2004) crops. Additionally, surface temperature and net radiation as well as soil moisture, temperature and heat flux were collected over each site. During the 2002 season the olives site was equipped with device to measure sap flow and thus plant transpiration. At the same time isotopic sampling at the surface boundary layer were used to separate soil and vegetation contribution to total evapotranspiration (Williams *et al.* 2004).

Regarding remote sensing data, ground-based surface reflectance and temperature were collected throughout the growing seasons using a hand held radiometer (CROPSCAN Inc. Model MSR87, a 8-band LANDSAT Thematic Mapper compatible model: 460-1750nm). This handheld radiometer is operated through a 3 m-long boom leaning at 45 degrees, which results in a patch of about 2 m^2. Since this instrument measures simultaneously both incoming solar radiation and reflected radiation—using upward and downward sensors—surface reflectance can be measured without a need of a reference panel. Prior the experiment CROPSCAN measurements were checked against data collected using an ASD precision spectroradiometer. Each measurement consisted of 10 points, spaced every 10 m along a fixed transect located accurately using a GPS.

Detailed analysis of surface characteristics were made in order to investigate the possible use of remote sensing sensor at various spatial resolution for their estimation. This was done for example in the case of Leaf Area Index (LAI) in relation to the VALERI program (Weiss *et al.* 2000; Baret *et al.* 2006) or in the case of surface temperature for the validation of satellite products such as AATSR (Noyes *et al.* 2004). The analysis of estimating LAI from NDVI was done by Duchemin *et al.* (2006a) and the possibility of estimating land surface thermal infrared emissivity was done by Olioso *et al.* (2006).

Historical satellite data collected from MSS and LANDSAT over a 30 years period were gathered. Additional time series of SPOT, LANDSAT-TM, ASTER and VEGETATION images have been collected since 2002. In 2006, high spatial and high temporal FORMOSAT-2 satellite data were collected throughout the growing season (Duchemin *et al.*, 2006b). In order to atmospherically correct satellite data collected during SUDMED, a CIMEL sun photometer was installed since 2003.

All these data have been archived and a document describing the experimental setup and the instruments used is being written. Regarding the data policy, beside high resolution satellite data which are covered by copy right, the other data will be available to the scientific community at the end of the program (2010).

4. Preliminary results

In the following section, significant preliminary results associated with each thrust areas mentioned above are provided. The first sub-section deals with data collection for basin characterization to feed a Geographic Information System. The second one is directed toward the understanding of the hydrological functioning of a mountain watershed. The main question that we aimed to address is whether a physically based hydrological model that provides good simulation of streamflow guarantees a realistic representation of intermediate water balance processes such as storage terms (e.g. snowmelt) and lateral flow redistribution (e.g. groundwater flow) ?. In the third sub-section we address the issue of the use of remote sensing data to estimate the flux of evapotranspiration (ET) and the biomass production. Here the main question is about the degree of complexity required to accurately derived ET and vegetation biomass at different space-time scale. In the forth sub-section we address the issue of aggregation and disaggregation. Regarding the aggregation issue the main question is whether one can derive analytical relationships between local and effective (area-averaged) surface parameters by matching the model equations at different scales?. While the disaggregation issue concerns essentially the possibility of using the soil moisture estimated from the Soil Moisture and Ocean Salinity (SMOS) satellite for hydrological application. SMOS will provide estimates of soil moisture at 40 km resolution while major hydrological processes occur at a scale of about 1 km or less. The issue is thus to develop algorithms to disaggregate SMOS based soil moisture from 40 to 1 km.

4.1. Basin characterisation and Geographic Information System development

The main goal of this thrust area is documenting various basin properties to be used for understanding, modelling and monitoring the hydrological cycle. Thanks to the good working relationship established with the different state agencies in the basin, topography, soil type, geological, and groundwater which were stored in different administrations and formats data has been collected and formatted. All these layers of information were included in a Geographic Information System (Cheggour *et al.*, 2004). This system is now used for both research and management operations.

Additionally land-use and land-cover maps have been derived from 8 Landsat-TM images (Simonneaux *et al.* 2006a). However, since these maps need to be updated every year and knowing the cost of high resolution satellite data, effort has been directed toward the development of approach that uses free coarse or moderate resolution satellite data such as SPOT-VEGETATION or MODIS (Benhadj *et al.* 2006). The approach is based on the adaptation of the well known linear unmixing model (see Cardot *et al.* 2004) to the semi-arid region of Tensift Al Haouz. The linear unmixing model was validated on two types of dataset: 1) simulated low resolution data, derived from high spatial resolution images; 2) VEGETATION and MODIS images. The analysis of the result depicted in Figure 6 showed a clear consistency of dominant classes (tree, bare soil , annual vegetation) across the different scales (Landsat-TM and MODIS). Quantitative evaluation was not performed against field data but against the map derived from high spatial resolution time series of Landsat-TM and SPOT-HRVIR images (Benhadj *et al.* 2006).

4.2. Snow dynamics, rainfall – runoff modelling, and surface water – ground water interaction

Dynamics of snow in semi-arid mountains has been poorly investigated despite the fact that snow may represent an important source of water for downstream populations especially in the spring and early summer. In the

Tensift watershed, the High-Atlas range represents the most important “water tower” of the region through liquid but also solid precipitation However, due to prevailing terrain and climatic conditions over the basin, the use of satellite sensor data to monitor snow dynamics is not trivial. Indeed, snow can fall and melt within one week. Under such conditions, appropriate monitoring of snow dynamics requires either dense ground network or space instruments that provide data with both high spatial and high temporal resolutions. The main difficulties are 1/ installing and monitoring a dense ground network is unfeasible because of financial limitations and 2/ satellite data with high spatial and temporal resolutions are not routinely available.

In this context a new approach has been developed that consists of combining data snow index derived by two types of instruments: low spatial and high temporal resolution (VEGETATION) and high spatial and low temporal resolution (LANDSAT-TM). This new approach improves the relationship between snow index and snow area (Hanich *et al.* 2003; Chaponnière *et al.* 2003 and 2005). The method was applied to a series of SPOT-VEGETATION images covering the period 1998 to 2005, over five mountainous watersheds. The temporal snow surface profiles obtained by this method are coherent with the observed downstream precipitation and runoff (i.e., increase in surface runoff in the spring while the precipitation is decreasing). Therefore, the proposed approach is reliable and will be used in the next phase of the program to assimilate snow cover in hydrological model.

In the context of a PhD thesis (Chaponnière, 2005) the hydrological model Soil and Water Assessment Tool (SWAT, Arnold *et al.,* 1993) has been implemented over a mountainous sub-watershed. The result shows although a hydrological model provides accurate estimates of the runoff, it can poorly describe hydrological components. For example, the SWAT total runoff was well reproduced in spite of unrealistic snowmelt parameterisation and unrealistic representation of surface-subsurface interactions. In a related paper, Chaponnière *et al.* (2007) addressed the fundamental problem of the lack of physics in rainfall-runoff models. They also showed that, via geochemical sampling of the river runoff, the groundwater contribution to runoff is quite constant and hardly fluctuates seasonally. In contrast the model simulates several annual variations related to varying soil moisture.

In order to understand surface water – ground water interaction, hydro geochemical characteristics have been analysed for meteoric and groundwater samples of the Tensift basin: ^{2}H, ^{18}O and Total Dissolved Ions (TDI). Objectives were 1/ identifying the main factors controlling the isotopic composition of snow and rainfall, and 2/ assessing runoff contribution to ground water recharge. The study showed the $\boldsymbol{\delta^{18}O - \delta^{2}H}$ relationship for precipitation over the High Atlas is approximately: $\boldsymbol{\delta^{2}H = 8.07\,\delta^{18}O + 13}$, and thus slightly different from the Global Meteoric Line: $\boldsymbol{\delta^{2}H = 8.07\,\delta^{18}O + 10}$ **(*Craig, 1961*)**. Data analysis also revealed the content of groundwater stable isotopes in the

Tensift basin is mainly controlled by the mixing of surface waters from different altitudes. Indeed, groundwater isotopic content mainly results from the recharge process which occurs between 1800 and 2500 Meter Above Sea Level (MASL). This is consistent with our knowledge of the Atlas piedmont, which is characterized by permeable outcrops (Raibi *et al.* 2004).

4.3 Basin scale evapotranspiration, vegetation functioning

4.3.1 Monitoring water transfers between land surface and atmosphere

Several models ranging from the most simple (FAO-56; Allen *et al.* 1998) to the most complex one (i.e. SVAT: Soil Vegetation Atmosphere Transfer) were implemented to estimate the spatio-temporal variability of evapotranspiration. The results show that the physically based SVATs such as ICARE (Merlin *et al.* 2006b; Gentine *et al.* 2007) and Sispat (Boulet *et al.* 2004) provide the best estimates of surface fluxes over all sites, but they required several input parameters which are not routinely available at the appropriate time scale. As most of the physically based SVAT models, ICARE and Sispat include a detailed description of the vegetation water uptake at the root zone, the interactions between groundwater, root zone and surface water, as well as the lateral surface and subsurface flows, are normally neglected, and consequently these models will fail to produce accurate results in areas where such interactions are important (Overgaard *et al.* 2006).

We are therefore faced here with the dilemma about choosing a SVAT model to accurately describe the surfaces fluxes in semi-arid regions. The choice of model in any given situation is a trade-off between 1/ the desirable but incompatible traits of realism and simplicity, and 2/ the quality of available information for forcing and validating (Olioso et *al.* 2002).

For operational purposes, the FAO-56 model was adapted to use satellite based vegetation index (Simonneaux *et al.* 2006a), the results show that despite the simplicity of the model and some theoretical limitation of its parameterisations for the soil water balance, basin scale estimates of ET were reasonable (Figure 7). The map presented in this figure is derived from a time series of 8 LandSat-TM images acquired during the 2002/2003 agricultural season, following a two-step procedure: 1) identification of land use, 2) driving of FAO-56 evapotranspiration model. However, the model was not able to separate soil and vegetation contributions to ET (Duchemin *et al.* 2006a, Er-Raki *et al.* 2007a). Beside this, it appears that FAO-56 method combined with remote sensing data in visible and near-infrared wavelengths alone is not sufficient to accurately estimate water consumption when soil evaporation and stress under full vegetation cover conditions occurred (Er-Raki *et al.* 2006). Additional information such as surface temperature from TIR sensors are required to overcome this difficulty (Boulet *et al.* 2004). In this regard, Er-Raki *et al.* (2007b) developed an approach based on the use of a simple energy balance model in conjunction with ASTER based surface temperature to estimate instantaneous ET values which where scaled up to daily ones before assimilating them in FAO-56. The result shows a clear improvement the seasonal ET estimates.

In the same vein, thermal infrared data has been used in conjunction with a SVAT and assimilation scheme to investigate the possibility of inverting the quantity of irrigation water through the minimization of the distance between observed and simulated surface temperature at the seasonal scale. This is of interest since the much needed ground water extraction volumes can then be derived through a water balance. In this context, Boulet *et al.* (2006) developed an original method using thermal infrared data to estimate time to stress, i.e. the time where the switch between atmospherically limited to surface limited evaporation occurs. The method is based on the difference between measured (actual) surface temperature and potential surface temperature obtained by solving the energy balance equation after setting the surface resistance to its minimal value. This difference was found be a good indicator of time to stress and thus to hydrodynamic soil parameters. Finally a relationship between this difference and the stress factor (ratio of actual to potential ET) has been developed and validated using data collected over wheat fields. However, the problem is high spatial resolution TIR data are not routinely available especially since NASA may cancel TIR bands from future LANDSAT missions. In this context, the scientific community needs to address the issue of disaggregating MODIS or AVHRR based TIR data which is not trivial.

4.3.2 Optimizing water supply for agricultural resources

In the context of linking the water and vegetation resources, the STICS crop model (Brisson *et al.* 2003) has been tested for irrigated wheat crops. The issue was twofold: 1) to identify the best practices in terms of sowing and irrigation time in the Marrakech plain, and 2) to test the possibility of obtaining yields and evapotranspiration maps from the model. Firstly it was confirmed that the model could be used in a semi-arid area and a calibration of the phenology of the main wheat variety cropped in the Marrakech plain has been proposed (Hadria *et al.* 2006a). In this study, we also have compared the case of crop managed with early and late sowing. For the 2003/2004 agricultural season, a set of simulations indicate that the amount of water required to reach potential yield was the double of that of late sowing. Furthermore, it was shown that a significant amount of water (around 50mm) can be saved if the best irrigation schedules were applied instead of the one we observed in the field. These trends should now be confirmed using several decades of climatic data in the perspectives of providing advice to the regional agricultural agency (ORMVAH). Secondly, two methods of coupling the model to remote sensing data have been tested in the objective of analysing the accuracy of some main output variables under various nominal satellite revisit time from 1 day to 15 days (Hadria *et al.* 2006b). The methodology includes the impact of cloudiness (lack of satellite observation) and atmospheric noise. The cloudiness has been simulated using a random number generator trained by a data set collected by 7 automated meteorological stations spread over the Haouz plain. The atmospheric noise is generated using a Gaussian law resulting in 5% error on NDVI value. The results are displayed on figure 8, which show that simulation errors vary according to the targeted variables, the method used to control the STICS crop models – calibration or driving –, and the time interval that separates two successive satellite acquisition. From this figure, it can be noticed that: 1) errors on leaf area index is much larger than errors on evapotranspiration, by a factor 4; 2) the calibration is more accurate and less sensitive to satellite revisit capacity than the driving; 3) the effect of the time between two successive satellite data is significant. This last finding contrasts with the results obtained for yield estimates, for which no significant effects was found for the time interval considered here (1 to 15 days). These results were obtained from simulated data and should be confirmed with the use of actual satellite data. Besides this, we investigated a new method of coupling which consists of using times series of leaf area index derived from remote sensing data for retrieving the main agricultural practices such as sowing, fertilisation and irrigation (Hadria *et al.* 2006c).

The STICS crop model simulates different interactions between agro-environmental conditions and plant physiological processes. Although its performance and accuracy have continuously made progress over the past few years, applications for yield forecasting over large areas have encountered major limitations which are difficult to overcome due to the large number of required parameters compared to the amount of observation available for their identification, as well as the lack of adequate and sufficient input data such as crop calendar, irrigation and fertilisation schedules which have large space variations. In the context of regional application, it may be more useful to have simple model which are able to deal with a strong heterogeneity than complex models that treat the surface as homogeneous. In this context, we have developed a simple model: the "Simple Algorithm For Yield estimate: SAFY) with the objective of representing only the most important processes involved in crop development and growth while maintaining the required parameters to a minimum (Duchemin *et al.* 2005). With this model vegetation growth can be simulated using standard data, i.e. climatic data and satellite imagery in solar wavelengths. The model simulates the increase of the dry above-ground phytomass based on the radiation-use efficiency theory of Monteith, with an explicit simulation of the dynamics of green leaf area index and of the effect of temperature. It has been coupled with a simple soil water balance model adapted from FAO-56 method, with some of the parameters linked to remote sensing data (Duchemin *et al.* 2006a). The transfers of nutriments from the soil to the plant were ignored, since they are not available at regional scale. The impact of nitrogen stresses can be adjusted from leaf area observations through one single parameter, which is named effective light-use efficiency. The first results have shown the good capacity of the model to simulate the dynamics of both vegetation (leaf area index, dry aerial phytomass and grain yield) and soil water status at a field scale (Benhadj *et al.* 2004, Duchemin *et al.* 2005). The model was coupled with time series of leaf area index images derived from SPOT and Landsat-TM images (see Duchemin *et al.* 2006a). This has allowed to derive maps of crop production and of the different terms of the soil water balance on a small irrigated area with wheat as the dominant crop. The example of seasonal irrigation is shown in figure 9. The range of variation (from 50 to 200 mm) is consistent with the irrigation amount distributed on average for the area (140mm), but the maps displays a high intra- and inter-fields heterogeneity. These studies are now in phase of validation and publication. Enhancements of all of these methods describing vegetation functioning are expected from the analysis of the data collected as part of the FORMOSAT-2/Tensift experiment (Duchemin *et al.* 2006b).

4.4 Aggregation, disaggregation and data Assimilation

The SMOS mission which will provide soil moisture map at the nominal spatial resolution of 40km starting 2007 will not be of very much use to basin scale hydrological modelling if this information is not disaggregated to at least 1 km. In this context, Merlin *et al.* (2005, 2006a) developed a novel disaggregation scheme based on the combination of a land surface model (SVAT) and high resolution (1km) information of surface temperature and LAI/vegetation index. The near-surface soil moisture derived from SMOS type data is disaggregated at fine scale and assimilated using an ensemble Kalman filter into a distributed SVAT model. Additionally, since satellite-based meteorological data (notably rainfall) are not currently available at fine-scale, coarse resolution data are used as forcing in both the disaggregation and the assimilation. The results showed the assimilation performs much better once SMOS data is disaggregated before the assimilation) (Merlin *et al.* 2006b).

Finally, the aggregation issue associated with flux estimates over heterogeneous surfaces has been addressed from both theoretical and experimental perspective (Chehbouni *et al.* 2000b). In this regard, Ezzahar *et al.* (2007a) investigated the applicability of the Monin-Obukhov similarity theory (MOST) over heterogeneous terrain below the blending height which the height where the atmosphere became "blend" to characteristics of individual patches of the surface. This is tested using two large aperture scintillometers (LAS), in conjunction with aggregation schemes to infer area-averaged refractive index structure parameters. At grid scale, aggregated structure parameter of the refractive index, simulated using the developed aggregation model, behaves according to MOST. This is important finding since MOST was originally developed for homogeneous surfaces. This aggregated structure parameter of the refractive index was obtained from measurements made below the grid scale blending height, and shows that MOST applies. Therefore scintillometers can be used at levels below the blending height. This is of interest since strictly respecting the height requirements poses tremendous practical problems, especially if one is aiming to derive surface fluxes over large scale. Based on this finding, Ezzahar *et al.* (2007b) showed the scintillometer data when combined with a simple model for deriving available energy can be used to monitor seasonal water consumption over a large transect (Fig. 10).

4.5 Education, capacity building and knowledge sharing

During the course of the first phase of the program (2002-2006), 9 PhD students (6 from Morocco and 3 from Europe) as well as 12 Master students have been working in the context of the SUDMED program; some of them have already graduated. Additionally several training sessions in remote sensing, geographic information systems, and micrometeorology were organized in Marrakech during the course of the program. These training sessions were open for students, young scientists and engineers working for different government agencies partners in the program.

Finally a Decision Support System dedicated to management of irrigation water has been developed. The DSS named "SAtellite Monitoring of Irrigation" (SAMIR) is a tool for irrigation management focusing on the use of remote sensing. Emphasis was put on the ability to incorporate and test many kinds of data used for ET estimation, regarding climate, land cover and phenology, albeit staying in the FAO context. The climate module needs daily values of reference evapotranspiration that can be derived either from climatology, ground stations or from the daily fields of climatic variables produced Moroccan weather forecast model (ALADIN). The land cover module offers to the user a standard map of the plain that was derived through the compilation of several images available for different years to improve its reliability. Finally, the phenology module offers the possibility to use either the standard Kcb profiles from the FAO tables, but the interest of SAMIR is rather to use satellite time series (about 10-12 images each year) to derive Kcb-NDVI relations for all crops of the area. The collaboration with the office in charge of irrigation (Office Régional de Mise en Valeur Agricole du Haouz (ORMVAH), led us to adapt the tool to the needs of the end-users, which became refined along with their takeover of the tool (Simonneaux *et al.* 2006b).

5. Concluding remarks

Substantial results have been obtained during this first phase of the SUDMED program (2002-2006). Regarding mountain hydrology, our study shows that evaluating the performance of a physically based hydrological model by only comparing simulated and observed streamflow is insufficient especially when parameter intercorrelation or compensation effects occurred. To be able to accurately assess the overall performance of a model it is important to verify separately the intermediate processes.

During this phase of the program, several approaches based on the use of remotely sensed data have been used/developed to estimate ET and vegetation growth and dynamics. Our result confirms that physically based models are the most accurate under different conditions. However these models need several input parameters which cannot easily be obtained at the appropriate space-time scale. This makes their use difficult if not impossible at regional scale. However these models have been used to assess the realism of simpler approaches such as SAFY and FAO-56. In this regard, the combination ET estimates from a simple energy balance with the FAO-56 model and an assimilation scheme has led to a substantial improvement of the performance of FAO method. This can be easily explained by the fact that this approach reduces both source of uncertainly in the FAO method, namely Kc through its derivation from NDVI and Ks through the assimilation scheme.

Regarding the disaggregation issue, our results provide a real breakthrough with respect to the use of SMOS data for hydrological modelling. This has been achieved through a clever combination of surface process model and surface temperature and NDVI (LAI) obtained from higher resolution satellite data. In the same vein, the aggregation work leads to two major findings: a- the fact that MOST can be extended to heterogeneous conditions; b- the fact the there is layer bellow the blending height where MOST still holds.

However it should be mentioned that we are far from achieving all the objectives of the program. The second phase of SUDMED (2007-2010) will build up on the achievement of the first phase and it will be directed towards the following tasks:

- The assimilation of remote sensing based snow and disaggregated soil moisture into hydrological model
- The use of low to very low resolution satellite data (VEGETATION, MSG) in conjunction with a desegregation scheme in the TIR to control the water balance in the FAO-56 and other SVAT models.
- The improvement of surface water-ground water interaction through the collect of additional data and model refinement.
- Integrative modelling: the coupling between different components of hydrological cycle.
- To test the impact of plausible scenario in terms of environmental on water resources in the basin through the combination of climate model outputs and possible changes in land use.
- Completing the development of the Decision Support System and delivering it to the end users.

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FIGURE CAPTIONS

Figure 1: Tensift basin location's. The grey line represents the limit of the basin

Figure 2: Spatial variability of rainfall over the basin

Figure 3: The extension of the city of Marrakech since 1975

Figure 4: Changes in irrigated surfaces since 1975

Figure 5: Variation of the water table level between 1986 and 2002 (no measurements available in the grey areas)

Figure 6: Maps of land cover proportions predicted using the simulated 250 m data (column 1), predicted using MODIS data (column 2), and estimated from a validation land cover map derived from data at high spatial resolution (column 3). The region of interest (coloured areas) is a part of the Tensift/Al Haouz plain covering about 35x60 km^2; areas outside the region of interest (Jbilet hills at North and Atlas foothills at South) are masked in black, as well as the rectangular area used as a training set for disaggregating moderate spatial resolution (250 m) data.

Figure 7: Evapotranspiration estimates at the Haouz plain derived through the combination and FAO-56 method and satellite based vegetation index from 8 LANDSAT-TM images.

Figure 8: Mean percentage error on leaf area index (top) and on actual evapotranspiration (bottom) for simulations controlled with remotely-sensed data using 2 methods and various time revisit (from 1 to 15 days). Each symbol corresponds to an average of 25 scenarios of cloudiness (after Hadria *et al.* 2006b).

Figure 9: Seasonal irrigation water retrieved by coupling remote sensing data and crop modelling. The map displays estimates of water irrigation accumulated through the 2002/2003 agricultural season for wheat crops over a 3x3 km^2 area. The coloured areas are wheat crops, for which the seasonal irrigation is indicated in mm. The black areas indicate either other crops or roads/irrigation channels between wheat fields".

Figure 10: Comparison between observed and simulated daily values over an oliveyard site during the 2003-2004 season (after Ezzahar *et al.* 2007b).

Figure 1

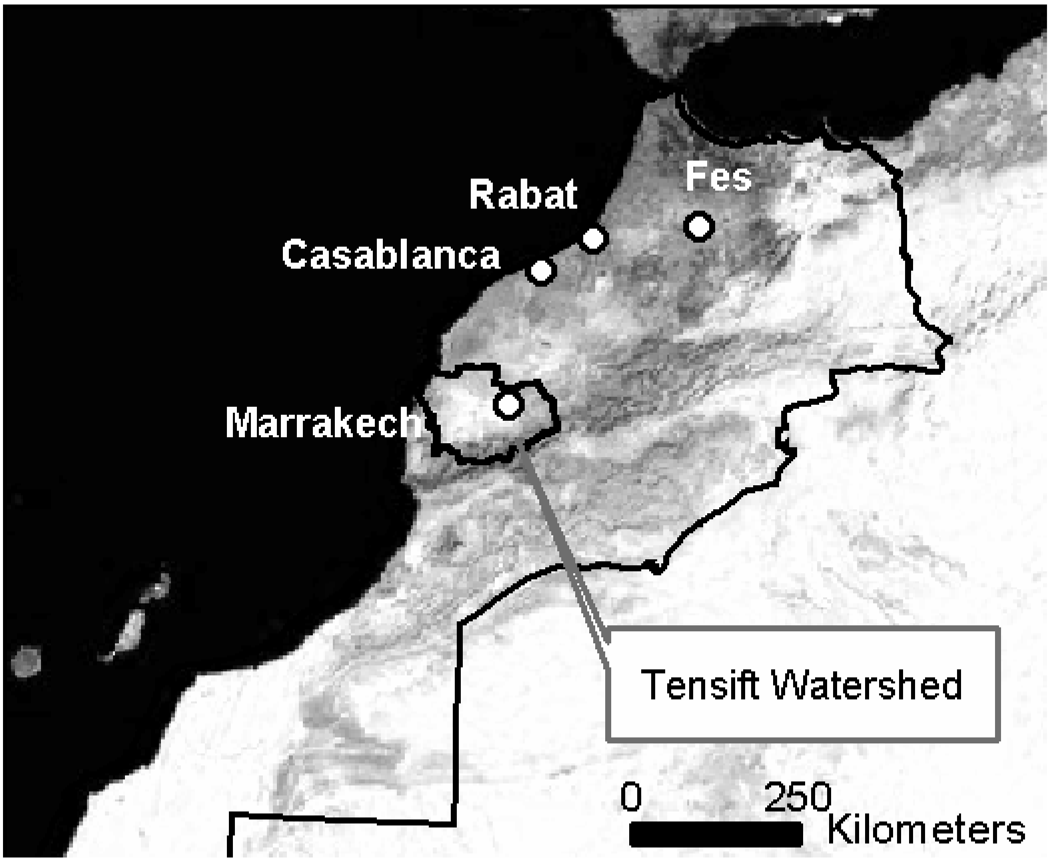

Rabat
Fes
Casablanca
Marrakech
Tensift Watershed
0
250
Kilometers

Figure 2

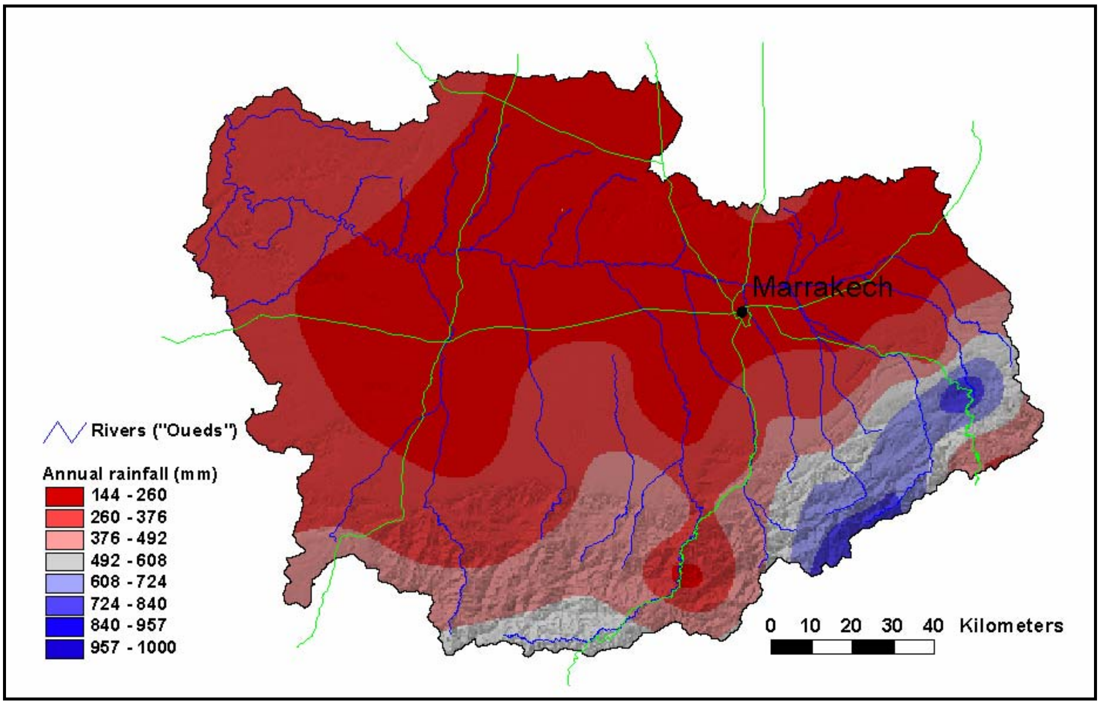

Marrakech
Rivers ("Oueds")
Annual rainfall (mm)
144 - 260
260 - 376
376 - 492
492 - 608
608 - 724
724 - 840
840 - 957
957 - 1000
0 10 20 30 40 Kilometers

Figure 3

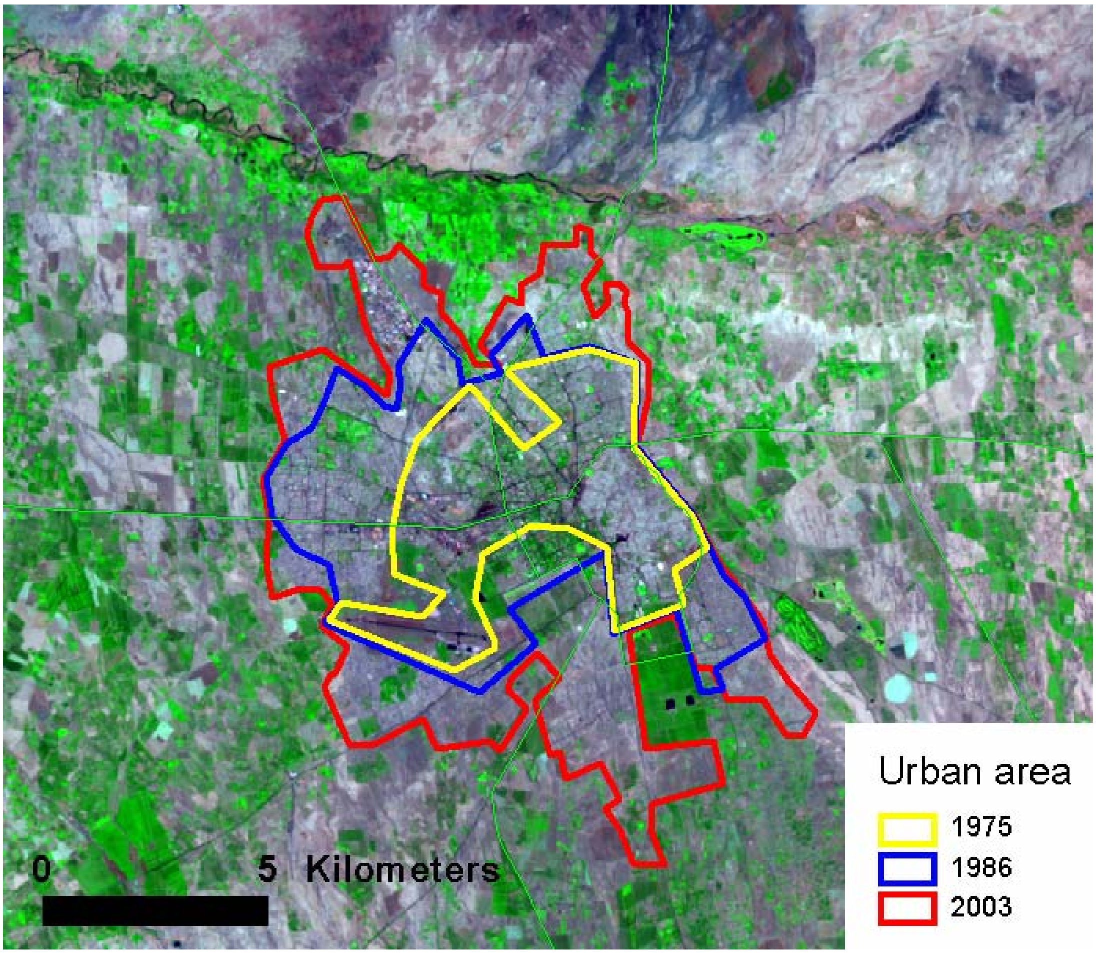


Figure 4

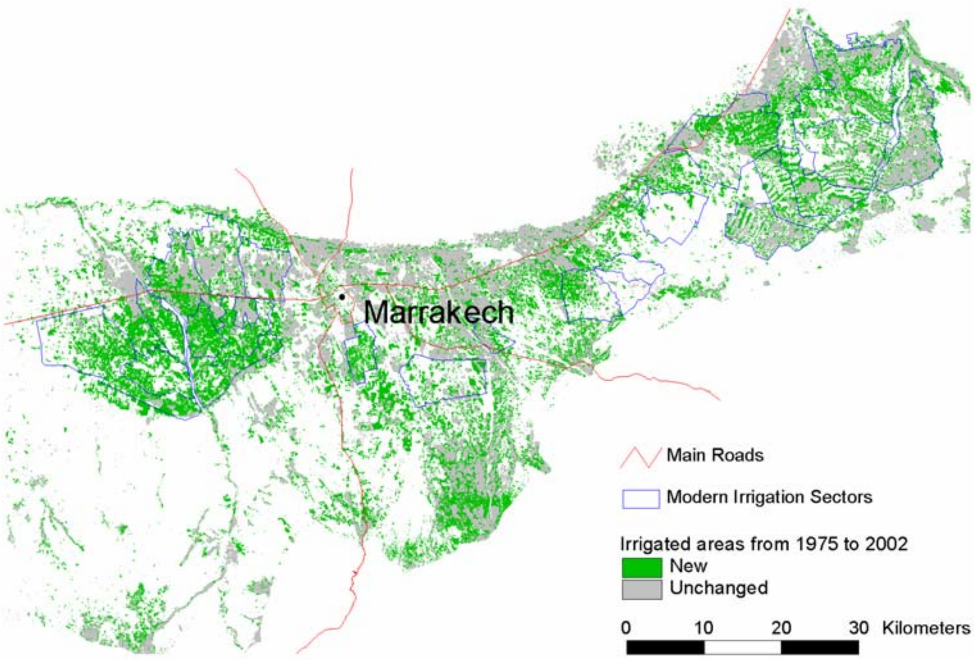

Marrakech
Main Roads
Modern Irrigation Sectors
Irrigated areas from 1975 to 2002
New
Unchanged
0
10
20
30
Kilometers

Figure 5

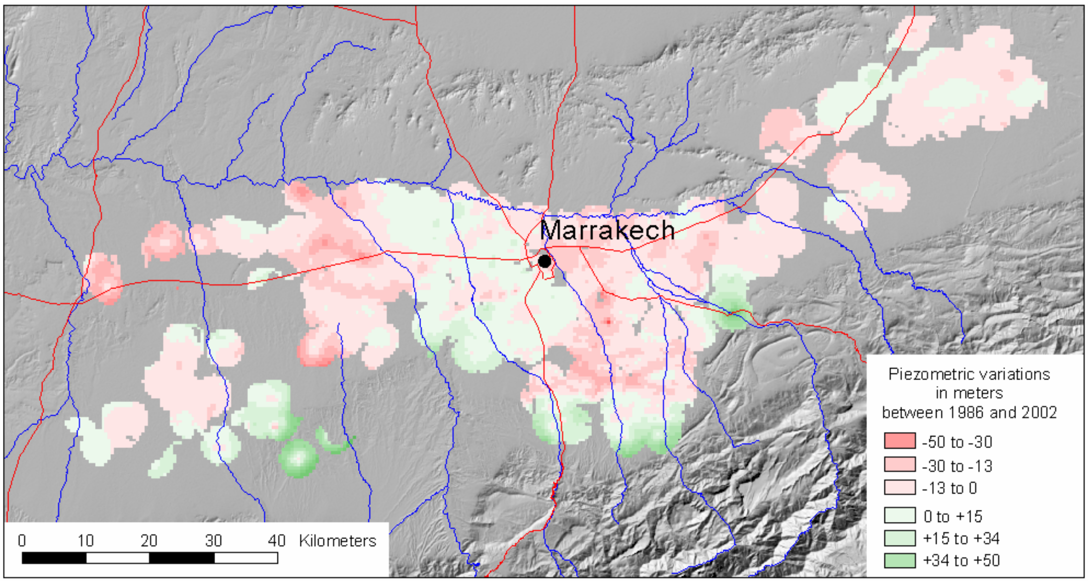
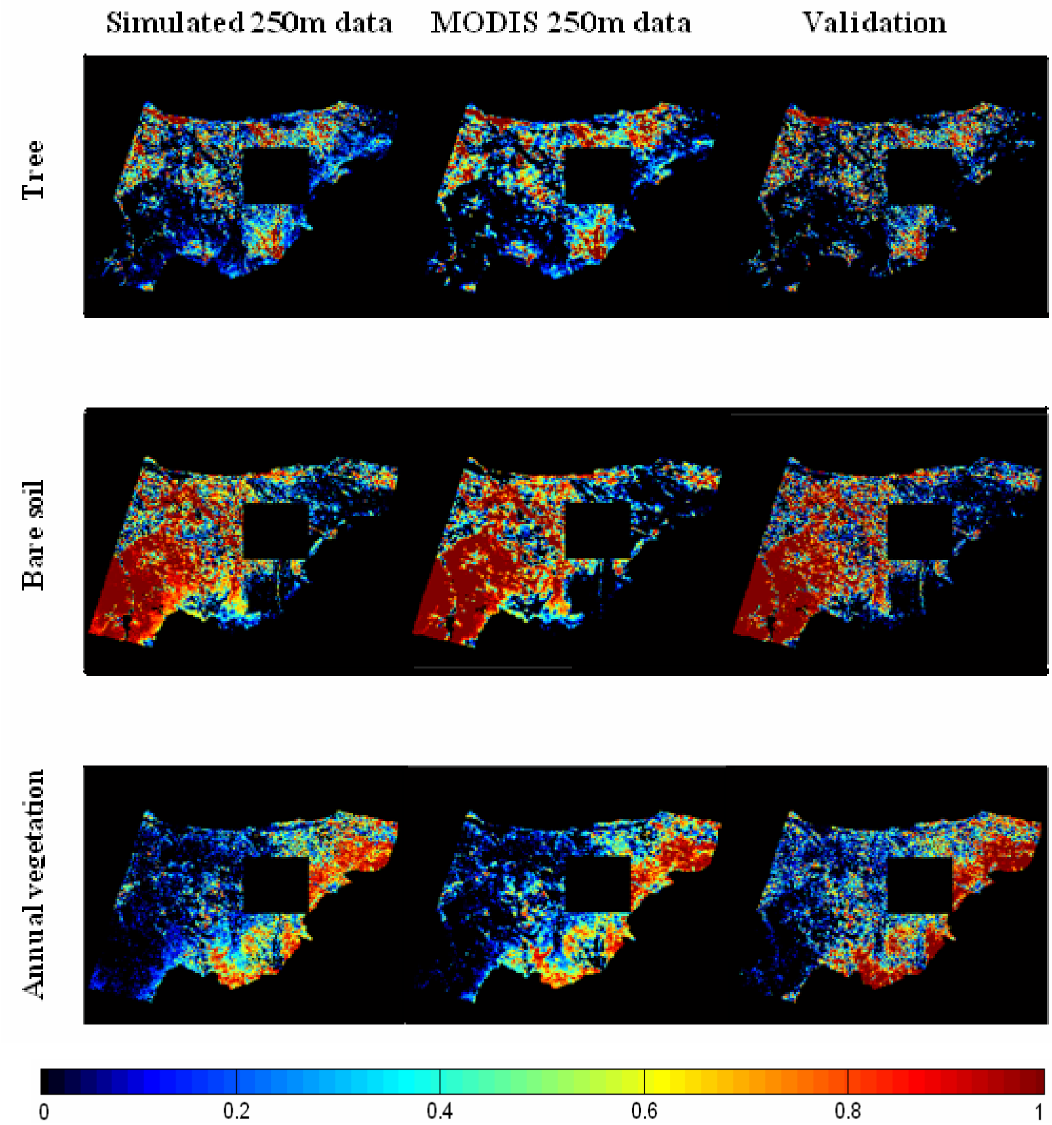

Marrakech
0
10
20
30
40
Kilometers
Piezometric variations
in meters
between 1986 and 2002
-50 to -30
-30 to -13
-13 to 0
0 to +15
+15 to +34
+34 to +50

Figure 6



Simulated 250m data
MODIS 250m data
Validation
Tree
Bare soil
Annual vegetation
0
0.2
0.4
0.6
0.8
1

Figure 7

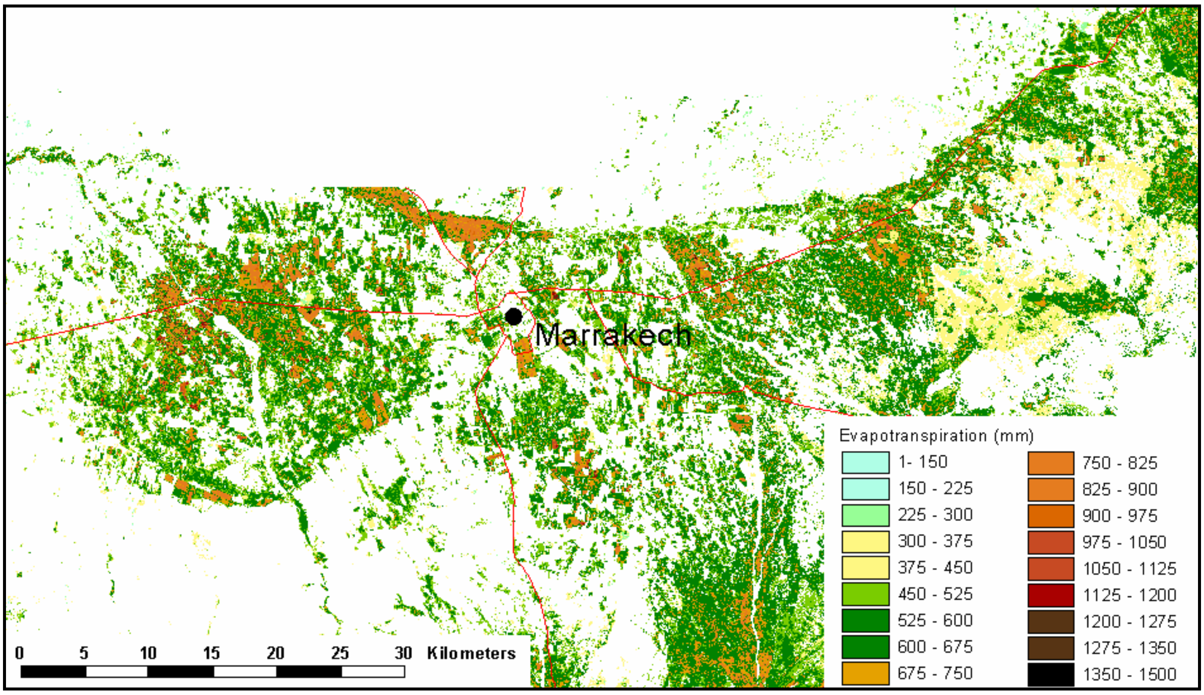

Marrakech
0 5 10 15 20 25 30 Kilometers
Evapotranspiration (mm)
1- 150
150 - 225
225 - 300
300 - 375
375 - 450
450 - 525
525 - 600
600 - 675
675 - 750
750 - 825
825 - 900
900 - 975
975 - 1050
1050 - 1125
1125 - 1200
1200 - 1275
1275 - 1350
1350 - 1500

Figure 8

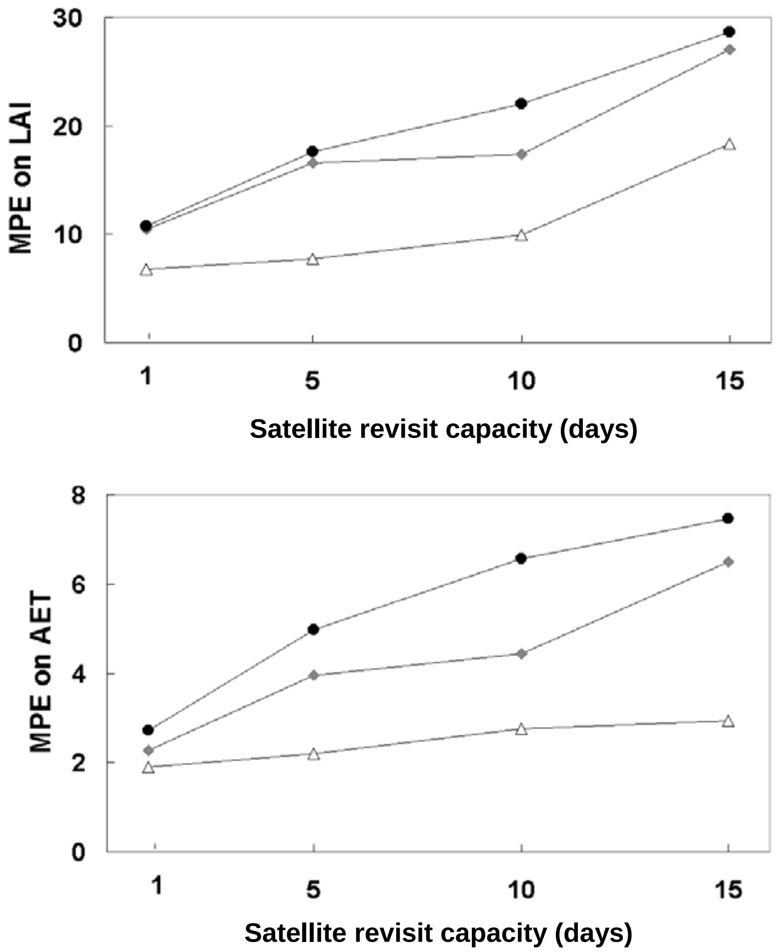

30
20
10
0
MPE on LAI
1
5
10
15
Satellite revisit capacity (days)
8
6
4
2
0
MPE on AET
1
5
10
15
Satellite revisit capacity (days)

Figure 9

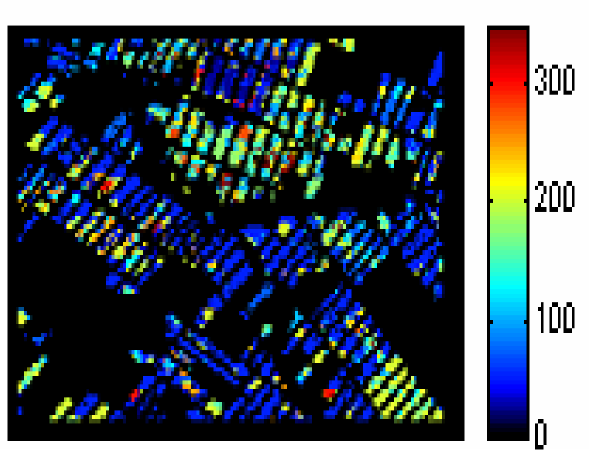
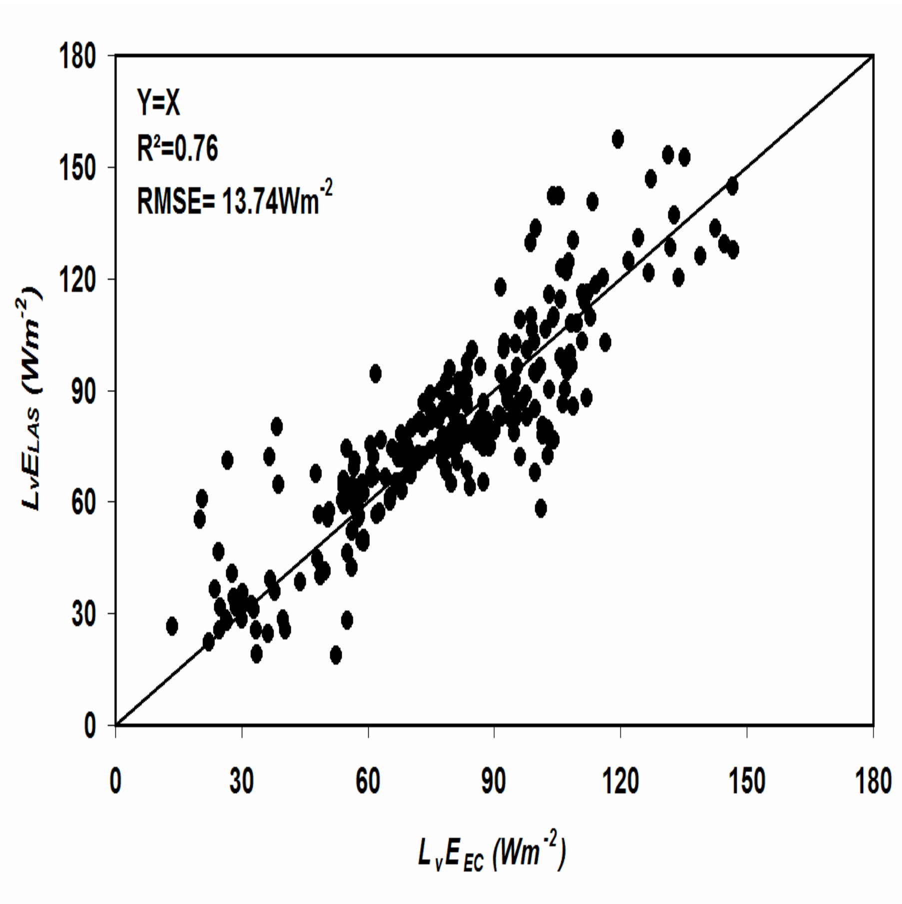


Figure 10



Y=X
R²=0.76
RMSE= 13.74Wm-2
LvELAS (Wm-2)
LvEEC (Wm-2)
0
30
60
90
120
150
180