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Assessing Evapotranspiration and Drought Stress over a Semiarid Agricultural Area in Algeria with Rs Data

Abderrahmane Hamimed, Mansour Zaagane,
Abdelkader Khaldi, Habib Azzaz and Ahmed Toufik Oualid

Laboratory of Research on Biological Systems and Geomatics, Mascara University, Mascara, Algeria

Abstract: The quantification of evapotranspiration from agricultural areas is important for agriculture water management, especially in arid and semiarid regions where water deficiency is becoming a major constraint in economic welfare and sustainable development. Remote sensing based energy balance models are presently most suited for estimating evapotranspiration at both field and regional scales. In this study, METRIC (Mapping EvapoTranspiration at high Resolution with Internalized Calibration), a remote sensing of spatializing, has been applied for the estimation of actual evapotranspiration in the Ghriss plain, a semiarid region in Algeria with heterogeneous surface conditions. Eight images acquired by the Lansat-7 satellite on 2002 were used. The METRIC model followed an energy balance approach, where evapotranspiration is estimated as the residual when the net radiation, sensible heat flux and soil heat flux are known. Different moisture indicators derived from the evapotranspiration were then calculated: evaporative fraction, Priestley-Taylor parameter and surface resistance to evaporation. These calculated indicators facilitate the quantitative diagnosis of moisture stress status in pixel basis. The obtained results concern the validation of the used model for spatial distribution analysis of evapotranspiration and moisture indicators. The evaluation of evapotranspiration and surface energy fluxes are accurate enough for the spatial variations of evapotranspiration rather satisfactory than sophisticated models without having to introduce an important number of parameters in input with difficult accessibility in routine. In conclusion, the results suggest that METRIC can be considered as an operational approach to predict actual evapotranspiration from agricultural areas having limited amount of ground information.

Key words: Evapotranspiration · Drought · Energy Balance · Metric · Remote Sensing · Algeria

INTRODUCTION

Agriculture is a human activity subject to climatic risks. Extreme climate phenomena such as hail, early and late frost, excessive rain and flooding represent a threat to agricultural production of a country. However at large scale, no phenomenon is more devastating than drought. Now more than in the past, irrigated agriculture management is conscious of the necessity of an optimal use of irrigation water. The interest in such rational management is obvious in agricultural, socio-economic as well as in ecological. Rational use of irrigation requires development of reliable and sensitive techniques for detection of canopy moisture stress. Currently, one of the most pertinent techniques is the infrared radiothermometry: the canopy temperature is in fact a good indicator of its evapotranspiration rate. The development of remote sensing (RS) techniques opened new perspectives for the use of these techniques to estimate evapotranspiration, evaluate soil moisture budget and detect canopy water stress. Evapotranspiration is one of the fundamental processes controlling the equilibrium of our planet. It constitutes the link between the hydrological and energetic equilibrium at the soil-vegetation-atmosphere continuum and its knowledge is crucial for climatic and agrometeorological studies.

Furthermore, the estimation of actual evapotranspiration, using visible and infrared satellite remote sensing data, has been at the centre of several methodological approaches during the thirty last years [1]. The deterministic models based on more complex

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Corresponding Author: Abderrahmane Hamimed, Laboratory of Research on Biological Systems and Geomatics, Mascara University, Mascara, Algeria. E-mail: hamimed@univ-mascara.dz.

models such as Soil-Vegetation-Atmosphere Transfer models (SVAT) [2] are mainly used for estimating evapotranspiration, surface energy exchanges and water balance. Most of the transfer mechanisms (radioactive, turbulent and water transfers) and some physiological processes (photosynthesis, stomata regulation) are described. Their time resolution is less than one hour in agreement with the dynamic of atmospheric and surface processes. These models are however more cumbersome and use many parameters which are difficult to measure and make them unsuitable to spatial integration in models that are very sensitive to such parameters. From an operational point of view, we prefer using semi-empirical algorithms that express the convective flux through simple relationships. In most cases, these algorithms have been developed for determining instantaneous or daily evapotranspiration. The "simplified" semi-empirical relationship has allowed expressing the daily actual evapotranspiration based on the difference between the midday surface and air temperature difference [3]. The advantage of these relationships is to avoid three problems: 1) the estimation of the roughness length (involving in the sensible heat flux), 2) the lack of continuous measurement of surface temperature and 3) the estimation of the soil heat flux which is negligible on daily timescales. However, it has limitations related to poor spatial representativeness of air temperature, measured locally and the difficulty of taking into account the surface heterogeneity. To take into account the fraction of vegetation cover in interpreting thermal infrared measurements, Gillies *et al*. [4] proposed a so-called "Triangle" method in which they exploit the dimensions of a triangle resulting from the correlation between vegetation index and surface temperature, highlighting the potential of this approach in estimating of evapotranspiration. Another possibility to estimate evapotranspiration is the use of so-called "residual" method, in which the latent heat flux is derived as the residual term of the energy balance equation. The implementation of these methods often requires additional information (weather, land use, vegetation height, etc.) at time of satellite overpass.

METRIC (Mapping EvapoTranspiration at high Resolution with Internalized Calibration) [5] is considered as a residual model. It was developed to solve the energy balance equation using minimum ground data and with a spatial approach assuming the existence of sites in extreme water conditions (very dry and very wet). Properties from these sites are used to determine some variables at the soil-vegetation-atmosphere interface not possible to obtain through remote sensing. In addition, this model offers the characteristic of using the hourly reference evapotranspiration in the calculation of the evaporation fraction, making it the model best suited under conditions of strong local advection that characterize the semiarid regions in Algeria.

The overall intent of this study is to explore means for obtaining evapotranspiration maps for irrigated areas in Algeria, where ground data are scarce and hard to collect. A remote sensing approach is required to be routinely applied as a tool for providing both historical and near-real time evapotranspiration and surface energy fluxes for performing a better management of the agricultural water resources of the area. For this purpose, we use in this study data from Landsat ETM+ satellite to develop a methodology based on the METRIC model for estimating evapotranspiration and monitoring canopies water stress through the surface energy balance equation.

MATERIALS AND METHODS

The Study Area: The study area selected for our application is located in the N-W of Algeria, three kilometers away in the south of the town of Mascara, between longitudes 0° 4' 33" E et 0° 18' 5" E and latitudes 35° 14' 58" N et 35° 23' 10" N. It covers an area of 172 km^2 (Fig. 1).

The selected area belongs to the Ghriss plain; which is a flat expanse of a surface of 550 km^2 and of an average altitude of 470 m, overhung by reliefs of elevated border up to 1100 m in the South (Nesmoth Mountain). The lands outcropping are from sedimentary formation with variable texture, consisting mainly of recent and ancient alluvions. Soils are mostly of calcimagnesic type, but sometimes one meets isohumic soils and poorly evolved soils. The northern limit of the plain is distant from the Mediterranean Sea of about 50 km and its southern boundary is located at a hundred kilometers of the Saharan Atlas. Therefore, it is found submitted to Mediterranean and Saharan influences. The latter are clearly predominant due to the screen formed by the mountains of Beni-Chougrane in the North [6]. The study area is characterized by a semi-arid climate and recurrent drought. Two main periods characterize this area, a rainy and dark period during the months of November to April and another dry and hot period during the months of May to September. Winter (from December to February) is usually cold enough. The absolute minimum of the air temperature descends to -4°C. Summer (from June to August) is usually hot and dry. The absolute maximum of

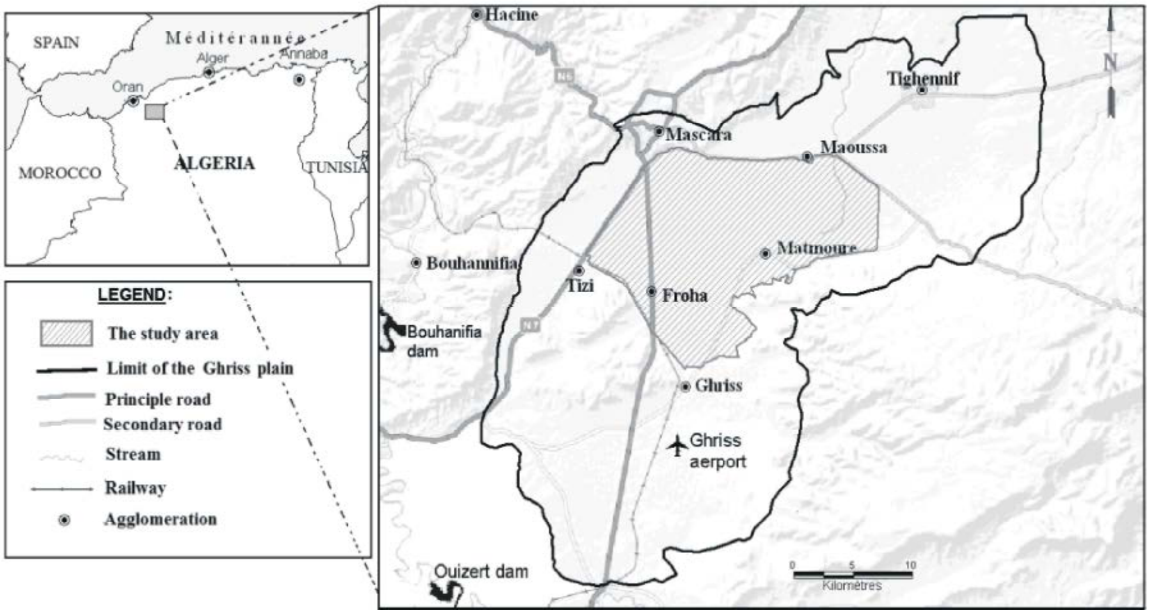

Fig. 1: Location of the study area

Table 1: Landsat 7-ETM+ images used in this study

(Path/Row)	Acquisition Date	Acquisition time (GMT)	DOY	Solar elevation (degree)
198/35	27/01/2002	10h27'	27	30.6
197/36	05/02/2002	10h21'	36	32.8
198/35	12/02/2002	10h27'	43	34.7
197/36	25/03/2002	10h21'	84	49.3
198/35	17/04/2002	10h27'	107	57.4
197/36	26/04/2002	10h21'	116	60.1
198/35	19/05/2002	10h27'	139	64.9
197/36	17/07/2002	10h20'	196	64.4

the air temperature is equal to +42 °C. Thermal maxima are accentuated by the sirocco, a hot drying wind from the South. Rainfall is concentrated during the cold period. The average annual rainfall for the period 1922-1989 oscillates between 300 and 600 mm, with an interannual average of 420 mm [6].

The study area is characterized by its significant agricultural potential, since more than 90% of its total area is currently used for agricultural activity. The land use is quite diverse, however, with a predominance of irrigated agriculture, mainly represented by the truck farming which covers about 70% of the total area of ??the study area. The forage crops, cereal crops and arboriculture are complementary. Groundwater, which is the main source of irrigation water supply, is mobilized by the Ghriss aquifer system. The latter takes the form of a superposition of three layers: the Quaternary alluvial aquifer, the aquifer of dolomitic calcareous of Pliocene and the aquifer of the lacustrine calcareous of Jurassic.

Used Data: The remote sensing data set used in this study consists of eight spectral bands of the Landsat-7 ETM+ (Enhanced Thematic Mapper Plus) sensor acquired on 2002 (from January, 7th to July, 15th) (Table 1).

Remote sensing data are completed by field measurements that were performed on a one point located in the experimental site of the agronomy department of University of Mascara. This point was located on wheat plot. These measurements were intended for the daily monitoring of energy fluxes at the soil-plant-atmosphere continuum [7]. They correspond to the radiometric surface temperature, the reflected radiation and the three components of surface energy balance, i.e. soil heat flux (G), sensible heat flux (H) and latent heat flux (LE). Global incoming solar and thermal radiations were measured on a meteorological station located in the study area using a pyranometer and a pyrgeometer, respectively. The meteorological station also provided measurements on the reference variables which are the air temperature, air humidity, wind speed, air pressure, insolation duration and daily potential evapotranspiration. On the experimental device, installed on the wheat plot, the albedo was given by the ratio of the reflected radiation (measured by an Apogee pyranometer (model MP-200) and the global incoming solar radiation. The net radiation (Rn) is assessed by the equation of radiative balance depending on the albedo, the global incoming solar and thermal radiations and the surface emission which is deduced from the radiometric surface temperature. The latter is measured by an Apogee infrared radiometer (IRTS-P model). The soil heat flux (G) is measured using Hukseflux conductive flux plates (HFP01SC model) installed at 5 cm depth in the soil. Sensible and latent heat fluxes were computed from two levels measurements of temperature and relative humidity (0.5 and 2.5 m above the surface) using the Bowen ratio method.

METRIC Model: To access the evapotranspiration, the METRIC model is based on the estimation of the latent heat flux (LE) through the energy balance equation:

$$Rn = G + H + LE \qquad (1)$$

This equation expresses the partition of the net radiation (Rn) between soil heat flux (G), sensible heat flux (H) and latent heat flux (LE), corresponding to evaporation for a bare soil and transpiration for vegetation canopy.

The net radiation is found from the various components of radiation exchanges:

$$Rn = (1 - r)\cdot Rg + L_d - L_u \qquad (2)$$

where Rg is the incoming global radiation, partly reflected depending on the albedo r, L_d and L_u are the downwelling and the upwelling long wave radiation, respectively.

The soil heat flux G is empirically estimated using the expression suggested by Bastiaanssen *et al.* [8]:

$$\frac{G}{Rn} = T_o(0.0038 + 0.0074 \cdot r)\,(1 - 0.98 \cdot NDVI^4) \qquad (3)$$

involving albedo, vegetation index, surface temperature and net radiation.

The sensible heat flux H is heat energy transferred between the surface and air when there is a difference in temperature between them. It is expressed as a function of the difference between the surface aerodynamic temperature (T_{aero}) and the air temperature (T_a) as:

$$H = \frac{\rho.Cp}{r_{ah}}(T_{aero} - T_a) \qquad (4)$$

This expression involves (outside constants ρ and Cp, air density and specific heat, respectively) the aerodynamic resistance to heat transport rah which is a function of wind velocity, thermal stability effects of the atmosphere and surface roughness.

In METRIC, the sensible heat flux is estimated without the need to know T_{aero} and T_a, not possible to obtain through RS data, instead a temperature difference dT between the two near surface heights z_1 et z_2 (generally 0.1 and 2 m) which is function of T_o as:

$$H = \frac{\rho.Cp}{r_{ah}}dT \qquad (5)$$

r_{ah} is estimated between the two near surface heights z_1 et z_2 (generally 0.1 and 2 m, respectively) using a wind speed extrapolated to some blending height (~200m) above the surface and an iterative procedure for correcting atmospheric stabilities to heat and momentum transfer, based on the Monin-Obukhov's similarity theory.

The difference dT between the two near surface heights 0.1 and 2 m is approximated by a simple linear function:

$$dT = a \cdot T_o + b \qquad (6)$$

The coefficients a and b of this function are empirically determined using the properties of pixels in extreme water conditions (hot/cold and dry/wet). These pixels are identified on the image by analyzing the relationship between the vegetation index and the surface temperature according to the triangle method [9]. The dry pixels are indicated at bare soils (NDVI values close to zero) having high surface temperature. However, the wet pixels are indicated at fully vegetation (NDVI >0.7) having low surface temperature.

With the identification of dry and wet pixels, we can evaluate the sensible heat fluxes for dry pixels (H_d) and wet pixels (H_w) from the energy balance equation as follows:

$$H_w = (Rn - G)_w - LE_w \qquad (7)$$

$$H_d = (Rn - G)_d - LE_d \qquad (8)$$

The dry pixel is characterized by a zero latent heat flux (LE_d=0). Therefore, LE of wet pixels (LE_w) is set to 1.05 times more than that of reference tall grass by assuming that these pixels have an evapotranspiration rate 5% higher than that of reference grass.

By inverting the equation (5), H_d et H_w values allow deducing the difference dT between the two near surface heights 0.1 and 2 m. The coefficients a and b of equation (6) are determined by fitting a line through the two pairs of dT and T_o values corresponding to dry and wet pixels.

The use of equation 6 enables us computing the sensible heat flux in pixel basis and solving the energy balance equation. This step leads mapping the latent heat flux. This should help interpreting accurately the behaviour of a surface with respect to water stress [8]. It is therefore preferable for an easier interpretation to deduce moisture indicators such as reference evaporative fraction (EF_{ref}), Priestley-Taylor parameter (α) and the surface resistance to evaporation (r_s).

In METRIC, the instantaneous latent heat flux, obtained by equation 1, is converted to hourly evapotranspiration ET_{hor} (in mm/h) according to:

$$ET_{hor} = \frac{3600}{\rho \cdot \lambda}.LE \tag{9}$$

where λ is the latent heat of vaporization of water (≈2, 45×10^6 J/kg at 20°C).

The reference evapotranspiration fraction (EF_{ref}) is expressed as the ratio between ET_{hor} and ET_r which is considered similar to its daily counterpart. It is generally used to estimate the daily actual evapotranspiration taking into account the effect of the horizontal advection.

RESULTS AND DISCUSSION

Through modelling the energy balance equation with METRIC, it has shown that the basic parameters (albedo, vegetation index and surface temperature) obtained from the satellite imagery leads to determine the latent heat flux (LE) as the residual term of this equation.

The albedo was derived from a combination of reflectance in the short wavelengths bands. It varies for canopy on the image between 0.15 and 0.19, which seems acceptable [7].

The surface temperature was calculated from the radiance in the thermal infrared band using the vegetation index for estimating surface emissivity.

Indeed, surface temperature is indirectly linked to the latent heat flux (LE) through the energy balance equation [3]. It provides important information on surface water status. The analysis of correlation between T_o and LE shows a strong dependence between these two variables (r=-0.945). However, the NDVI and albedo, although they provide interesting information in interpretation of thermal data [4], are less significant in the discrimination of surface water status.

The latent heat flux (LE) which is the energy consumed by evapotranspiration is generally high for dense canopy and low for dry bare soils having high surface temperatures, low net radiations and high sensible heat fluxes. Table 2 summarizes the results of energy fluxes and moisture indicators (evaporative fraction EF_{ref}, Priestley-Taylor parameter α and the surface resistance to evaporation r_s) obtained for the different land use categories. It shows that high values of evapotranspiration (LE) are observed on the irrigated areas with dense vegetation, while low values are on the bare soils, corresponding to high values of albedo. This allows emphasizing that the spatial distribution of METRIC-derived evapotranspiration is correlated to the water regimes of the different land use units.

In Fig. 2, daily actual evapotranspiration for the different images used in this study varies between 0 and a maximum of 10.8 mm with a clear dominance of surfaces subject to water stress more or less strong. However, the optimal water condition is only observed on the images for DOY 107 and 116, because of the substantial rainfall quantities that preceded the acquisition date of these images.

The estimated evapotranspiration should be considered with caution and have only a relative value, because there is no method of validation over wide scales of time and space [9]. However, the used approach gave maximum values of the actual daily evapotranspiration which is close than the daily evaporation measured by the Piche evaporimeter.

Another method can be used for validating the obtained results. It is to compare latent heat flux values obtained by METRIC from the image with those estimated on the ground using Bowen ratio [7]. The result of this comparison is shown in Fig. 3. It shows a significant discrepancy between remote sensing and ground estimates of latent heat flux, with a RMSE about 36.1 W.m^{-2} (corresponding to 15.91% in relative value) and a determination coefficient of 0.87, that was ascribed to inaccuracies on the intermediate variables such as surface emissivity, soil heat flux, roughness length and air temperature.

Table 2: Variation of surface energy fluxes and moisture indicators with land use in the Ghriss plain for DOY 27, 36, 116 and 196

Satellite image date	Land use category	Rn	G	H	LE	EF_{ref}	α	r_s
27/01/2002 (DOY 27)	Bare soil	226.03	22.41	71.72	131.89	0.64	0.82	193.42
	Sparse vegetation	250.04	20.37	43.88	185.78	0.80	1.10	81.36
	Moderate Vegetation	268.36	17.25	23.59	227.51	0.90	1.39	49.56
	Dense Vegetation	266.41	13.97	13.79	238.64	0.94	1.60	41.24
	Very dense Vegetation	259.61	11.37	9.04	239.195	0.96	1.74	31.77
05/02/2002 (DOY 36)	Bare soil	302.75	34.87	142.19	122.04	0.46	0.66	570.48
	Sparse vegetation	309.88	32.50	108.85	165.60	0.60	0.84	252.24
	Moderate Vegetation	321.13	28.63	74.78	215.45	0.74	1.14	141.68
	Dense Vegetation	326.34	23.04	43.31	258.29	0.85	1.44	73.13
	Very dense Vegetation	326.05	18.11	25.07	281.55	0.91	1.60	47.29
26/04/2002 (DOY 116)	Bare soil	421.07	94.31	189.40	137.36	0.41	0.54	792.50
	Sparse vegetation	459.13	92.15	131.64	235.33	0.63	0.67	234.57
	Moderate Vegetation	514.99	81.46	52.92	380.60	0.87	0.99	57.22
	Dense Vegetation	536.84	67.34	26.07	443.42	0.94	1.17	48.24
	Very dense Vegetation	539.48	53.15	15.50	470.82	0.96	1.29	57.77
15/07/2002 (DOY 196)	Bare soil	415.29	103.26	202.43	109.58	0.34	0.42	1136.84
	Sparse vegetation	464.58	101.46	137.88	225.23	0.61	0.67	298.94
	Moderate Vegetation	436.90	90.60	62.14	374.75	0.85	1.04	63.13
	Dense Vegetation	542.07	75.29	32.32	434.44	0.92	1.23	35.16
	Very dense Vegetation	548.20	60.88	14.58	472.74	0.96	1.31	27.77

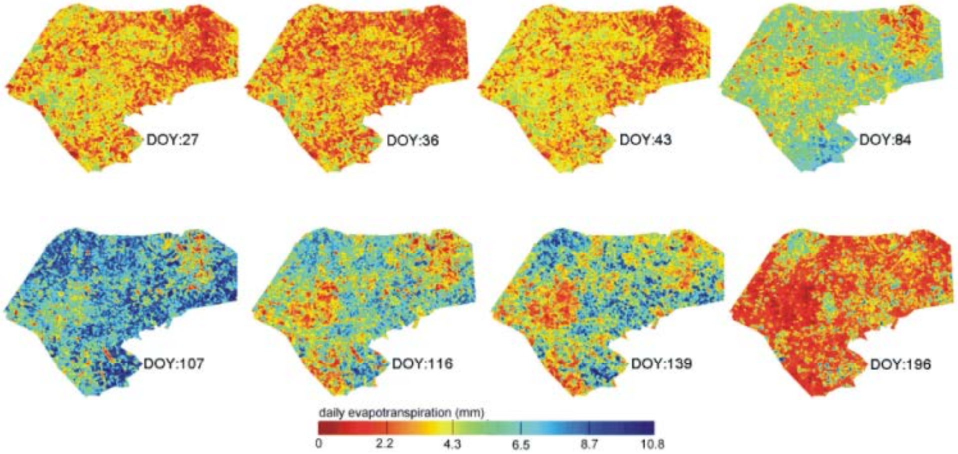

Fig. 2: Spatial distribution of the daily actual evapotranspiration in the study area

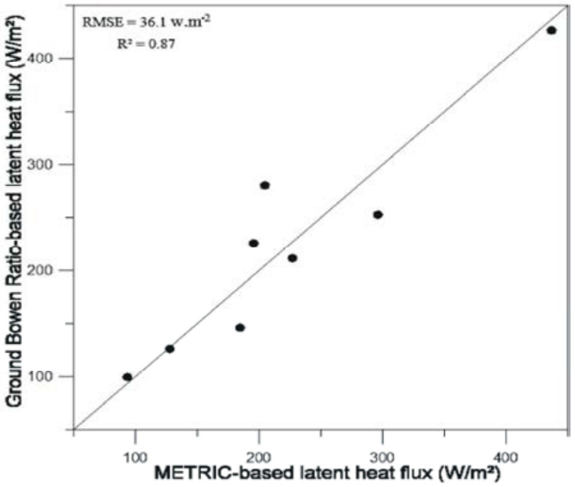

Fig. 3: Comparison of ground-based and satellite-derived estimates of latent heat flux

CONCLUSION

Recent developments in remote sensing techniques have resulted in many new applications. One of these applications is to study the interactions between land surface and atmosphere at a regional scale.

The remote sensing radiances in the visible, near infrared and thermal infrared ranges can be used to determine albedo, vegetation index and surface temperature. By incorporating various models, these parameters can be used to estimate evapotranspiration and surface energy fluxes.

The aim of this study was to map evapotranspiration from Landsat-7 ETM+ data using the METRIC approach.

The results obtained confirm the opportunities presented by high resolution remote sensing satellites, such as Landsat or ASTER, to solve the energy balance equation, assess the water stress degree and clearly differentiate the parcels subject to different water systems. However, the evapotranspiration and surface energy fluxes estimates cannot be regarded as very accurate compared to data points. We noted in this part a significant discrepancy between remote sensing and ground estimates of latent heat flux, with a RMSE about 36.1 $W.m^{-2}$ and a correlation coefficient of 0.87, that was ascribed to inaccuracies on the intermediate variables such as surface emissivity, soil heat flux, roughness length and air temperature.

Despite these inaccuracies, the used approach is quite suitable for a real exploitation of satellite data to estimate a number of parameters at the soil-plant-atmosphere continuum. These parameters have the advantage of being spatialized and provide a spatiotemporal coverage better than the data points measured operationally. However, they pose the problem to be indirect and require the use of radiative transfer modelling within the atmosphere and at the surface for their interpretation in terms of physical parameters.

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