Estimating actual evapotranspiration by means of Remote Sensing data and Sap Flow measurements in *Pinus sylvestris* forest stands in a Mediterranean mountain region

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***Abstract*—The aim of this study is to monitor daily actual evapotranspiration (AET_d) in *Pinus sylvestris* forest stands using a simplified methodology. To compute AET_d we have followed the *B*-method, which is based on the energy budget, using a series of TERRA/AQUA MODIS and Landsat-5 TM as Remote Sensing data from 2003 to 2004. We have compared Remote Sensing AET_d estimates with sap flux measurements obtaining a RMSE of 0.78 mm in the case of Landsat data, 0.93 mm in the case of TERRA MODIS and 0.91 mm in the case of TERRA AQUA using a variable B parameter in AET_d modeling.**

Keywords: Evapotranspiration modelling, Sap Flow, Landsat, MODIS, Pinus sylvestris, Mediterranean region.

I. Introduction

Evapotranspiration monitoring has important implications on global and regional climate modelling, as well as, in the knowledge of the hydrological cycle and to assess about environmental stress that affects forest and agricultural ecosystems [1]. The atmospheric gas concentration and other climatic elements such as precipitation, cloudiness, humidity and wind distribution will also affect temperature. Evapotranspiration is one of the processes which could be affected due to these changes. An evapotranspiration rise while precipitation remains constant or is reduced could decrease water availability for natural and agricultural systems and human needs. Consequently, hydrological balance methods like the evapotranspiration modelling have been widely used to estimate the global change effects [2], as well as, crop and forest water needs [3].

Currently, the 38% of Catalonia (NE of the Iberian Peninsula) is covered by forests, and one of the most important forest species is Scots Pine (*Pinus sylvestris*) which represents the 18.4% of the area occupied by forests [4].

The aim of this study is to model AET_d in *Pinus sylvestris* forest stands, in a Mediterranean mountain region, using remote sensing data and compare it with stand-scale sap flow measurements.

II. Study Area

The experimental plot is a part of the Vallcebre research area (42º 12' N, 1º 49' E), located in the Eastern Pyrenees (NE of the Iberian Peninsula). Climate is sub-Mediterranean, with an average air temperature of 7.3 ºC (measured at 1440 m a.s.l.) and 924 mm of annual rainfall. Mudstone and limestone substrates are predominant, resulting in clayey soils in the first case, and bare rock areas or thin soils in the latter [5]. Climacic vegetation in the area corresponds to the *Buxo-sempervirentis-Quercetum pubescentis* association, but most of the land was terraced and deforested for cultivation in the past, and then progressively abandoned during the second half of the twentieth century. The present landscape is mainly a mosaic of mesophilous grasslands of the *Aphyllantion* type and patches of *Pinus sylvestris*, which colonized old agricultural terraces after their abandonment [5].

III. Material

A. *Meteorological data*

Air temperature, wind speed and net radiation data have been collected over the *Pinus sylvestris* stand by means of HMP35AC (Vantaa, Finland), A100R (Vector Instruments) and NR-Lite (Kipp & Zonen) sensors, respectively, every 15 minutes.

B. *Remote sensing data*

To perform this study a set of 183 TERRA-MODIS images and 164 AQUA-MODIS images from June 2003 to December of 2004 and a set of 10 Landsat-5 TM images of path 198 and rows 31 and 32 corresponding to 01/07/2003, 17/07/2003, 02/08/2003, 19/09/2003, 10/02/2004, 16/05/2004, 17/06/2004, 08/11/2004, 24/11/2004 and 26/12/2004 have been selected to perform AET_d modeling in *Pinus sylvestris* forest stands.

AQUA/TERRA MODIS images have been downloaded by means of the EOS Gateway (http://edcimswww.cr.usgs.gov/pub/imswelcome/). We have selected three different types of products which contain the remote sensing data we have used to model AET_d: MOD11A1 and MYD11A1 (which contains TERRA and AQUA daily LST, respectively), MOD09GHK and MYD09GHK (which contains TERRA and AQUA daily reflectances, respectively), and MOD05 (which contains daily water vapor).

Although image time acquisition is different for each satellite, Landsat and TERRA satellites pass over Catalonia at a similar time, between 9:30 and 10:30 local solar time. On the other hand, AQUA passes over the same area, but between 13:00 and 14:00 local solar time.

IV. METHODOLOGY

A. *Remote sensing daily evapotranspiration model*

To compute AET_d we have followed a simplified methodology, the B-method, proposed by [6] and [7], which is based on the energy budget, that needs as an input variables net radiation (Rn) and the difference between land surface temperature (LST) and air temperature (T_a):

$$AET_d = Rn_d - B\,(LST - Ta)^{n} \tag{1}$$

where subindex $_d$ means daily periods, AET and Rn are in mm day^{-1} and both temperatures are in K. Coefficient n is a correction for non-neutral static stability that could be assigned to one as [8] suggested.

B can be defined as an exchange coefficient that in (1) represents an average bulk conductance for daily integrated sensible heat flux [9] and following the methodology proposed by [10] can be expressed as:

$$B = (Rn_d / Rn_i) * (\rho\, C_p / r^{*}_{a}) \tag{2}$$

where Rn is instantaneous net radiation (W m^2) and subindex i means instantenoeus, C_p is the air specific heat at a constant pressure (J kg^{-1} K^{-1}) and r^{*}_{a} is the effective aerodynamic resistance [10]. Despite we do not have measurements of effective aerodynamic resistance, we can consider aerodynamic resistance of *Pinus sylvestris* equal to 28.1 m s^{-1} as [11] determined.

Because of the importance of B parameter in AET_d retrieval we would use three methodologies to compute it in order to establish which offers best AET_d results:

1) *Fixed B parameter:*

In this case we have used a fixed value of Rn_d / Rn_i (from now on Rn_d / Rn_i will be called Rn ratio) of 0.3 as [8] suggested.

2) *Variable B parameter*

In our study area we have noted that the Rn ratio is lower than 0.30 and varies during the year. For this reason, we will use a daily Rn ratio instead of a fixed Rn ratio. However, this ratio remains constant from 9:00 to 18:00 in our study area and, therefore, it can be used in Landsat and TERRA/AQUA AET_d modeling.

3) *B parameter depending on NDVI:*

Using a simple equation proposed by [6] (obtained from a SVAT model) that integrates the main factors in which B depends, such as wind velocity and aerodynamic resistance, B can be also defined as:

$$B = 0.109 + 0.51\,(NDVI^*) \tag{3}$$

where NDVI* is a scaled vegetation index based on the NDVI.

B. *Sap-flow daily mesurements*

We have compared remote sensing daily actual evapotranspiration estimates with canopy transpiration measured with heat dissipation sap flux sensors applying a correction to account for radial patterns of sap flow using the Heat Field Deformation method [12]. Sap flux density was measured in 12 trees per stand, sampled according to diametric distribution, and then scaled-up to stand level transpiration using tree sapwood areas. As sap flow measurements only account for the transpiration fraction from the whole stand, they are more comparable with AET_d values in the *Pinus sylvestris* stand, where understorey evaporation is not significant [12].

C. *Landsat-5 TM data processing*

The computation of the Landsat-5 TM data used in air temperature modeling has been carried out by means of the following methodologies:

- Geometric correction: Images have been corrected by means of conventional techniques based on first order polynomials taking into account the effect of the relief of the land surface using a Digital Elevation Model [13]. Landsat-5 TM bands have been resampled to the Landsat-5 TM thermal band spatial resolution, 120 m.
- Radiometric correction (non-thermal bands): Radiometric correction has been done following the methodology proposed by [14] which allows to reduce the number of undesired artifacts that are due to the effects of the atmosphere or to the differential illumination which is, in turn, due to the time of the day, the location in the Earth and the relief (zones being more illuminated than others, shadows, etc). Digital number to radiance conversion has been done by means of image header parameters taking into account the considerations exposed by [15].
- LST: Landsat-5 TM thermal band has been atmospherically corrected using a monowindow algorithm based on a variation of [16] methodology introducing in LST retrieval water vapor obtained from TERRA-MODIS products and air temperature obtained from meteorological data at satellite pass time.

- Surface emissivity (ε): this has been computed following the methodology proposed by [17]. This methodology proposes to calculate surface emissivity values by means of the NDVI - emissivity relation and field and laboratoty emissivity values.

D. MODIS data processing

Due to daily AQUA/TERRA MODIS reflectance and LST products have already been corrected geometrically and radiometrically by USGS, these products have only been imported, reading all the necessary metadata to process NDVI and LST. Before that images have been reprojected to UTM-31 N. Water vapor product has been geometrically corrected using HEG-WIN software.

E. AET_d remote sensing model validation

We have computed the root mean square error (RMSE) using the sap flow measurements and AET remote sensing models using all selected dates.

V. RESULTS AND DISCUSSION

Table I shows the RMSE of the different models depending on the B parameter. Best results have been obtained using a variable B parameter in all cases and worse results have been obtained using a fixed B. Although [8] suggests a Rn ratio of 0.3, in our case the annual mean Rn ratio is 0.16 with an σ of 0.11 for TERRA and Lansat images and a mena of 0.18 with an σ of 0.13 for AQUA images. This means that a constant Rn ratio of 0.3 during do not offer good estimates of B parameter during all the year and, therefore, to obtain better results a daily Rn ratio is needed.

Rn ratio in winter and autumn is very low but in spring and summer is closed to 0.3 (see figure 1). Using a fixed Rn ratio in winter and autumn dates increases the error in B parameter computing and in final AET_d modeling (see table I). In order to determine B parameter if there is no availability of Rn ratio, a better option is to choose the B parameter depending on the NDVI that offer lower RMSE instead of a fixed B parameter. Although in this case the RMSE is higher than the variable B, this option offers an easiest computation methodology. Using (3) we have obtained mean B values of 0.55, in the MODIS case, and 0.42 in the Landsat case, which are in agreement with previous studies [9] and [11].

Using variable B values in (1), we have obtained, in the case of TERRA/AQUA MODIS AET_d modeling, a RMSE of 0.92 mm and in the case of Landsat-5 TM AET_d modeling, a RMSE of 0.78 mm. These results are in agreement with other studies [11] that present an estimation error of about ± 30%.

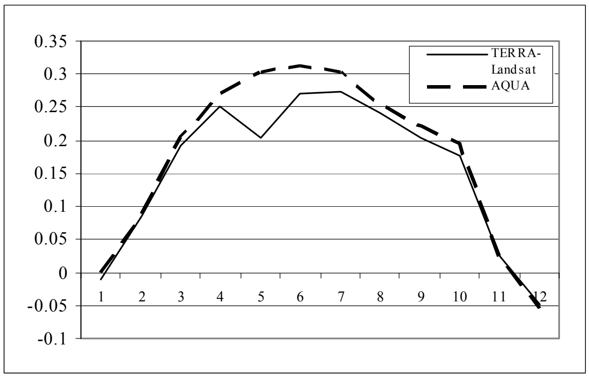

Figure 1. Monthly Rn ratio variation in *Pinus sylvestris* stands.

However, other studies [11] have reported lower RMSE (0.81 mm) in more homogeneous *Pinus sylvestris* areas.

The differences between spatial resolutions are due to the heterogeneity of the area where *Pinus sylvestris* stands are located. The study area does not cover a 1 km pixel and, therefore, the remote sensing data, especially LST, is less representative than a Landsat pixel of 120 m.

Table II displays the descriptive statistics of the obtained AET_d. Measurements with sap flow technique show a mean, minimum and maximum AET_d values of 1.71, 0.10 and 3.60 mm day $^{-1}$, respectively. It is interesting to note that in AET_d modeling using remote sensing data, obtained minimum values is always negative. This mainly happens in winter and autumns dates where the mean Rn is negative and the AET_d is low (daily mean of 0.35 mm d^{-1}). The used methodology is often used in spring and summer dates where mean Rn is positive. Therefore, in winter and autumn dates the use of this methodology it should be limited only in days where the Rn budget is positive.

Figure 2 shows the difference between the AET_d sap flow measurements and the AET_d modeled with remote sensing data. Daily differences have been monthly aggregated for a better understanding of the error distribution. Difference increases when AET_d of *Pinus sylvestris* present higher values (spring and summer) and decreases when AET_d is lower (winter and autumn). In all the cases except in winter dates, the difference is always positive, that means that remote sensing AET_d modeling tends to overestimate AET_d. In winter, this difference is positive because of the negative Rn budget that gives negative remote sensing AET_d modeled values.

Finally, it is interesting to note that modeled AET_d in the case of TERRA/AQUA MODIS (see table I) offers similar results despite both sensor overpasses the study area at a

TABLE I. RMSE OF AET_D MODELED BY MEANS OF LANDSAT AND TERRA/AQUA MODIS IMAGES

RMSE (mm)	variable B	fixed B	NDVI B
Landsat	0.78	1.24	1.05
TERRA MODIS	0.93	1.31	1.28
AQUA MODIS	0.91	1.51	1.55
Mean	0.87	1.35	1.29

TABLE II. DESCRIPTIVE STATISTICS OF OBTAINED AET_D MEASUREMENT S USING SAP FLOW AND REMOTE SENSING DATA

AET (mm)	min	max	mean	σ
Sap flow	0.1	3.6	1.71	0.86
Landsat	-0.63	3.54	1.32	1.52
TERRA MODIS	-1.63	5.86	1.52	1.73
AQUA MODIS	-1.61	7.23	1.53	1.89

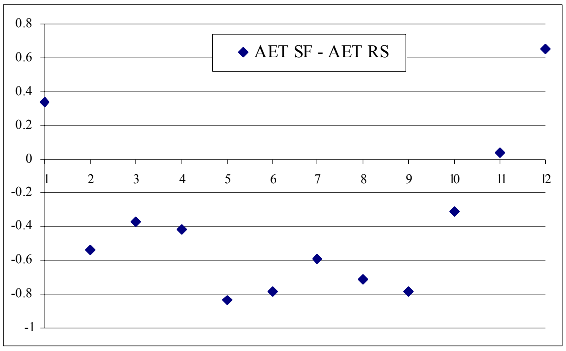

Figure 2. Monthly aggregated daily differences between AET_d sap flow measurements (AET SF) and AET_d modeled with remote sensing data (AET RS).

different time of the day. Therefore, we can consider both mid-morning remote sensing measurements and afternoon measurements useful to compute AET_d.

VI. CONCLUSIONS

We have obtained modest AET_d modeling results using Landsat and TERRA/AQUA MODIS with the B-method. These results are in agreement with other studies that present an estimated error of ± 30%.

Best AET_d results have been obtained using a variable B parameter with a daily Rn ratio instead of using a fixed B parameter with a fixed Rn ratio. B parameter depending on the NDVI has given intermediate results.

Rn ratio has showed to be an important parameter to be taken into account if the B-method is used. Although this ratio in spring and summer months is closed to 0.3, in winter and autumn months it should be changed to obtain better AET_d results.

AET_d modeled using TERRA (mid-morning overpass) and AQUA (afternoon overpass) MODIS have presented similar results making them useful to increase AET_d knowledge.

ACKNOWLEDGMENTS

It would not have been possible to carry out this study without the financial assistance of the Ministry of Science and Technology and the FEDER funds through the research project: “Compression and interactive transmission of high resolution images. Remote Sensing and Geographical Information Systems applications” (TSI2006-14005-C02-02). We would like to express our gratitude to the Catalan Water Agency and to the Department of the Environment and Housing of the Generalitat (Autonomous Government) of Catalonia for their investment policy and the availability of Remote Sensing data, which has made it possible to conduct this study under optimal conditions. We would also like to thank

Finally, we wish to thank Dr. J. A. Sobrino and J. C. Muñoz from the Global Change Unit of the Department of Thermodynamics of the University of Valencia for his help in Landsat atmospheric thermal correction.

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