ASSESSMENT OF DAILY ACTUAL EVAPOTRANSPIRATION WITH SEBAL AND S-SEBI ALGORITHMS IN COTTON CROP

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ABSTRACT

The main objective of this study is to assess the daily ET accuracy obtained by remote sensing algorithms in comparison with measurements *in situ*. The experiment was conducted in the State of Ceará, Brazil, in a cotton experimental field of EMBRAPA using Bowen ratio measurements to obtain the energy balance components. SEBAL and S-SEBI algorithms were used with four TM Landsat – 5 images of 2005, in order to determine the actual evapotranspiration of cotton crop. The comparison between the estimated values by remote sensing algorithms and the measured values *in situ* showed that the methods (SEBAL and S-SEBI) presented satisfactory results. The S-SEBI algorithm is an important tool to be applied in ET analysis of semi-arid regions, due its practicability to solve the energy balance and its processing is simpler than SEBAL algorithm which needs the solution of an iterative process.
Keywords: Energy balance, Landsat, Bowen ratio, semi-arid

Resumo: AVALIAÇÃO DA EVAPOTRANSPIRAÇÃO REAL DIÁRIA ESTIMADA COM OS ALGORITMOS SEBAL E S-SEBI NA CULTURA DO ALGODÃO
 O principal objetivo deste estudo foi avaliar a precisão de ET diária, obtida por algoritmos baseados em sensoriamento remoto, em comparação com os valores obtidos em campo pelo método da razão de Bowen na cultura do algodão. Esta campanha experimental foi desenvolvida no Estado de Ceará, Brasil, no campo experimental de EMBRAPA. Foram usadas neste estudo 4 imagens Landsat – 5 TM do ano de 2005, para aplicação dos algoritmos SEBAL e S-SEBI. A comparação entre os valores obtidos pelos algoritmos e os valores medidos em campo apresentou precisão satisfatória com um evidente melhor desempenho do algoritmo SEBAL. Os resultados comprovaram que o algoritmo S-SEBI é uma ferramenta importante a ser aplicada na análise da ET em regiões semi-áridas, devido a sua praticidade na obtenção do balanço de energia, assim como, por seu processamento ser mais simples do que o do algoritmo SEBAL, o qual necessita da solução de um processo iterativo.
Palavras-chave: Balanço de energia, Landsat, Razão de Bowen, semi-árido

1. INTRODUCTION

The evapotranspiration (ET), which includes water evaporation from soil surfaces and vegetation transpiration, represents a fundamental process of hydrological cycle and is a key element of water resources management, particularly in semi-arid and arid regions (Budyko, 1974; Bouwer et al.,

2008). Some studies have demonstrated that the temporal and spatial patterns of ET depend on a large variety of influencing factors like vegetation and soil types, topography, and the meteorological conditions (Milly and Dunne, 2001; Gordon et al., 2003; Bouwer et al., 2008). The primary methods used conventionally to measure ET are dependent of the field or landscape scales (Bowen ratio, eddy covariance, soil water

balance), but do not allow the estimation of fluxes when dealing with larger spatial scales due to the inherent heterogeneity of land surfaces and the dynamic nature of water vapour transport processes (Gao et al., 2008).

The quantification of the ET losses on a regional scale and in high spatial resolution is an essential element for hydrological modeling, analysis of the water use on basin scale and adoption of correct irrigation management. Nowadays, with the increasing resolution of the satellite imagery, the remote sensing is an important technique for providing parameters at various temporal and spatial scales required to estimate ET. Surface Energy Balance Algorithm for Land (SEBAL) (Bastiaanssen et al., 1998a, and 1998b) uses spectral radiance recorded by satellite sensors and meteorological data to obtain the surface energy balance at regional scale. Another important algorithm is the Simplified Surface Energy Balance Index (S-SEBI) (Roerink et al., 2000). The main difference between these algorithms is in the methodology to determine the sensible heat flux (H). SEBAL calculates the ET using the residual from the surface energy balance while the S-SEBI calculates it using the evaporative fraction (Λ) theory, that is obtained by the parameterizations based on surface albedo and land surface temperature (Roerink et al., 2000), and instantaneous available energy.

The extrapolation of instantaneous ET for daily values constitutes an important step in the remote sensing methods. In SEBAL (Bastiaanssen et al., 1998a and 1998b; Bastiaanssen, 2000) and S-SEBI (Roerink et al, 2000; Sobrino et al.,

2005, 2007) the daily ET is estimated based on daily fluxes conservation (Brutsaert and Sugita, 1992) admitting that the relationship between the latent heat flux and available energy is kept relatively constant during the day. This methodology uses as input parameter the daily net radiation, which is usually calculated as a function of the daily solar radiation measured in meteorological station (Roerink et al., 2000; Bastiaanssen, 2000; Gomez et al., 2005, Sobrino et al., 2005; 2007).

The emphasis of this study is to evaluate the daily ET based on the energy balance obtained by SEBAL and S-SEBI algorithms. The estimates of these methods are compared with field observations of a cotton crop using the Bowen ratio method. The studied area is located in a semi-arid region of Brazil, with few meteorological stations in operation. For this reason, the application of different remote sensing algorithms, to obtain the ET, are necessary and the analysis of accuracy is important to identify which algorithm is more appropriate.

2. MATERIALS AND METHODS

2.1 Study Area and Data

This study was conducted in a semi-arid region in Ceará State, Brazil (Figure 1). The studied area comprises the experimental field of EMBRAPA (Empresa Brasileira de Pesquisa Agropecuária), located at 7º17'S and 39º16'W, and other irrigated crops and native vegetation. The regional
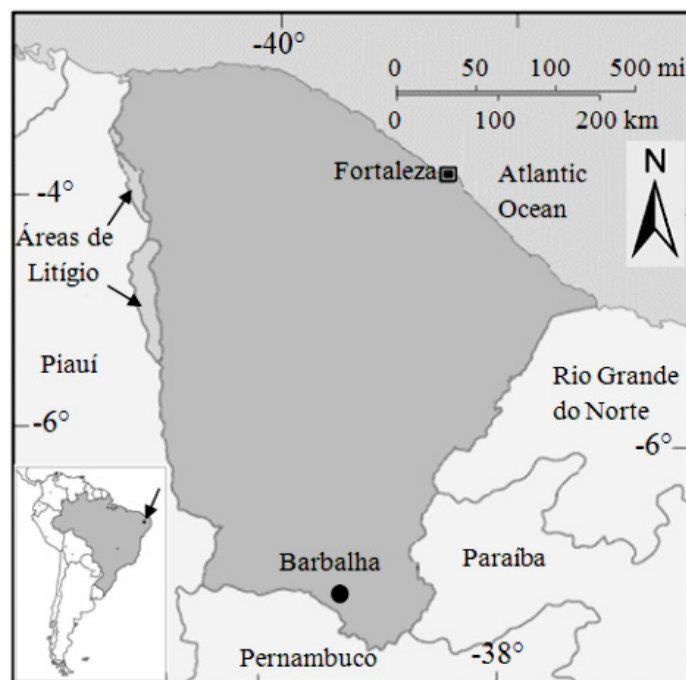
Figure 1 - Experimental area location in relation to Ceará State and Brazil.

climate, according to Thornthwaite and Mather (1955) climatic classification is ClA'wa' dry sub humid with moderate water excess during the summer months. This climate type is created because the Apodi plateau influences. Four TM Landsat – 5 images of DOY (day of the year) 272, 288, 304, 320 of 2005 were used with SEBAL and S-SEBI algorithms, covering the complete growth cycle of the cotton crop. The data used in the validation of remote sensing methods were collected in an experimental campaign accomplished on the herbaceous cotton crop, cultivar 200-brown BRS, using Bowen ratio technique.

The partition of energy at the surface between sensible and latent heat fluxes is usually obtained by the Bowen ratio energy balance (BREB) method (Perez et al., 1999; Azevedo et al., 2007; Silva et al., 2007) using the average of the Bowen ratio (Perez et al., 2008). According to Perez et al. (2008) over an averaging period (in general 30 minutes) a relationship between fluxes and vertical gradients can be formulated as:

$$\lambda E = -\frac{\rho_a c_p}{\gamma} k_v \frac{\partial e}{\partial z} \quad (1)$$

$$H = \rho_a c_p k_h \frac{\partial T}{\partial z} \quad (2)$$

where λE is the latent heat flux (W m^{-2}), H is the sensible heat flux (W m^{-2}), ρ_a is the mean air density at constant pressure (kg m^{-3}), c_p is the specific heat of air at constant pressure (J kg^{-1} ºC^{-1}), γ is the psychometric constant (Pa/ºC), e is the actual vapour pressure of the air (Pa), T is the temperature (ºC), k_h is the turbulent heat transfer coefficient and k_v is the turbulent vapour transfer coefficient.

Assuming $k_h = k_v$ (Verma et al., 1978) and taking measurements between two levels within the adjusted surface layer, the Bowen ratio (β) is obtained as:

$$\beta = \gamma \frac{\partial t / \partial z}{\partial e / \partial z} = \gamma \frac{\Delta T}{\Delta e} \quad (3)$$

where ΔT and Δe are temperature and vapour pressure differences at two measurement levels above the cotton crop canopy. According to Perez et al. (2008) this technique is used to obtain λE and H from equations 1 and 2 when available energy is accurately measured.

The air temperature difference between the dry and wet bulbs was measured using the thermocouples (type T copper-constantan) installed at two levels (0.5 and 1.5 m) above the crop canopy. The net radiation (R_n) was measured using a net

radiometer (NR-LITE; Kipp & Zonen, Delft, The Netherlands). Incoming solar radiation (R_g) and outgoing solar radiation (R_g) were obtained with a solar (or shortwave) radiometer (CM3; Kipp & Zonen, Delft, The Netherlands), all radiation instruments were installed at 1.0 m above crop canopy, and soil heat flux (G) was measured with two soil heat flux plates (model HFP01SC-L, Campbell Scientific, Inc., Logan, UT) at 0.05 m soil depth.

The actual ET was obtained using the surface energy balance equation:

$$\lambda ET = R_n - H - G \quad (4)$$

where λET is the latent heat flux in the atmosphere boundary layer (W m^{-2}), R_n is the net radiation (W m^{-2}), H is the sensible heat flux (W m^{-2}) and G is the soil heat flux (W m^{-2}).

2.2 Algorithm Descriptions

I) SEBAL

The R_n obtained by SEBAL and S-SEBI algorithms, was calculated using the following equation:

$$R_n = (1 - \alpha)R_{S\downarrow} + R_{L\downarrow} - R_{L\uparrow} - (1 - \varepsilon_0)R_{L\downarrow} \quad (5)$$

where α is the surface albedo, R_L is the longwave radiation (thermal) emitted by the surface, ε_o is the surface emissivity obtained through Leaf Area Index (LAI), $R_S\downarrow$ is the short-wave incoming solar radiation, $R_L\uparrow$ is the longwave incoming radiation, estimated from the Stefan-Boltzmann equation based on the air temperature at the satellite overpass (Bastiaanssen et al., 1998a). Figure 2 shows the flowchart of the computational steps used to obtain the R_n at the surface.

The following equation was developed by Bastiaanssen (2000) to obtain G and it is used in the SEBAL and S-SEBI algorithms:

$$G = \left[\frac{Ts}{\alpha}\left(0.0038\alpha + 0.0074\alpha^2\right)\left(1 - 0.98NDVI^4\right)\right]Rn \quad (6)$$

where α is the surface albedo, T_S is the surface temperature, and $NDVI$ is the Normalized Difference Vegetation Index, obtained based on the reflectance in channels 3 and 4 of Landsat 5-TM.

The difficult task in SEBAL is the method to obtain H that is computed using the following heat transport equation:

$$H = \frac{(\rho c_P dT)}{r_{ah}} \quad (7)$$
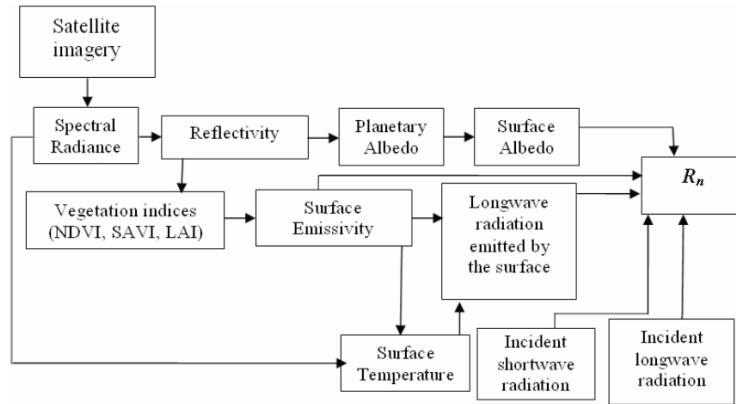
Figure 2 - Flowchart of computational steps used to obtain R_n at the land surface.

where ρ is the air density (kg m^{-3}), c_P is the air specific heat at constant pressure (J kg^{-1} K^{-1}), dT is the temperature difference ($T_1 - T_2$) between two heights (z_1 and z_2), and r_{ah} is the aerodynamic resistance to heat transport (s m^{-1}). This calculation is developed as a function of the temperature gradient, surface roughness and wind speed. Nevertheless, the Equation 7 is difficult to solve, because dT and r_{ah} terms are difcult to measure. However, by using the "anchor" pixels, called hot and cold pixels, to solve this problem representing maximum conditions of temperature and humidity from the known values of H and dT. The acquisition of the r_{ah} and dT values from the images is computed admitting initial neutral atmospheric conditions. The Monin-Obukhov similarity theory (Bastiaanssen et al., 1998a) is applied in order to correct u$_*$ and r$_{ah}$ iteratively until the stabilization is achieved.

Allen et al. (2002), Trezza (2002) and Tasumi (2003) showed that the reference ET Fraction ($ETrF$) is similar to the crop coefficient (Kc) (Allen et al., 1998) and can be obtained by:

$$ETrF = \frac{ET_{hour}}{ET_r} \tag{8}$$

where ET_r is the hourly reference evapotranspiration, calculated using the FAO-Penman-Monteith method and data originating from a weather station. Considering, $ETrF$ equal to Kc (Allen et al, 2002; Trezza, 2002), and maintaining constant during the daytime, the daily actual ET was calculated by the classic FAO-Penman-Monteith method (Allen et al., 1998):

$$ET = ETr.FET_{y(24)} \tag{9}$$

where $ET_{r(24)}$ is the daily reference evapotranspiration, which is also calculated using weather station data and FAO-Penman-Monteith method (Allen et al., 1998).

II) S-SEBI

S-SEBI algorithm uses the evaporative fraction (Λ) theory to solve the surface energy balance through a parameterization proposed by Roerink et al. (2000):

$$\Lambda = \frac{T_H - T_S}{T_H - T_{\lambda E}} \tag{10}$$

where T_s is the land surface temperature, T_H is the temperature of maximum sensible heat flux pixels, obtained by linear relationship between the surface temperature (dependent variable) and albedo (independent variable), $T_{\lambda E}$ is temperature of the maximum latent heat flux pixels which is also obtained using linear relationship between temperature and albedo. Figure 3 shows the schematic representation of obtaining T_H and $T_{\lambda E}$.

Thus, substituting the linear regression of T_H and $T_{\lambda E}$ in Equation 10, Λ was calculated as:

$$\Lambda = \frac{a_H + b_H \alpha - T_S}{a_H - a_{\lambda E} + (b_H - b_{\lambda E})\alpha} \tag{11}$$

The H and λE are obtained using the available energy and Λ, according to:

$$H = (1 - \Lambda)(R_n - G) \tag{12}$$

and

$$\lambda ET = \Lambda (R_n - G) \tag{13}$$

Finally, the daily ET estimation by S-SEBI is based on the theory that the instantaneous evaporative fraction (Λ_i) is equal to the daily evaporative fraction (Λ_d):
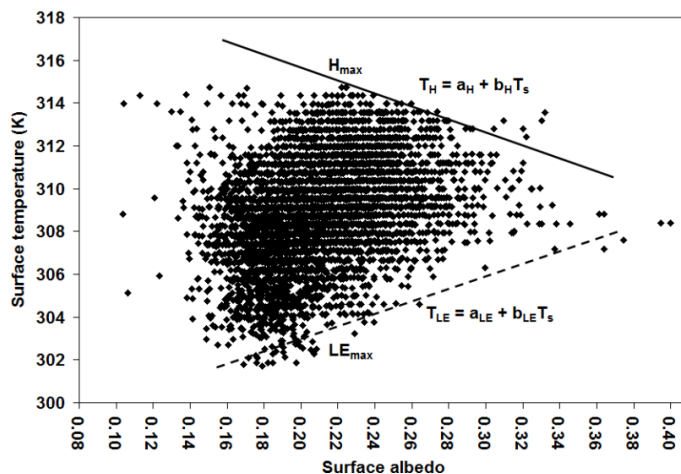
Figure 3 - Schematic representation of the relationship between land surface temperature and surface albedo.

$$\Lambda_i = \Lambda_d = \frac{\lambda ET_i}{(R_{ni} - G_i)} = \frac{\lambda ET_d}{(R_{nd} - G_d)} \quad (14)$$

Considering that the integrated daily soil heat flux is approximately equal to zero (Allen et al., 1998), the daily ET was calculated by:

$$ET = \lambda ET_i \frac{R_{nd}}{\lambda R_{ni}} \quad (15)$$

where R_{ni} is instantaneous net radiation at the time of satellite overpass, calculated using Equations 5 and 6, respectively, and R_{nd} is the daily net radiation. The calculation of R_{nd} in S-SEBI applications has been made using the procedure proposed by Seguin and Itier (1983). They showed that the ratio between instantaneous and daily values of net radiation is constant during the daytime.

3. RESULTS AND DISCUSSION

The SEBAL and S-SEBI algorithms present different methodologies for obtaining daily ET. However, they presented similar spatial and temporal results of ET, according to figure 4. Nevertheless, it is possible to identify which ET values obtained by SEBAL are higher than the ET values obtained by S-SEBI. The maximum daily ET values (white areas) correspond to well irrigated crops (for example the cotton field), where data were collected for validation of these algorithms used in this study, while the black areas correspond to bare soil or short and sparse native vegetation. Similarities between SEBAL and S-SEBI results have been identified by Weligepolage (2005) that observed strong correlations between both algorithms, presenting coefficient of correlation (r) of 0.97. The comparison

between the estimated values by remote sensing algorithms and the ground measurements showed satisfactory accuracy, in comparison with the analyses obtained by Weligepolage (2005).

The values presented in Figure 5, Tables 1 and 2, evidence the best performance of the SEBAL algorithm, with differences between the methods lesser than 0.5 mm day^{-1}, daily errors less than 7.1% and Mean Absolute Difference (MAD) of 0.30 mm day^{-1}. SEBAL results observed by Wilegepolage (2005) presented differences above 0.4 mm day^{-1} on seven studied dates in Hupselse Beek, The Netherlands, when compared with scintilometer measurements with a MAD of 0.98 mm day^{-1}. However, The Netherlands is a region which presents different climate conditions in comparison with the study area in Brazil and the scintilometry is a technique to provide direct measurements of fluxes contrasting with the Bowen ratio technique used in this study.

The results obtained using the S-SEBI algorithm presented a maximum difference of 1.0 mm day^{-1} and maximum error of 16.1% for the DOY 320. For the other dates, the differences were inferior to 0.5 mm day^{-1} and errors less than 10%, with MAD less than 0.5 mm day^{-1} as shown in Table 2. Gómez et al. (2005) and Sobrino et al. (2005) also obtained differences between estimated values by S-SEBI and measured value lower than 1.0 mm day^{-1}. Wilegepolage (2005) obtained differences varied between 0.7 and 1.6 mm day^{-1} in comparison with values obtained using scintilometer measurements.

Table 3 presents the r values at a statistical significance level of 5% (p<0.05), Mean Bias Error (MBE) and Root Mean Square Error (RMSE), between the daily ET values of 6,000 pixels extracted from the images obtained by SEBAL and S-SEBI algorithms. In general, the correlations between them presented values greater than 0.85, evidencing a stronger agreement between these algorithms. The MBE presented a
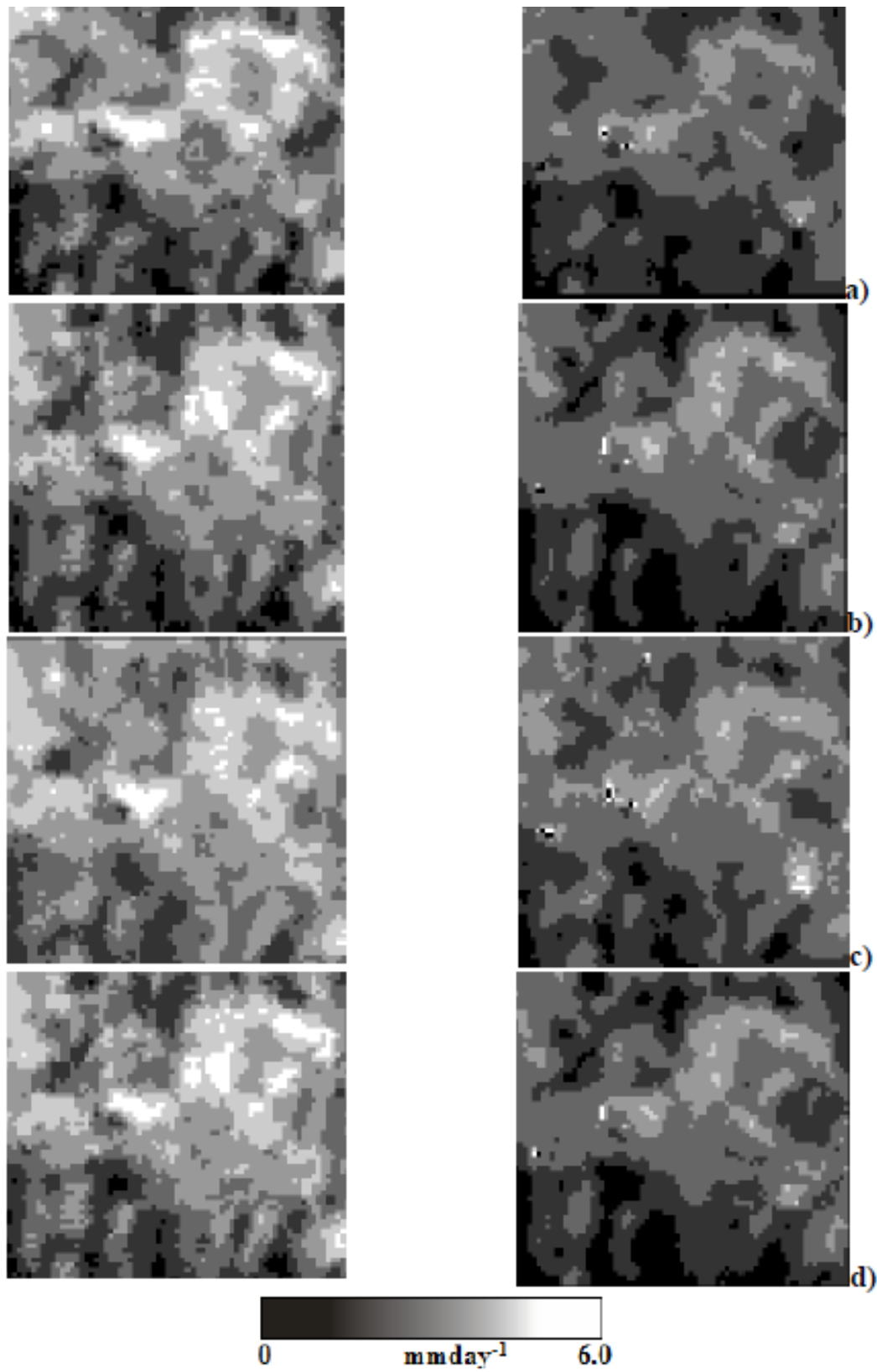
Figure 4 - Spatial distributions of actual evapotranspiration calculated by SEBAL (left) and S-SEBI (right) on DOY **a**) 272, **b**) 288, **c**) 304, and **d**) 320.

Table 1 - Observed daily evapotranspiration in the cotton crop field using the Bowen ratio method and the estimated value by SEBAL algorithm using Landsat 5 – TM images.
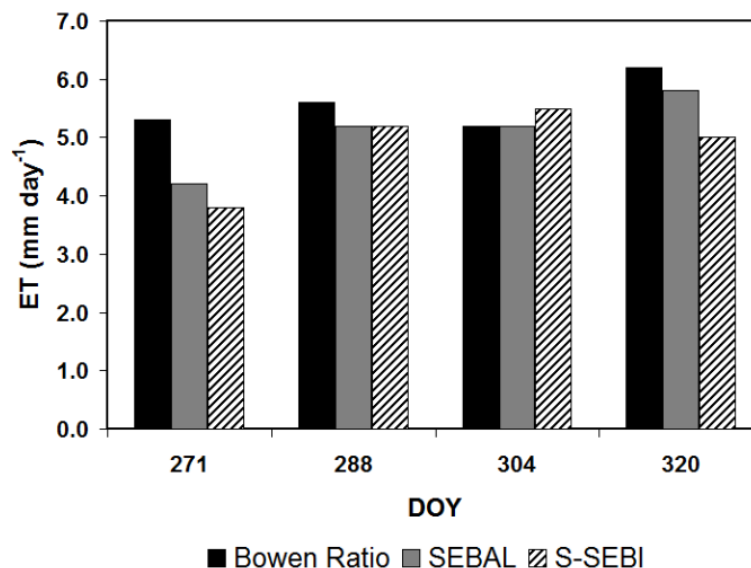
DOY	Measured (mm day^{-1})	SEBAL (mm day^{-1})	Absolute Difference [a] (mm day^{-1})	Percentual Error [b] (%)	MAD [c] (mm day^{-1})
272	4.5	4.2	0.30	6.7	
288	5.6	5.2	0.40	7.1	
304	5.3	5.2	0.10	1.9	0.30
320	6.2	5.8	0.40	6.5	

[a]*Absolute difference = |observed – estimated |;* [b]*Percentual Error = (Absolute difference / observed)x100 and*

$$^{c}MAD = \frac{1}{n}\sum_{i=1}^{n}|observed - estimated|$$

Table 2 - Observed daily evapotranspiration in a cotton crop field using the Bowen ratio method and the estimated value by S-SEBI algorithm using Landsat 5 – TM images.

| DOY	Measured (mm day^{-1})	S-SEBI (mm day^{-1})	Absolute Difference [a] (mm day^{-1})	Percentual Error [b] (%)	MAD [c] (mm day^{-1})
272	4.5	4.2	0.30	6.7	
288	5.6	5.2	0.40	7.1	
304	5.3	5.5	0.20	3.8	0.48
320	6.2	5.2	1.00	16.1	

Figure 5 - Comparison between measured and estimated values of ET.

Table 3 - Correlation coefficients, MBE and RMSE to ET values of the 6,000 pixels obtained by SEBAL and S-SEBI algorithms.

DOY	r (SEBAL/S-SEBI) [a]	MBE (mm day^{-1})	RMSE (mm day^{-1})
272	0.93	0.04	0.38
288	0.92	-0.02	0.45
304	0.86	0.04	0.56
320	0.90	-0.02	0.47

[a] Statistically significant at 5% level (p<0.05)
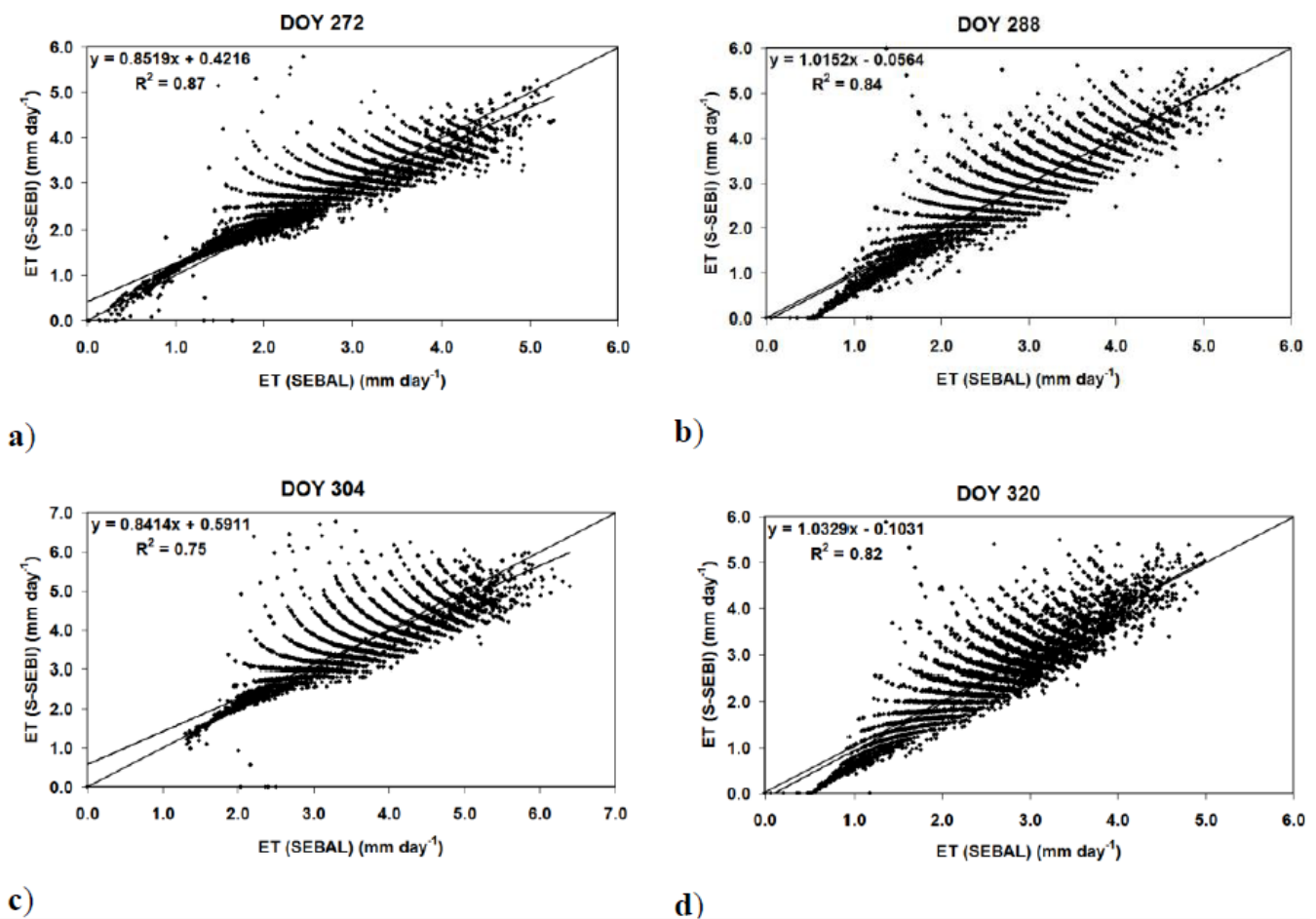
Figure 6 - Correlation between the daily ET values to DOY 272(**a**), 288(**b**), 304(**c**) and 320(**d**) obtained by SEBAL and S-SEBI algorithms.

maximum value of 0.04 mm day^{-1} and a minimum value of 0.02 mm day^{-1}, with RMSE of 0.56 mm day^{-1} and 0.38 mm day^{-1} (maximum and minimum values, respectively).

In Figure 6, it is possible to observe the behavior of the correlation between the ET estimated by SEBAL and S-SEBI to different images. In general, it is possible to identify pixels presenting the same values to both algorithms, however, the minimum ET values obtained by S-SEBI algorithm were underestimated (see the equations in the figure 6) in comparison with the SEBAL algorithm values.

According with Roerink et al. (2000) and Sobrino et al. (2007) the main disadvantage of the S-SEBI methodology is that it requires extreme values of surface temperature and its application with images of low resolution (AVHRR, for example), because the algorithm is based on the contrast between wet and dry areas (Figure 3), and these two conditions

can be present in the same pixel due to the spatial cover presenting estimates of inaccuracy. The SEBAL algorithm shows better results in obtaining ET, but needs the determination of difficult parameters.

4. CONCLUSIONS

In this paper the methods suggested by Bastiaanssen et al. (1998a, 1998b) (SEBAL) and Roerink et al. (2000) (S-SEBI) for ET retrieval from high spatial resolution data (30 m) have been applied. The comparison between the estimated values by remote sensing algorithms and field observations showed the satisfactory accuracy of the methods with mean absolute difference between SEBAL and Bowen ratio of 0.30 mm day^{-1} and between S-SEBI and Bowen ratio of 0.48 mm day^{-1}. The SEBAL algorithm performance has been better than S-SEBI algorithm. Analyses of the correlation between daily ET values obtained by SEBAL and S-SEBI algorithms, presented correlation coefficients greater than 0.85, evidencing a better agreement between these algorithms. The results presented in this study evidence that the S-SEBI algorithm as a promising tool to be applied in semi-arid and arid regions, especially in Brazilian semi-arid region that has few weather stations in operation. Such a situation represents limitations for SEBAL applications and other remote sensing algorithms.

5. ACKNOWLEDGEMENTS

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