Modern Environmental Science and Engineering (ISSN 2333-2581)
October 2018, Volume 4, No. 10, pp. 953-960
Doi: 10.15341/mese(2333-2581)/10.04.2018/005
Academic Star Publishing Company, 2018
www.academicstar.us

Evapotranspiration Estimations in the Brazilian Semi-Arid by Using MODIS Reflectance Products and Agrometeorological Stations

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Abstract: The semi-arid region of Northeast Brazil has experienced several cases of strong water scarcity together with increasing land-use changes, demanding large-scale evapotranspiration studies to subsidize water policies. Aiming to subsidize the rational water resources management under these scenarios, the use of the reflectance bands from the MODIS MOD13Q1 product together with a net of 14 weather stations was tested to acquire large-scale actual evapotranspiration (ET) along the dry year 2016. The SAFER (Simple Algorithm for Evapotranspiration Retrieving) algorithm was applied for modelling ET in the counties of Petrolina and Juazeiro, respectively Pernambuco and Bahia states, Northeast Brazil. Clearly one could see higher ET values for irrigated crops (IC) than for natural vegetation (NV) in both counties. Even they presenting similar water flux dynamics along the year, in Juazeiro, ET rates represented 78% of those for Petrolina. One reason for the smaller values in Juazeiro could be attributed to the lower crop water consumption from the São Francisco River. It was demonstrated the potential to monitor large-scale ET at the 16-day MOD13Q1 time-scale by combining remote sensing and agrometeorological measurements in mixed agroecosystems of semi-arid environments.

Key words: remote sensing, water resources, SAFER

1. Introduction

Water scarcity occurs several times in semi-arid regions and its impacts are significant and widespread, affecting many economic sectors, increasing disputes over water resources. Increasing conflicts are expected as land use changes and the competition for scarce water supplies intensifies. Under these circumstances, large-scale actual evapotranspiration (ET) quantifications are important for subsidizing water policies [1].

The counties of Petrolina and Juazeiro, respectively Pernambuco (PE) and Bahia (BA) states, both under the semi-arid conditions of the Brazilian Northeast, are agricultural growing regions, due to irrigation technology advances at the vicinities of the São Francisco River. Under these land-use changes scenarios, applications of geotechnologies to retrieve vegetation and water parameters are strongly relevant.

On the one hand, the largest part of the dynamic agricultural products, are in general fruits for the external markets. On the other hand, the main impact between the use of the water resources and the environment is the pollution caused by the agricultural drainage, with the negative effects becoming worse under increasing water scarcity in the last years [2].

Algorithms for large-scale ET estimations need to be biophysically realistic but simple enough for implementation on large-scales [3]. The use of the

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Penman-Monteith (PM) equation has been suggested for application together with remote sensing parameters, for acquiring both, ET and the crop coefficient (K_c). This last coefficient is the ratio of ET to the reference evapotranspiration (ET_0) in optimum plant root-zone moisture conditions [4], while the lower ET/ET_0 values indicate water stress situations [5].

Based on modelling of the ET/ET_0 ratio, the SAFER (Simple Algorithm for Evapotranspiration Retrieving) algorithm was developed, being validated and applied for ET and K_c acquirements under different environmental Brazilian conditions [2, 6-7]. Although some researchers had been done by using MODIS images including the thermal band in the Brazilian semi-arid region [2], it is interesting to test the reflectance MODIS MOD13Q1 product to retrieve large-scale ET at the 250 m spatial resolution, involving different water and vegetation conditions along the year.

The objective of the current paper is the SAFER application to the MODIS MOD13Q1 product having interpolated data from a net of agrometeorological stations in the Brazilian semi-arid region, covering different thermohydrological conditions along the year 2016, to acquire large-scale ET values in mixed agro-ecosystems inside the Petrolina and Juazeiro counties, respectively Pernambuco and Bahia states.

The results may subsidize public policies for the rational water resources management under the actual scenarios of climate and land-use changes together with increasing water competitions among different water sectors.

2. Material and Methods

Fig. 1 shows the location of the net of agrometeorological stations in the Petrolina and Juazeiro counties, respectively Pernambuco (PE) and Bahia (BA) states, inside the semi-arid region of Northeast Brazil.

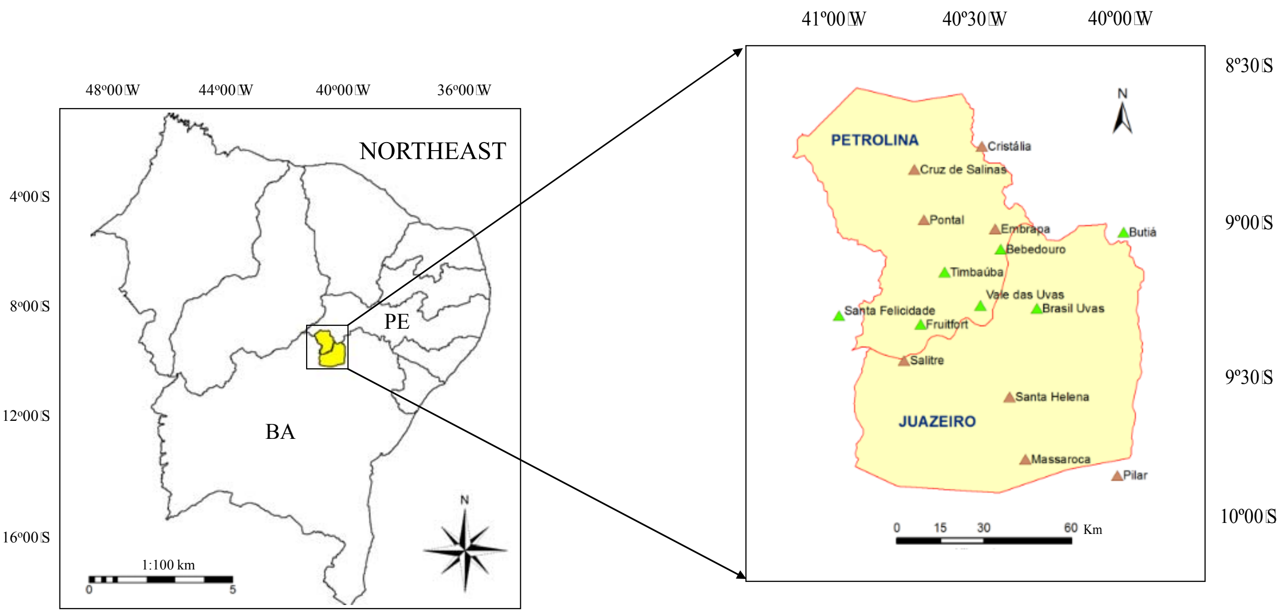

Fig. 1 Location of the agrometeorological stations in the Petrolina and Juazeiro counties, respectively Pernambuco (PE) and Bahia (BA) states, inside the semi-arid region of the Northeast Brazil. Green triangles are those inside irrigation farms, whereas the brown ones indicate those in natural vegetation ("Caatinga").

Petrolina and Juazeiro counties are located in the Brazilian Northeast, under the semi-arid conditions of the Low-Middle São Francisco River basin, in respectively Pernambuco and Bahia states. Excluding the areas of high altitude, annual averaged air temperatures (T) are higher than 24°C, even larger than

26°C in the depressions at 200 m to 250 m of altitude. The warmest months are October and November (21°C-29°C) when the sun is around the zenith position and the coldest months are June and July (19°C-25°C) at winter solstice in the southern hemisphere.

The long term basin annual precipitation (P) is in average 693 mm with 70% of the rainy period concentrated during the months January-April, being March (50-230 mm) and August (0-50 mm) the wettest and the driest months, respectively. Because of the temporal variability of rainfall, there are water deficits in the climatic water balance along the year, with the exception of March, when the conditions of this month are rarely dry [1].

The downloaded MOD13Q1 product resulted in 23 reflectance images of the MODIS bands 1 and 2 along the year 2016. These images together with the net of agrometeorological stations, made it possible to acquire the large-scale ET pixel values under different thermohydrological conditions at 16-day periods [2, 7]. Fig. 2 shows the flowchart of the steps for modeling actual evapotranspiration throughout SAFER algorithm and interpolated agrometeorological data to the MODIS MOD13Q1 reflectance product.

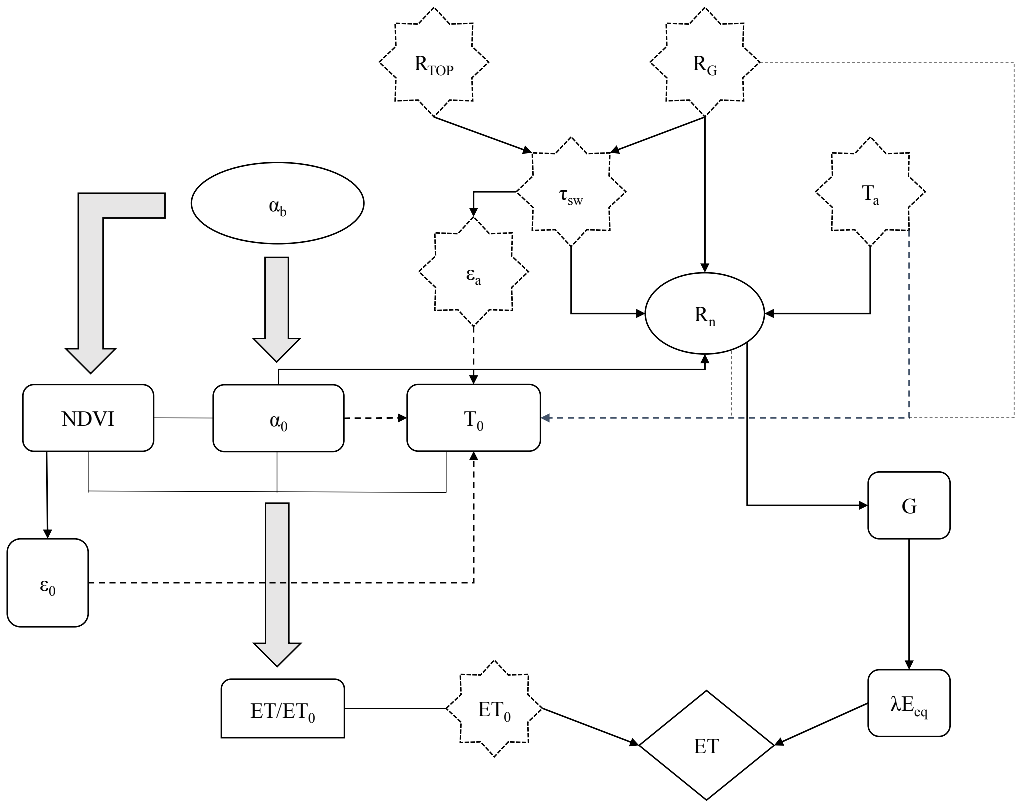

Fig. 2 Flow-chart for modelling the actual evapotranspiration (ET) throughout application of SAFER (Simple Algorithm for Evapotranspiration Retrieving) algorithm and interpolated agrometeorological data to MODIS MOD13Q1 reflectance product.

The parameterizations for acquiring ET, by using the SAFER algorithm in Fig. 2 were done in the semi-arid region of Brazil with simultaneous satellite and field measurements, under strong contrasting agro-ecosystems and thermohydrological conditions throughout different years [2, 7-8]. In addition, acquiring T_0 as residue in the radiation balance gives mutual compensation, reducing possible errors in this model input parameter, as in the upward and downward longwave fluxes, they are self-canceling.

Accordingly to Fig. 2, the band-reflectances (α_b), bands 1 (α_1) and 2 (α_2), in the red and near infrared of the solar spectrum, respectively, were extracted from the MOD13Q1 product, which provides cloud-free temporal composed images, at 16-day periods, totaling 23 images for each band along the year 2016.

For the surface albedo (α_0) calculation, the following equation was applied [9]:

$$\alpha_0 = a + b\alpha_1 + c\alpha_2 \tag{1}$$

where a, b and c are regression coefficients, considered as 0.08, 0.41, 0.14 for the Brazilian semi-arid conditions.

The Normalized Difference Vegetation Index (NDVI) was calculated as:

$$NDVI = \frac{\alpha_2 - \alpha_1}{\alpha_2 + \alpha_1} \tag{2}$$

The atmospheric emissivity (ε_A) was estimated as follows [8]:

$$\varepsilon_A = a_A \left(-\ln \tau_{SW}\right)^{b_A} \tag{3}$$

where τ_{SW} is the short-wave atmospheric transmissivity calculated as the ratio of R_G to the incident solar radiation at the top of the atmosphere (R_{TOP}); and a_A and b_A are regression coefficients 0.94 and 0.10, respectively.

The surface emissivity (ε_S) was estimated as follows [10-11]:

$$\varepsilon_S = a_S \ln NDVI + b_S \tag{4}$$

where a_S and b_S are regression coefficients 0.06 and 1.00, respectively.

The net radiation (R_n) can be described by the 24-hour values of net shortwave radiation, with a correction term for net longwave radiation [2, 7, 10-11]:

$$R_n = \left(1 - \alpha_0\right) R_G - a_L \tau_{SW} \tag{5}$$

where a_L is the regression coefficient of the relationship between net long wave radiation and τ_{SW} on a daily scale.

The a_L coefficient from Eq. (5) was correlated with the 24-hour T_a values [8]:

$$a_L = dT_a - e \tag{6}$$

where d and e are the regression coefficients 6.99 and 39.93 respectively.

The MODIS surface temperature (T_0) product was not used because with a lower spatial resolution (1000 km), there were cloud contaminations in some parts of the Petrolina/Juazeiro areas along the year. Instead, T_0 was retrieved by residue in the radiation balance (residual method) after having estimated the atmospheric and surface emissivities [12]:

$$T_0 = \sqrt[4]{\frac{R_G\left(1-\alpha_0\right) + \sigma\varepsilon_a T_a^4 - R_n}{\sigma\varepsilon_s}} \tag{7}$$

where T_a is the daily averaged air temperature and σ is the Stefan-Boltzmann constant (5.67×10^{-8} W m^{-2} K^{-4}).

The SAFER algorithm was used to model the ET/ET_0 ratio at the satellite overpass time:

$$\frac{ET}{ET_0} = \exp\left[a_s + b_s\left(\frac{T_0}{\alpha_0 NDVI}\right)\right] \tag{8}$$

where a_s and b_s are regression coefficients [2, 7].

The 24-hour ET pixel values were then estimated multiplying the daily grids of ET_0 by the results of Eq. (8):

$$ET = \left(\frac{ET}{ET_0}\right) ET_0 \tag{9}$$

where daily ET_0 values were obtained from data on R_G, T_a, relative humidity (RH) and wind speed at 2 m height (u) applying the Penman-Monteith method [13]. These weather data were interpolated by the Moving Average geostatistical method [10-12].

3. Results and Discussion

Fig. 3 presents the tendencies of the 16-day MODIS average totals for the climatic water balance components in terms of Day of the Year (DOY) in the counties of Petrolina-PE and Juazeiro-BA, Northeast Brazil, along the year 2016.

Along the year, P was more changeable than ET_0, with rain concentrations in January (DOY 001 to 032), when P accumulated values were three times of the

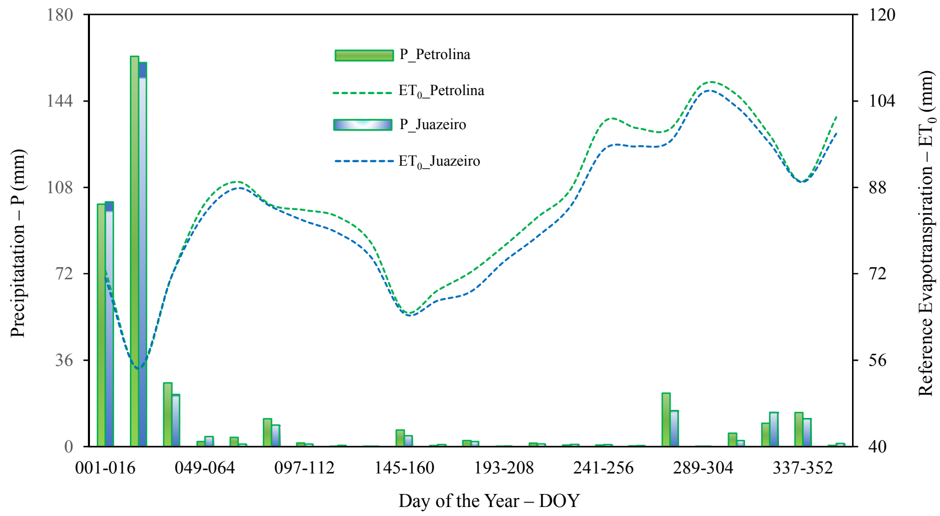

Fig. 3 Climatic water balance components in terms of Day of the Year (DOY), inside the counties of Petrolina-PE and Juazeiro-BA, Northeast Brazil, along the year 2016. Precipitation (P) and reference evapotranspiration (ET_0).

ET_0 corresponding ones during the first half of the month, in both counties. However, after January, rainfall declined, being close to 0% of ET_0, indicating strong climatic water scarcity along the year, with the annual total being 53% of the long-term value [1].

The highest ET_0 rates occurred at the start and at the end of the year, with the 16-day values above 80 mm. Although the annual rainfall amount in Petrolina (P = 374 mm yr^{-1}) being higher than that for Juazeiro (P = 355 mm yr^{-1}), with the atmospheric demand larger in the first County (ET_0 = 1952 mm yr^{-1}) than in the second one (ET_0 = 1905 mm yr^{-1}), the rains attended only 19% of ET_0 in both counties. This evidences that irrigation is indispensable for agriculture in the Brazilian semi-arid region, however should be carried out in a rational way, based on the crop water requirements, what brings importance of ET quantifications in its mixed agro-ecosystems.

Fig. 4 shows the spatial distributions and averages for some of the 16-day ET values, involving different thermohydrological conditions along the year 2016, in Petrolina-PE and Juazeiro-BA, Northeast Brazil.

The spatial and seasonal ET variations are very clear along the year, mainly comparing the 16-day rainy period at the start of the year with the drier ones (see Figs. 3 and 4), confirming the SAFER's sensitivity for detecting the water and vegetation conditions when applied to MODIS products.

Excepting the first months of the year, when occurred some storms, one can strongly distinguish irrigated crops from the "Caatinga" species at the vicinities of the São Francisco, with the much larger ET rates for the first ecosystem. Pixel with ET values around 5.0 mm d^{-1} represent mainly well-irrigated fruit crops.

Santos et al. [14], applying the SEBAL (Surface Energy Balance Algorithm for Land) algorithm to Landsat images, reported ET maximum values of 6.0 mm d^{-1} in the Brazilian semiarid. Also under these environmental conditions, but using the METRIC (Mapping Evapotranspiration at high Resolution with Internalized Calibration) algorithm, Folhes et al. [15] found lower ET pixel values for "Caatinga" species (< 2.0 mm d^{-1}) and moderate ones for fruit crops (3.0 a 6.0 mm d^{-1}), similar to those of the current study.

The reason for the higher "Caatinga" ET values at the start of 2016 in the actual study was the rain storms, making the natural species opening stomata and presenting ET rates similar or even higher than those for irrigated crops.

Fig. 5 presents the average 16-day ET values and standard deviations for each 16-day periods, involving different thermohydrological conditions along the year 2016 in the counties of Petrolina-PE e Juazeiro-BA, Northeast Brazil.

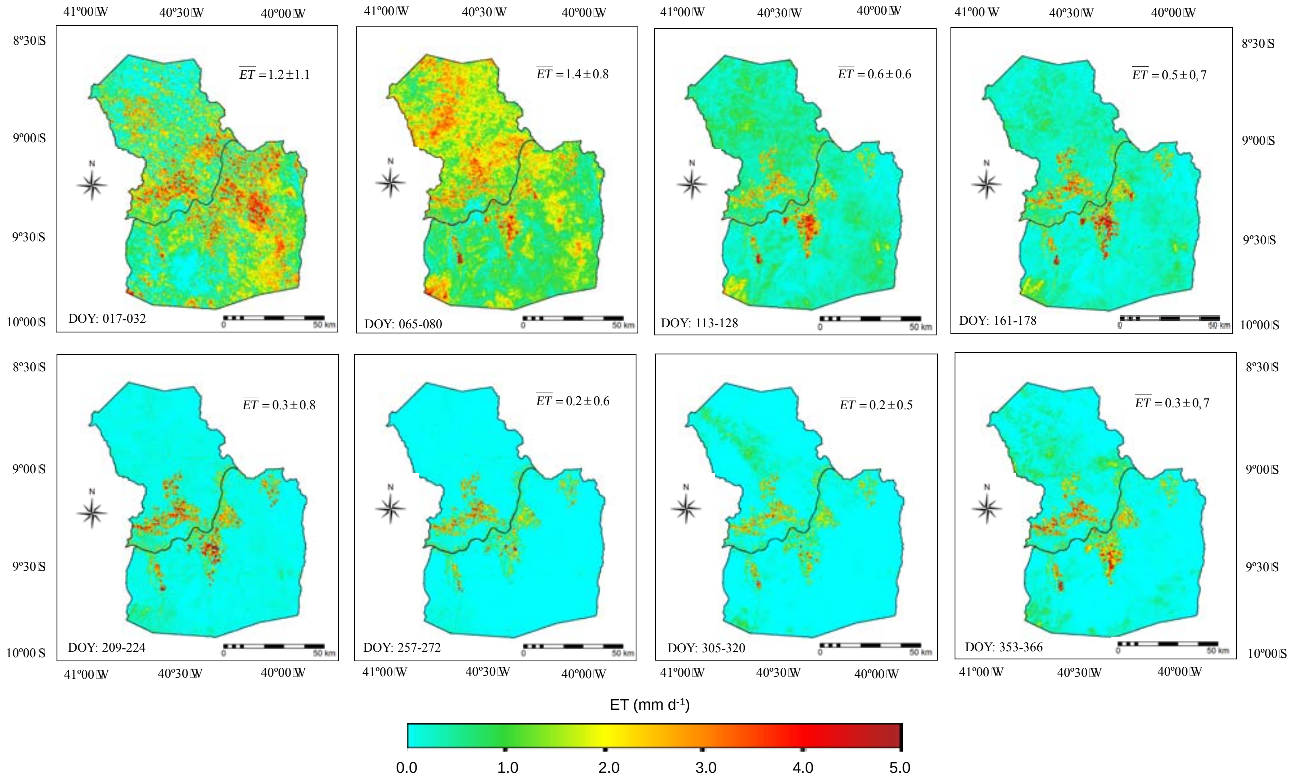

Fig. 4 Spatial distributions and averages for some 16-day actual evapotranspiration (ET) values, involving different thermohydrological conditions along the year 2016, in Petrolina-PE and Juazeiro-BA, Northeast Brazil. Overbars mean average pixel values shown together with the standard deviations.

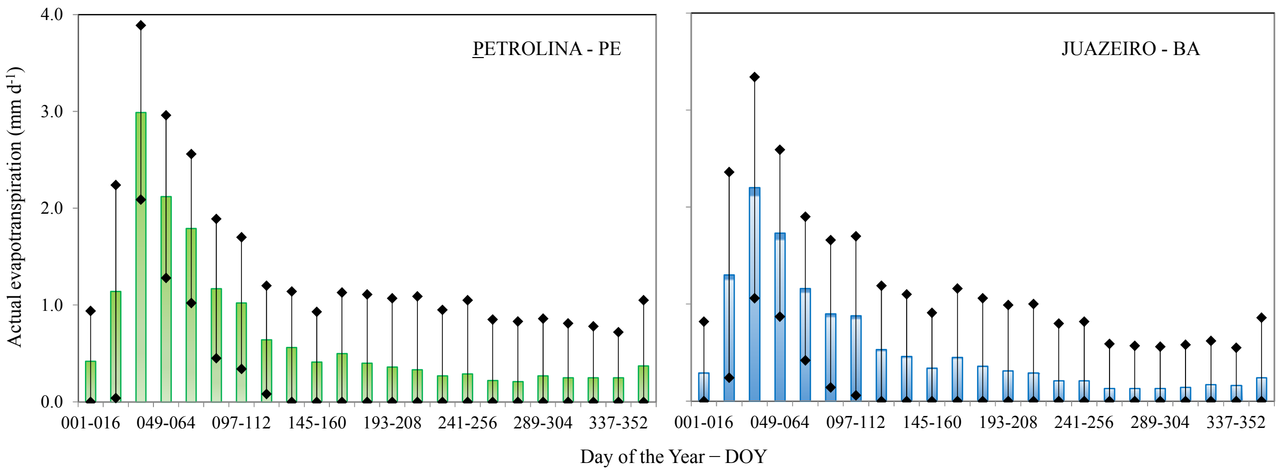

Fig. 5 Average values of actual evapotranspiration (ET) and standard deviations for each 16-day periods, involving different thermohydrological conditions along the year 2016 of Petrolina-PE and Juazeiro-BA counties, Northeast Brazil.

The highest ET rates were from January to April, for both counties. During this period, considering the high limit of the standard deviation values, the rates for crops reached to mean values of 4.0 mm d^{-1} (DOY 033-049), representing the coupled effect of rains and irrigation. After DOY 128, first half of May, the natural species ("Caatinga"), controlled transpiration, because of rains absence/decline, picturing strong water scarcity conditions (see also Fig. 3).

Leivas et al. [16] applying the SAFER algorithm to the MOD13Q1 MODIS reflectance product in areas with irrigation pivots inside the semi-arid region of Minas Gerais state, Southeast Brazil, reported average ET values of 3.5±1.0 mm d^{-1}, similar to those for irrigated crops in the current study. The authors concluded that ET monitoring in irrigation pivots with MODIS images could be valuable, despite their low spatial resolution limitations.

Although Petrolina and Juazeiro counties presenting similar temporal water flux dynamics along the year 2016, the ET rates in the second County were 78% of those for the first one. Even with less rainfall amounts in Juazeiro, the moisture conditions were balanced by the lower atmospheric demand. Thus, one reason for the lower ET rates in Juazeiro County should be less irrigation water use from the São Francisco River by crops.

4. Conclusion

It was possible to model the large-scale actual evapotranspiration (ET) values, under different thermohydrological conditions, throughout the SAFER algorithm applications by coupling the MODIS MOD13Q1 reflectance product and a net of agrometeorological stations under the semi-arid conditions of Petrolina and Juazeiro counties, respectively Pernambuco (PE) and Bahia (BA) states, Northeast Brazil.

The combination of the derived remote sensing parameters and weather data proved efficiency to detect the water and vegetation dynamics. During the analyzed year 2016, Juazeiro presented lower rainfall amounts when compared with Petrolina, however, under lower atmospheric demands, the evapotranspiration rates in the first County resulted in lower crop water consumption from the São Francisco River.

The limitations of the low spatial resolution of 1 km for the thermal MODIS band was solved, by retrieving the surface temperature from the residual emitted long wave radiation from the surfaces together with agrometeorological data, allowing the downscaling the 16-day ET rates to a spatial resolution of 250 m along the year.

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