

ORBITAL AND SURFACE EVAPOTRANSPIRATION COMPARED TO FAO-56 STANDARD IN STATE OF ACRE

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1 ABSTRACT

Evapotranspiration is a critical component of the hydrological and life cycles, with a major impact on water consumption by the population, agricultural activities, and the global climate. This study aims to compare the reference evapotranspiration (ET_o) eight different empirical methods with the FAO-56 standard, using orbital and surface data for the years 2003 and 2008 in the State of Acre. For surface data methods, the Irmak-2 and Val-4 showed a higher performance and the Alexandris method showed the worst performance compared with the FAO-56 standard. The spatial distribution of ET_o derived of the orbital data method were compared based on the annual mean, presenting lower ET_o (2.26 mm d^{-1}) in 2003 and higher average (3.94 mm d^{-1}) in 2008. This interannual variability of ET_o may be associated with moderate El Niño events in 2003 and strong La Niña in 2008. The statistical analysis showed satisfactory results of the evapotranspiration mean values for the years 2003 and 2008 obtained by MODIS sensor data, but it is important to have a greater representation of weather stations in the state for future studies. The results serve as a subsidy for water demand estimates of vegetation, as well for biomass productivity and changing landscape studies.

Keywords: orbital platforms, water availability, weather stations.

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EVAPOTRANSPIRAÇÃO ORBITAL E DE SUPERFÍCIE COMPARADOS AO PADRÃO FAO-56 NO ESTADO DO ACRE

2 RESUMO

A Evapotranspiração é um componente crítico do ciclo hidrológico e da vida, com grande impacto no consumo de água pela população, em atividades agrícolas e no clima global. O

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presente trabalho tem por objetivo comparar a evapotranspiração de referência (ET_0) a partir de diferentes métodos ao padrão FAO-56, utilizando dados orbitais e de superfície para os anos de 2003 e 2008 no Estado do Acre. Para os dados de superfície, o Irmak-2 e o Val-4 mostraram um maior desempenho e o método proposto por Alexandris o pior desempenho em comparação ao padrão FAO-56. A distribuição espacial dos valores de ET_0 foi comparada com base nos valores médios anuais, sendo que o período de 2003 apresentou ET_0 mais baixa (2.26 mm d^{-1}) e o ano de 2008 os valores mais elevados (3.94 mm d^{-1}). Esta variabilidade de ET_0 pode estar associada aos eventos de El Niño moderado em 2003 e La Niña forte em 2008. A análise estatística apresentou resultados satisfatórios dos valores médios para os anos de 2003 e 2008 de evapotranspiração obtidos pelo sensor MODIS, porém é importante que haja uma maior representatividade das EMS no estado para estudos futuros. Os resultados servem como subsídio para estimativas de demanda hídrica da vegetação, como também para estudos de produtividade de fitomassa e mudança da paisagem.

Palavras-Chave: plataformas orbitais, disponibilidade de água, estações meteorológicas.

3 INTRODUCTION

The reference evapotranspiration (ET_0) is part of a set of essential parameters for water resource planning and management, both in terms of watersheds and in irrigated agricultural activities. Thus, the ET_0 is a parameter used for different purposes, such as the water balance estimate, climate and hydrological modeling, and to characterize the climate of a particular region (SILVA et al., 2014).

The ET_0 can be estimated by empirical or physical-physiological models according to the weather elements. The models range from the simple, such as those based only on air temperature (e.g. Thornthwaite and Hargreaves-Samani), to the most complex, involving energy balance in terms of vegetation, such as the Penman-Monteith model (ANJOS et al., 2016). The adjusted Penman-Monteith model (ALLEN et al., 1998) adopted by the Food and Agriculture Organization of the United Nations (FAO-56) is considered the most widely used standard method for ET_0 estimation (COSTA; MANTOVANI; SEDIYAMA et al., 2015). However, this method requires surface data for a large number of variables such as air temperature, solar radiation, relative humidity and wind speed. Many localities do not have weather stations to obtain such data or, where they are present, have only a few variables and/or low quality data.

In view of this, several alternative empirical methods to FAO-56 model have been proposed for estimating ET_0 (IRMAK et al., 2003; ALEXANDRIS; KERKIDES; LIAKATAS, 2006; VALIANTZAS, 2013) in order to simplify the equations and thus reduce costs, while maintaining a good level of accuracy. Most methods use surface data, so for representing ET_0 in extensive areas, the data retrieval is required in different locations to ensure a good representation for a determined region. However, methods based on remote sensing data have also been developed (NAGLER et al., 2005), allowing large-scale studies, regional to global, and providing spatialized estimates.

In Brazil, some studies have been developed for the determination of ET_0 from different methods (OLIVEIRA et al., 2010; SOUZA et al., 2011; COSTA; MANTOVANI; SEDIYAMA, 2015; RIBEIRO et al., 2015). In the state of Acre, city of Cruzeiro do Sul, Souza et al. (2011) evaluated the performance of three simplified methods for estimating ET_0 under the climatic conditions of the region. The evaluated models showed unsatisfactory performance

in the monthly scale, presenting overestimation and underestimation in monthly ET_0 values. In the state of Rio de Janeiro, with the objective of estimating evapotranspiration with the model proposed by Nagler et al. (2005), using remote sensing techniques through the MODIS sensor, Anjos et al. (2016) found satisfactory results, but it is important to have a greater representation of Surface Weather Stations (SWS) for future studies. Other studies using environmental satellites in estimating evapotranspiration were performed in the irrigated perimeter of the Brazilian Semi-Arid (SILVA et al., 2012), in the state of Minas Gerais (FERREIRA; DANTAS, 2014), in Rio Jardim in Ceará (DANTAS et al., 2015) among others.

There were few studies in Acre related to evapotranspiration, concerning the comparison and prognosis of their distribution patterns, especially in spatial scale, given the limited surface data in this state. Thus, this study aims to evaluate the performance of different methods to estimate reference evapotranspiration in relation to the FAO-56 standard for the state of Acre, using orbital and surface data.

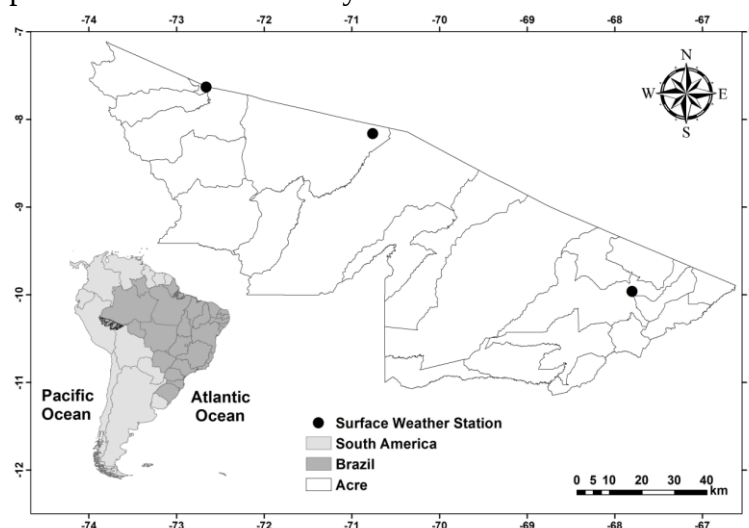
4 MATERIAL AND METHODS

4.1 Study Area and Data

The study area comprises the state of Acre, in Brazil, which presents a climate classified according to Koppen in Af (Tropical rainforest climate; average precipitation of at least 60 mm in every month) and Am (Tropical monsoon climate; driest month which nearly always occurs at or soon after the "winter" solstice for that side of the equator with precipitation less than 60 mm, but more than 4% the total annual precipitation). The Af climate represents 70.5% of the territory, spanning from the region of Cruzeiro do Sul/AC to the region of Tarauacá/AC. The remaining 29.5% of Acre correspond to the Am climate, including the region of Rio Branco/AC (ALVARES et al., 2014). The average annual rainfall is 2166 mm, with March being considered the rainiest month whilst July presents the lowest average rainfall. The average air temperature in Acre is 24.5 °C and the average relative humidity is 85% (DUARTE, 2005).

The surface data were obtained from three SWS of the National Institute of Meteorology (INMET), located in the municipalities of Rio Branco, in the eastern part; Tarauacá, in the central part; and Cruzeiro do Sul, in the far west (Figure 1).

Figure 1. Geographical location of the study area with their surface weather stations.



The SWS are located in the following geographical coordinates: 67°08'00" W and 09°06'00" S (Rio Branco); 70°06'00" W and 08°16'00" S (Tarauacá); 72°06'00" W and 07°03'00" S (Cruzeiro do Sul). For each SWS, daily data for the days of the year 9, 41, 73, 105, 137, 169, 201, 233, 265, 297, 313 and 345 were obtained, covering all the months of the years 2003 and 2008, for the following variables: maximum, minimum and average air temperature, average relative humidity, average wind speed at 2 meters high and cloudiness.

For the estimation of the reference evapotranspiration based on remote sensing, MODIS sensor data was used, aboard the Aqua/Earth Observing System PM-1 satellite, with a spatial resolution of 1 km and crossing the Equator at 1:30 pm. The MYD11A2 and MYD13A2 products were obtained in order to acquire LST (Land Surface Temperature) and EVI (Enhanced Vegetation Index) data, respectively, for the period from January to December of 2003 and 2008. In order to provide images free of clouds and with atmospheric correction, the MYD11A2 and MYD13A2 products are generated from the 8 and 16 days averages, respectively (LATORRE et al., 2003). The H11V10, H11V09 and H10V09 tiles were obtained, covering the entire state of Acre, through the "United States Geological Survey - Global Visualization Viewer" (USGS - GLOVIS), available at link <http://glovis.usgs.gov/>. The orbital data, obtained in sinusoidal projection and HDF format, were converted to the Geographic Coordinate System (GCS) projection and Geotiff format through Modis Reprojection Tool (MRT) software. This program also allowed the realization of mosaic of the tiles, as well as allowing select the LST layer of MYD11A2 and EVI layer of MYD13A2 products.

4.2 Estimation of ET_0 by the standard method FAO-56

Using the daily weather data for each day of the astronomical year, the daily ET_0 was estimated by the Penman-Monteith model (FAO-56) (Equation 1) following the method described by Allen et al. (1998), which is considered as a reference in relation to other evaluated.

$$ET_0 = \frac{0.408 * \Delta * (Rn - G) + \gamma * \frac{900}{T+273} * u_2 * (e_s - e_a)}{\Delta + \gamma * (1 + 0.34 * u_2)} \quad (1)$$

Where:

- ET_0 = reference evapotranspiration (mm d^{-1});
- Rn = net radiation at the plant surface ($\text{MJ m}^{-2} \text{d}^{-1}$);
- G = soil heat flux density at the soil surface ($\text{MJ m}^{-2} \text{d}^{-1}$);
- T = average air temperature at 2 m height ($^{\circ}\text{C}$);
- u_2 = wind speed at 2 m height (m s^{-1});
- e_s = saturation vapour pressure (kPa); e_a = actual vapour pressure (kPa);
- Δ = slope of the vapour pressure curve ($\text{kPa } ^{\circ}\text{C}^{-1}$);
- γ = psychrometric constant ($\text{kPa } ^{\circ}\text{C}^{-1}$) and
- 0.408 = conversion factor to the term $(Rn - G)$ from $\text{MJ m}^{-2} \text{d}^{-1}$ for mm d^{-1} .

4.3 Alternative empirical methods of ET_0

Table 1 presents a summary of the eight empirical methods for estimating ET_0 , seven of them based on surface data, from the approaches developed by Irmak et al. (2003), Alexandris,

Kerkides e Liakatas (2006) and Valiantzas (2013), and one of them, proposed by Nagler et al. (2005), based on remote sensing data.

Table 1. Empirical methods of ET_o .

Method ID	Equation	Variables	Reference
Val-1	$ET_o = 0,0393 \text{ Rs } \sqrt{T + 95} - 0,19 \text{ Rs}^{0,6} \phi^{0,15} + 0,048 (T + 20) \left(1 - \frac{RH}{100}\right) u^{0,7}$	Rs, T, ϕ, RH, u	Valiantzas (2013)
Val-2	$ET_o = 0,0393 \text{ Rs} \sqrt{T + 95} - 0,19 \text{ Rs}^{0,6} \phi^{0,15} + 0,0037 (T + 20) (1,12T - T_{\min} - 2)^{0,7}$	$Rs, T, T_{\min}, \phi$	
Val-3	$ET_o = 0,0393 \text{ Rs } \sqrt{T + 95} - 0,19 \text{ Rs}^{0,6} \phi^{0,15} + 0,078 (T + 20) \left(1 - \frac{RH}{100}\right)$	Rs, T, ϕ, RH	
Val-4	$ET_o = 0,0393 \text{ Rs } \sqrt{T + 95} - 0,19 \text{ Rs}^{0,6} \phi^{0,15} + 0,0037 (T + 20) (1,12T - T_{\min} - 2)^{0,7} U_{av}^{0,7}$	$Rs, T, T_{\min}, \phi, U_{av}$	
Irmak-1	$ET_o = -0,611 + 0,149 \text{ Rs} + 0,079 \text{ T}$	Rs, T	Irmak et al. (2003)
Irmak-2	$ET_o = 0,489 + 0,289 \text{ Rn} + 0,023 \text{ T}$	Rn, T	
Alex	$ET_o = 0,057 + 0,227 \text{ C}_2 + 0,643 \text{ C}_1 + 0,0124 \text{ C}_1 \text{ C}_2$	Rs, T, RH	Alexandris, Kerkides e Liakatas (2006)
	$C_1 = 0,6416 - 0,00784 \text{ RH} + 0,372 \text{ Rs} - 0,00264 \text{ Rs RH}$		
Nagler	$C_2 = -0,0033 + 0,00812 \text{ T} + 0,101 \text{ Rs} + 0,00584 \text{ Rs T}$	EVI^*, LST	Nagler et al. (2005)
	$ET_o = 0,355 (1 - \exp^{(-2,28 \text{ EVI}^*)}) (LST - 20,3) + 0,7$		

Rs = solar radiation ($MJ m^{-2} d^{-1}$); T = daily average air temperature ($^{\circ}C$); ϕ = latitude of the station (radians); RH = daily average relative humidity of the air (%); u = daily average wind speed at 2 m height ($m s^{-1}$); T_{min} = daily minimum air temperature ($^{\circ}C$); U_{av} = local long-term average annual wind speed ($m s^{-1}$); Rn = net radiation ($MJ m^{-2} d^{-1}$); EVI^* = adjusted Enhanced Vegetation Index; LST = Land Surface Temperature.

Valiantzas (2013) developed simplified equations to approximate the Penman-Monteith equation for estimating ET_o from the limited data. The first suggested equation, here called Val-1, uses routinely measured data: air temperature, solar radiation, relative humidity and wind speed. Simplifications of this equation were made to be applied in places where wind speed data (Val-3), relative humidity (Val-4) or both (Val-2) are not available.

The equations proposed by Irmak et al. (2003) were developed from the Penman-Monteith method (FAO-56). The first equation, Irmak-1, uses solar radiation and air temperature, and the second equation, Irmak-2, uses net radiation and air temperature. The equations were derived by using 15 years of daily FAO-56 ET_o , estimated from meteorological data of Florida. Alexandris et al. (2006) developed an empirical equation for daily reference evapotranspiration using data from three attributes (solar radiation, temperature and relative humidity). The equation coefficients were determined by a bilinear surface regression analysis.

The method of Nagler et al. (2005) was developed to estimate ET_o in riparian forest along the Middle Rio Grande River in New Mexico, based on vegetation indices and land surface temperature derived from remote sensing. For the application of this model to the state of Acre, it took some adjustments of data of vegetation index and the surface temperature, processed on the premises of the Rural Federal University of Rio de Janeiro - Environmental Remote Sensing and Applied Climatology Laboratory - LSRACA by through ArcGIS 10.2[®] software. It was held the clipping of the study area with the Acre state boundaries in *shapefile* format, obtained by the Brazilian Institute of Geography and Statistics (IBGE). The data of the

MYD11A2 product were converted to temperatures in Kelvin (T_K) (Equation 2) and then to degrees Celsius (T_C) (Equation 3) using the following equations:

$$T_K = MYD11A2 * 0,02 \quad (2)$$

$$T_C = T_K - 273,15 \quad (3)$$

Furthermore, the EVI available in the MYD13A2 product has range from -1 to 1, and therefore, it was necessary to rescale the data to positive values (EVI*) according to Equation 4.

$$EVI^* = \frac{EVI+1}{2} \quad (4)$$

From this stage, the yearly maps of ET_o have been generated by the following equation:

$$ET_y = \frac{\sum ET_m}{12} \quad (5)$$

Where:

ET_y is the annual evapotranspiration (mm d^{-1});

ET_m is the monthly evapotranspiration (mm d^{-1}).

4.4 Statistical analysis

For the comparison of the FAO-56 ET_o - in relation to the surface methods and the method of Nagler et al. (2005), based on remote sensing data, the following statistical parameters were used: Mean Error (ME, Equation 6), Root Mean Square Error (RMSE, Equation 7), Pearson's linear correlation coefficient (r , Equation 8) and agreement index (d , Equation 9) proposed by Willmott et al. (1985). The equations used are presented below:

$$ME = \frac{\sum_{i=1}^n (E_i - O_i)}{n} \quad (6)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^n (E_i - O_i)^2}{n}} \quad (7)$$

$$r = \frac{\sum_{i=1}^n (E_i - \bar{E})x(O_i - \bar{O})}{\sqrt{\sum_{i=1}^n (E_i - \bar{E})^2 \sum_{i=1}^n (O_i - \bar{O})^2}} \quad (8)$$

$$d = 1 - \left[\frac{\sum_{i=1}^n (E_i - O_i)^2}{\sum_{i=1}^n (|E_i - O_i| + |O_i - \bar{O}|^2)} \right] \quad (9)$$

Where:

E_i = estimated value of ET_o in the time interval i ;

O_i = value of FAO-56 standard in the time interval i ;

n = number of analyzed data;

$\bar{E}$ = estimated average value of ET_o ;

$\bar{O}$ = average value of FAO-56 standard.

The correlation coefficient was evaluated by the t-Student test, at a significance level of 5%. We used the R software, version 3.1.0 to perform the statistical analysis of data set in the period January to December for the years 2003 and 2008.

5 RESULTS AND DISCUSSION

The average values of ET_0 and their respective standard deviations, derived from the nine methods discussed in this work, for the three regions of the state of Acre, are shown in Table 2.

Table 2. Average and standard deviation (sd) values of ET_0 (mm d^{-1}) according to the different methods in the three regions studied.

Method	Rio Branco		Tarauacá		Cruzeiro do Sul	
	Average	sd	Average	sd	Average	sd
FAO-56	4.97	1.53	4.49	1.49	4.26	1.63
Val-1	3.75	1.15	3.29	1.07	3.23	1.27
Val-2	3.47	1.11	3.15	1.04	3.11	1.19
Val-3	3.90	1.17	3.41	1.05	3.47	1.34
Val-4	3.99	1.17	3.67	1.18	3.56	1.23
Irmak-1	4.07	0.83	3.84	0.79	3.88	0.83
Irmak-2	5.79	1.51	5.29	1.39	5.10	1.61
Alex	3.07	0.96	2.81	0.97	2.65	1.04
Nagler	4.33	1.02	4.00	0.97	3.90	0.91

Note that the average ET_0 estimated by the method Nagler was the one that was closer to the FAO-56 standard in the three study areas, considering the average of the evaluated period (2003 and 2008). As a result, this method had the lowest mean error (Table 3) for the three regions.

Table 3. Orbital and surface methods compared with FAO-56 evapotranspiration (2003 and 2008) for the state of Acre.

Method	Rio Branco				Tarauacá				Cruzeiro do Sul			
	ME	RMSE	R	d	ME	RMSE	r	d	ME	RMSE	r	d
Val-1	-1.22	1.32	0.97	0.74	-1.20	1.28	0.99	0.76	-1.04	1.14	0.97	0.81
Val-2	-1.50	1.58	0.98	0.70	-1.34	1.41	0.99	0.73	-1.15	1.25	0.99	0.79
Val-3	-1.07	1.19	0.96	0.76	-1.08	1.18	0.98	0.78	-0.80	1.03	0.92	0.83
Val-4	-0.99	1.06	0.99	0.80	-0.82	0.88	0.99	0.84	-0.71	0.83	0.99	0.87
Irmak-1	-0.90	1.16	0.97	0.78	-0.64	0.95	0.99	0.83	-0.38	0.89	0.98	0.86
Irmak-2	0.81	0.83	0.99	0.86	0.80	0.81	1.00	0.87	0.84	0.86	0.99	0.87
Alex	-1.91	2.00	0.99	0.63	-1.68	1.76	1.00	0.67	-1.61	1.73	0.99	0.71
Nagler	-0.65	1.19	0.75	0.78	-0.49	1.20	0.66	0.78	-0.36	1.24	0.68	0.80

ME and RMSE in mm d^{-1}

However, the lowest annual average RMSE was observed in the methods Irmak-2 (0.83 mm d^{-1} ; 0.81 mm d^{-1} and 0.86 mm d^{-1} , to Rio Branco, Tarauacá and Cruzeiro do Sul,

respectively) and Val-4 (1.06 mm d^{-1} ; 0.88 mm d^{-1} and 0.83 mm d^{-1} , to Rio Branco, Tarauacá and Cruzeiro do Sul, respectively). The RMSE of the method Nagler was higher than the mean error (in magnitude), because it showed overestimation of ET_o in few months and underestimation in others (Figure 2), making these positive and negative errors to be eliminated in the mean error statistic.

The other methods of ET_o based on surface data (Val-1, 2, 3 e 4, Irmak-1 and Alex) presented underestimation in approximately every month or overestimation in all months, in the case of the method Irmak-2 (Figures 2 and 3).

Figure 2. Monthly mean error of methods Val-4, Irmak-1, Irmak-2, Alex and Nagler in relation to the FAO-56 standard, for the three SWS.

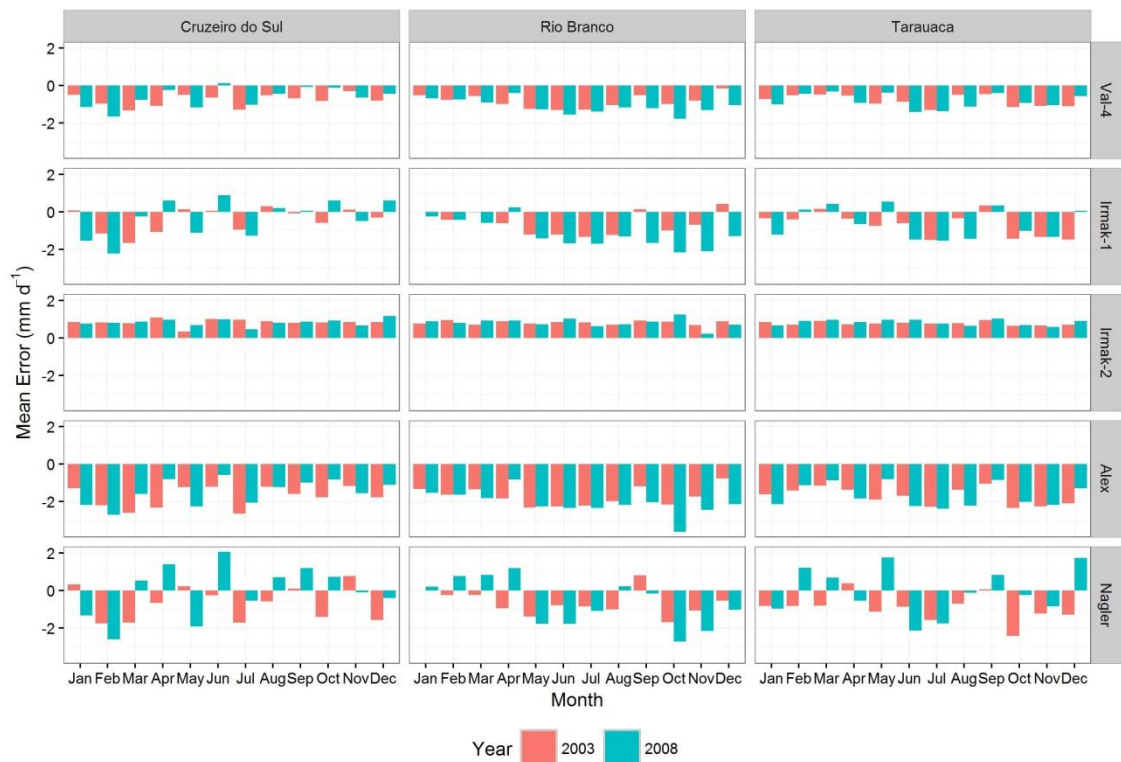
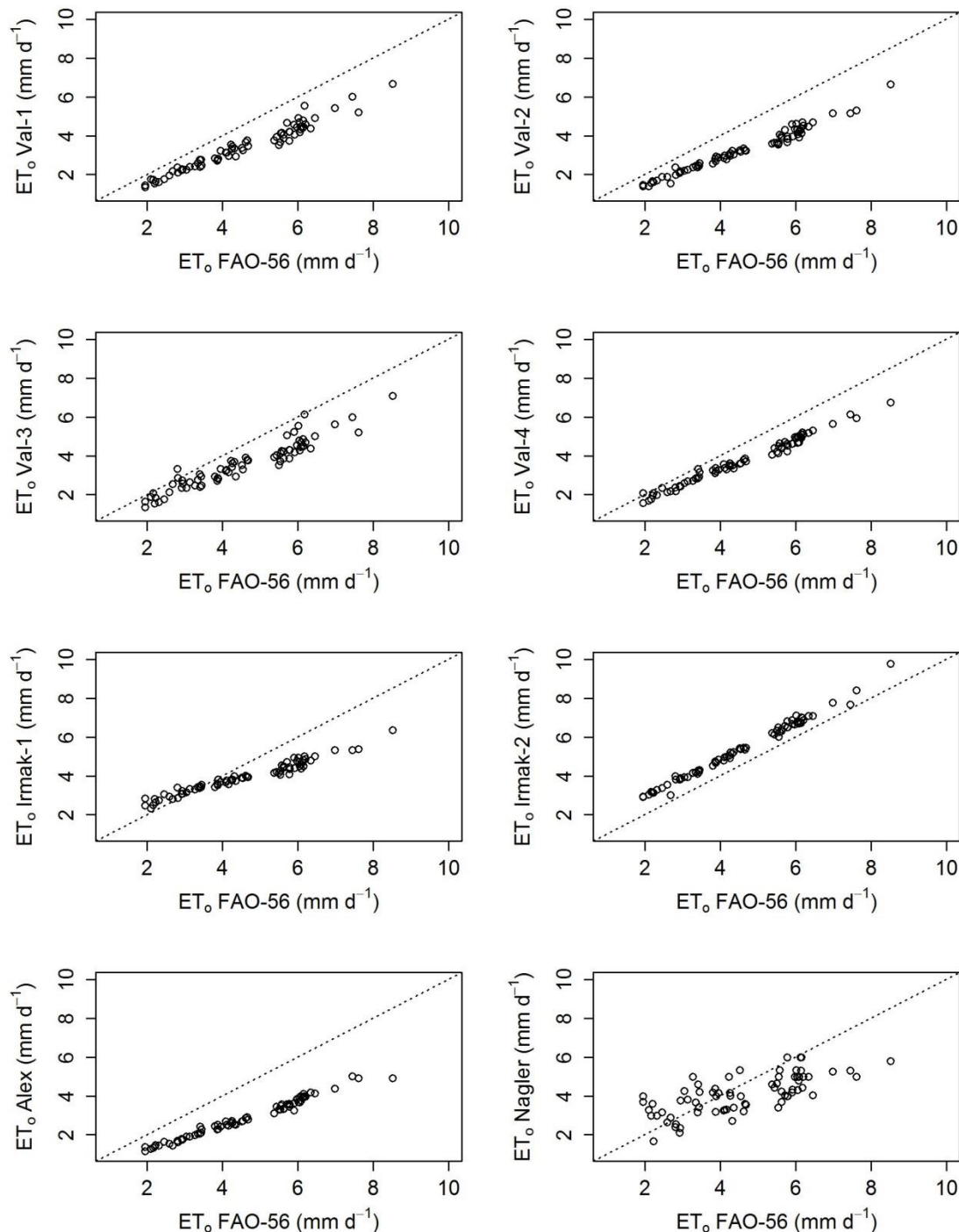


Figure 3. Relationship between ET_o estimated by different methods and ET_o FAO-56 standard.

The negative values of mean error for most methods and positive values for Irmak-2, reflect these tendencies of under or overestimation of ET_o (Table 3).

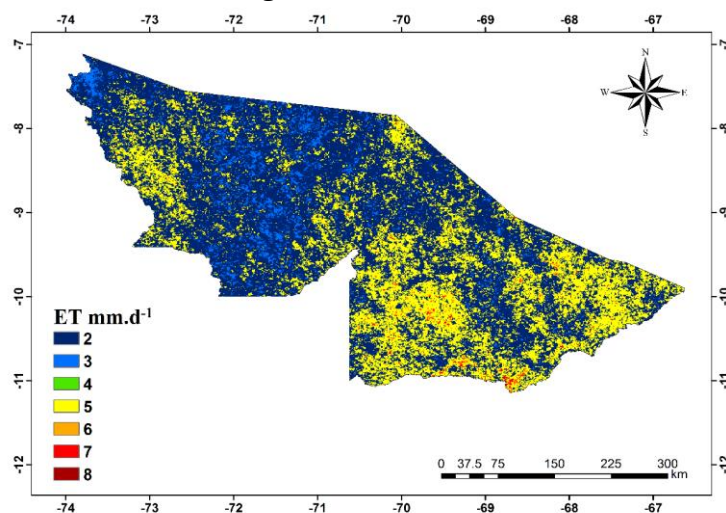
All methods showed significant linear correlation ($p < 0.05$ significance) in relation to the FAO-56 standard. The methods based on surface data presented Pearson's correlation coefficient very close to 1, however, the Willmott's agreement index generally showed lower values, between 0.63 and 0.87, due to estimation errors. Among the methods evaluated, the model proposed by Alexandris (2006) showed the worst performance in relation to the FAO-

56 standard, since it had the highest values of ME and RMSE and the lowest values of Wilmott's index for the three regions studied (Table 3).

In Figure 3, it is observed that, in most methods, the error is small for smaller ET_o values and increases as the ET_o increases. Only the Irmak-2 method had a lower ratio between the error and the ET_o according to FAO-56 ($r = -0.32$). The Val-1, Val-2, Val-3, Val-4 and Alex methods showed higher underestimation error for larger values of ET_o , that is, the estimates generated by these methods were closer to the FAO-56 standard for lower ET_o values (below 4 mm.d^{-1}). The methods of Nagler and Irmak-1 also showed this pattern, but the estimates of lower ET_o values tended to be overestimated. This indicates that the above methods perform better for low evapotranspiration values, as they were originally developed for other regions different of the Amazon, which has higher evapotranspiration rates.

In the analysis of Figure 4, the eastern and southeastern portions of the state of Acre had the highest evapotranspiration values ranging from 5 to 6 mm.d^{-1} .

Figure 4. Spatial distribution of average ET_o in Acre for 2003.

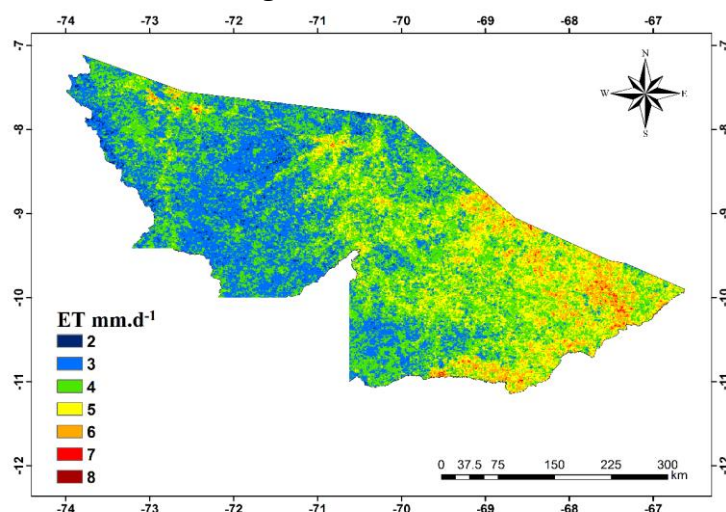


The values below 2 mm d^{-1} were concentrated in the west and northwest of Acre (Figure 4), with the main features being the rugged terrain and high altitudes. Giongo e Vettorazzi (2011) found similar results for evapotranspiration in Corumbataí River Basin in the state of São Paulo, where the areas more rugged showed lower evapotranspiration due to the lower incidence of solar radiation.

According to Weather Forecasting and Climate Studies Center (CPTEC, 2016a), 2003 was a year of moderate El Niño, which may have reduced water availability due to lower rainfall rates in this region. According to fire foci database of the National Institute for Space Research (CPTEC, 2016b), there were 14780 fires outbreaks in this year in Acre, which may be related to lower values of water availability and higher incidence of biomass loss for this year.

The 2008 mean value of spatial evapotranspiration to the state of Acre was 3.94 mm d^{-1} , with the highest values found in the eastern and southeastern portions of the state (Figure 5).

Figure 5. Spatial distribution of average ET_o in Acre for 2008.



It was observed that the highest evapotranspiration, approximately 8 mm d^{-1} , occurred in areas occupied predominantly by pastures, agriculture and urban areas, extending by regions of low altitude.

According to the Weather Forecast and Climate Studies Center (CPTEC, 2016a), 2008 was a year of strong La Niña, which may have increased the water availability as a result of higher rainfall rates in this region. According to fire foci database of the National Institute for Space Research (CPTEC, 2016b), there were 5129 fire foci in Acre in 2008, which is significantly lower than the one recorded in 2003, probably due to the increased water availability in the region.

6 CONCLUSIONS

Regarding the ET_o FAO-56 standard, the Irmak-2 and Val-4 methods showed a higher performance due to the lower values of RMSE and higher values of Wilmott's agreement index. The Alex method presented the worst performance compared to FAO-56 standard. Statistical analysis of ET_o values observed by SWS and estimated by MODIS sensor, from the method of Nagler, presented satisfactory index on an annual scale, becoming an applicable model for hydrologic studies in large areas. It is necessary that other comparisons be made with large amounts of SWS and other sensors, in order to take into account other spatial resolutions and regions of Acre.

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