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Analysis of Precipitation and Evapotranspiration in Atlantic Rainforest Remnants in Southeastern Brazil from Remote Sensing Data

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Abstract

The Atlantic Rainforest has been intensely devastated since the beginning of the colonization of Brazil, mainly due to wood extraction and urban and rural settlement. Although the Atlantic Rainforest has been reduced and fragmented, its remnants are important sources of heat and water vapor to the atmosphere. The present study aimed to characterize and to analyze the temporal dynamics of precipitation and evapotranspiration in the Atlantic Rainforest remnants in São Paulo state, southeastern Brazil, for the period from January 2000 to December 2010. To achieve this, global precipitation and evapotranspiration data from TRMM satellite and MOD16 algorithm as well as forest remnant maps produced by SOS Mata Atlântica Foundation and Brazilian National Institute for Space Research (INPE) were used. Results found in this study demonstrated that the use of remote sensing was an important tool for analyzing hydrological variables in Atlantic Rainforest remnants, which can contribute to better understand the interaction between tropical forests and the atmosphere, and for generating input data necessary for surface models coupled to atmospheric general circulation models.

Keywords: hydrological variables, Atlantic Rainforest, South America, TRMM, MOD16, remote sensing

1. Introduction

The Atlantic Rainforest stretches across Brazil, Argentina, and Paraguay, and is considered the second largest tropical forest in the American continent [1]. In Brazil, the Atlantic Rainforest covers 17 states, from Ceará to Rio Grande do Sul, and is located along coastal and inland regions, over mountains and plateaus [2]. The great longitudinal and latitudinal extension and, consequently, the wide variability in rainfall and temperature provide, combined with altitude gradient and ancient vegetation formations, a high degree of biodiversity and endemism [3].

The Atlantic Rainforest was heavily devastated since the beginning of Brazilian colonization, mainly due to wood extraction and rural and urban settlement. Thus, from the original forest cover, only isolated remnants with variable sizes in different successional stages were left [4]. Recent studies show that only 8.5% of the original Atlantic Rainforest, estimated in 1.3 million km^2, still exists [5]. The state of São Paulo (henceforth referred to as SP), despite its high levels of agricultural and urban development, presents the largest remnants of Atlantic Rainforest in the country. Estimates show that 13.9% of the original Atlantic Rainforest still exists in SP [6].

Although Atlantic Rainforest has been reduced and fragmented, its remnants are an important source of heat and water vapor to the atmosphere. This is because latent heat released as evapotranspiration influences the atmospheric circulation in the tropics and the water vapor contributes to the regional precipitation regime [7]. In this context, knowing the annual and interannual variability of precipitation and evaporative processes in tropical biomes is necessary for a better understanding of the energy and water partitioning between surface and atmosphere, which allows for a better parameterization of the boundary layer processes used in climate and weather forecasting models [8, 9].

Usually, precipitation and evapotranspiration are measured by instruments equipped in conventional meteorological stations; however, these measurements are expensive and do not represent well the spatial variability of these processes [10]. Hence, the use of remote sensing techniques becomes a methodological alternative since it enables to obtain different biophysical parameters at the Earth's surface with high temporal and spatial coverage. The Tropical Rainfall Measuring Mission (TRMM) [11] and the MOD16 algorithm [12, 13], developed, respectively, to estimate global surface precipitation and evapotranspiration, have been widely used by the scientific community in large-scale hydrological studies [14].

The purpose of this study was to characterize and analyze, based on both TRMM and MOD16 imagery, the temporal dynamics of precipitation and evapotranspiration in the Atlantic Rainforest remnants of SP, southeastern Brazil, during a 10-year period (January 2000 to December 2010). We have implemented a wavelet transform to evaluate the temporal variability of these parameters. Wavelet analysis is becoming a common tool for researches involving remote sensing and land-atmosphere interactions. It provides an efficient method for extracting relevant information from large datasets and has been applied to a wide range of variables and different types of ecosystems [15].

2. Materials and methods

2.1. Study area

The study area is located in SP, southeastern region of Brazil (**Figure 1**). The Atlantic Rainforest remnants are mainly located in the slopes of Serra do Mar (1), Bocaina (2), and Mantiqueira (3) mountains and Ribeira (4) and Paraíba (5) valleys, where the natural vegetation cover was less affected due to the difficulty of agricultural mechanization [16]. The main formations of Atlantic Rainforest observed in SP are dense ombrophilous Forest, mixed ombrophilous forest and seasonal semideciduous forest [6].
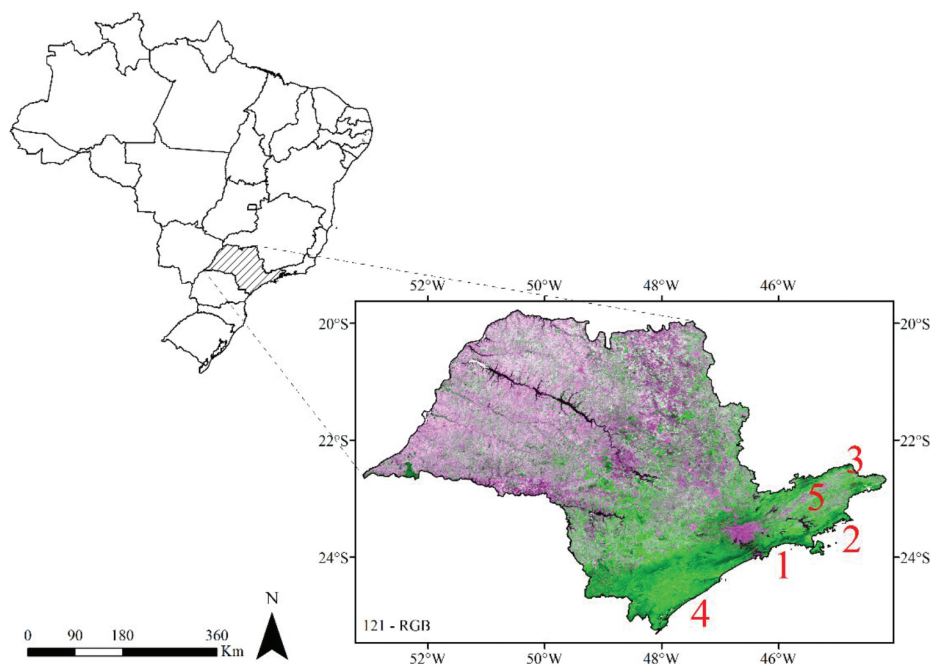

Figure 1. Map showing the location of São Paulo State, Brazil. The color composite was obtained from MODIS/Aqua images of June 23, 2006. The green areas represent dense vegetation, while the beige, magenta, and black areas represent, respectively, agriculture (mostly pasture and sugarcane plantations), bare soil (or urban areas), and water bodies. The numbers 1–5 show, respectively, the location of the slopes of Serra do Mar, Bocaina and Mantiqueira mountains and Ribeira and Paraíba valleys.

2.2. TRMM data

The TRMM satellite was designed from a cooperative program between National Aeronautics and Space Administration (NASA) and Japan Aerospace Exploration Agency (JAXA). Its main goal is to monitor the distribution of precipitation in tropical and subtropical regions [11]. The satellite was launched in 1997 and has three main sensors onboard for studying precipitation: (i) precipitation radar (PR), (ii) microwave imager (TMI), and (iii) Visible and Infrared Scanner (VIRS). PR is an active sensor, the first of its kind in orbit, presenting as the most important characteristic for studying precipitation providing a three-dimensional view of the structure of precipitation [17]. TMI is a passive microwave radiometer operating in five frequencies that

provide information about the integrated content of the precipitation column, intensity and type of precipitation. The VIRS sensor, derived from the AVHRR/NOAA sensor, has five spectral bands in visible and infrared regions performing observations of clouds, such as cover, type, and top temperature [18].

For this study, monthly precipitation data derived from TRMM (3B43 product) version 7 (v7) were used, covering the period from January 2000 to December 2010. The 3B43 product is calculated using data from multiple satellites, in addition to TRMM, as well as meteorological stations data from the Global Precipitation Climatological Center (GPCC) and the Climate Assessment and Monitoring System (CAMS) [19]. 3B43 imagery were acquired from the electronic address (http://gdata1.sci.gsfc.nasa.gov/daac-bin/G3/gui.cgi?instance_id=TRMM_Monthly), presenting spatial resolution of ~30 km in mm month^{-1}. Images were processed in ENVI version 4.5, where the steps of reprojecting, resampling of pixels to 1 km (same spatial resolution of MOD16 data) using nearest neighbor method, and clipping to Atlantic Rainforest remnants in SP were performed.

2.3. MOD16 data

The MOD16 algorithm [12, 13] was developed in the context of the Earth Observing System/NASA (EOS/NASA) program, aiming to estimate global evapotranspiration using data from Moderate Resolution Imaging Spectroradiometer (MODIS) sensor (Terra and Aqua) and meteorological data from Global Modeling and Assimilation Office (GMAO). In general terms, MOD16 is a revision of the algorithm proposed by [20], who adapted the Penman-Monteith equation (Eq. (1)) to be used with remote sensing data:

$$\lambda E = \frac{sA + \rho C_p \left(e_{\text{sat}} - e\right)/r_a}{s + \gamma\left(1 + r_s/r_a\right)} \tag{1}$$

where λE is the latent heat flux (W m^{-2}) and λ represents the latent heat of evaporation (J kg^{-1}), $s = d(e_{\text{sat}})/dT$ is the slope of the curve which relates saturated pressure of water (e_{sat}) and temperature (Pa K^{-1}), A is the energy available at surface (W m^{-2}), ρ represents air density (kg m^{-3}), C_p is the specific heat of air (J kg^{-1} K^{-1}), e is the real pressure of water vapor (Pa), r_s is the surface resistance, r_a is the aerodynamic resistance (s m^{-1}), and γ represents the psychrometric constant (66 Pa K^{-1}).

MODIS input data required for MOD16 algorithm have spatial resolution between 500 m and 1 km, and include global products of land use and land cover (MOD12Q1), leaf area index (LAI) and photosynthetically active radiation (PAR-MOD15A2), and albedo (MCD43B2). Regarding the meteorological parameters required for the algorithm, daily reanalysis data of GMAO referring to incident solar radiation, air temperature, and water vapor pressure, with spatial resolution of 1.00° × 1.25°, are used [13, 21]. In summary, MOD16 data have a spatial resolution of 1 km and covers ~109 million km^2 of vegetated global areas. Among the products generated, we highlight the potential and actual evapotranspiration and potential and actual latent heat flux products, in intervals of eight (MOD16A2) and 30 days (MOD16A3) [22].

MOD16 data were acquired from the Numerical Terradynamic Simulation Group/The University of Montana repository (http://www.ntsg.umt.edu/project/mod16). Tiles H13V10 and H13V11, corresponding to the monthly real evapotranspiration product, in mm month^{-1}, were selected for the period between January 2000 and December 2010. As MOD16 data are available in sinusoidal projection, images were initially reprojected to geographic coordinates with datum WGS 84 and converted to GeoTIFF format using the MODIS Reprojection Tool (MRT). Then, a number of steps were undertaken using ENVI 4.5. These steps included clipping of the study area, multiplication by scale factors, and application of the land-water and urban areas mask over the datasets.

2.4. Atlantic rainforest remnants

Since the 1980s, the SOS Mata Atlântica Foundation, jointly with the National Institute for Space Research (INPE), is regularly mapping forest cover in the Atlantic Rainforest biome. These institutions use remote sensing imagery to produce the "Atlas of Forest Remnants of Atlantic Rainforest." Resulting maps enable us to determine the spatial distribution of forest remnants and ecosystems associated to Atlantic Rainforest, keep track of changes in vegetation cover, and generate permanently improved and updated information of this biome [23, 24].

The spatial distribution of the forest remnants was obtained from the database provided by [5]. This database was used to update the period corresponding to 2011–2012, that is, to update changes occurred in the polygons previously classified as forest fragments (forest remnants, mangrove, or restinga) in previous versions of the "Atlas." To this end, images of the LISS III/RESOURCESAT-1 orbital sensor corresponding to the second semester of 2012 were used. Vector files of the forest fragments polygons were acquired from the electronic address http://mapas.sosma.org.br/ and edited in ARCGIS version 9.3. The editing process consisted in selecting polygons of forest remnants with area equal or greater than 100 ha. Selecting only ≥100 ha polygons intended to create a spatial homogeneity of the analyzed areas. It should be noted that the study comprehends the period between 2000 and 2010 and it is understood that the forest remnants mapped by [5], referring to the update of 2011–2012, are representative of the period analyzed.

2.5. Wavelet analysis

Wavelet analysis has become a widely used method to study variations of energy in environmental time series [25, 26]. The decomposition of a time series in the time-frequency space allows the determination of dominant modes of variability and its variation modes in time [27]. Time series for TRMM and MOD16 were analyzed with continuous wavelet transform using the algorithm developed by [28]. Generally, continuous wavelet transform is used to visualize, in a three-dimensional diagram, the relationship between components of different frequencies according to the time scale of the series studied [29]. Several functions are used to generate wavelets; in this study, the Morlet complex function was used, which is composed of a plane wave modulated by a Gaussian envelope, as shown in Eq. (2):

$$\Psi\left(\eta\right) = \pi^{-1/4} e^{i\omega_0 \eta} e^{-\eta^2/2} \tag{2}$$

where η is the dimensionless time parameter, and ω_0 represents the dimensionless frequency. Here, it is important to point out that Torrence and Compo algorithm was compiled in MATLAB version 7.9.0 and that the analysis was performed exclusively for forest remnants of Atlantic Rainforest. Therefore, values used to generate wavelets referred to the monthly average precipitation (TRMM) and evapotranspiration (MOD16) in the analyzed forest remnants.

3. Results and discussion

3.1. Precipitation and evapotranspiration in São Paulo State between 2000 and 2010

Figure 2 shows the spatial distribution of monthly average precipitation (January to December) in SP between 2000 and 2010 obtained from TRMM satellite data.
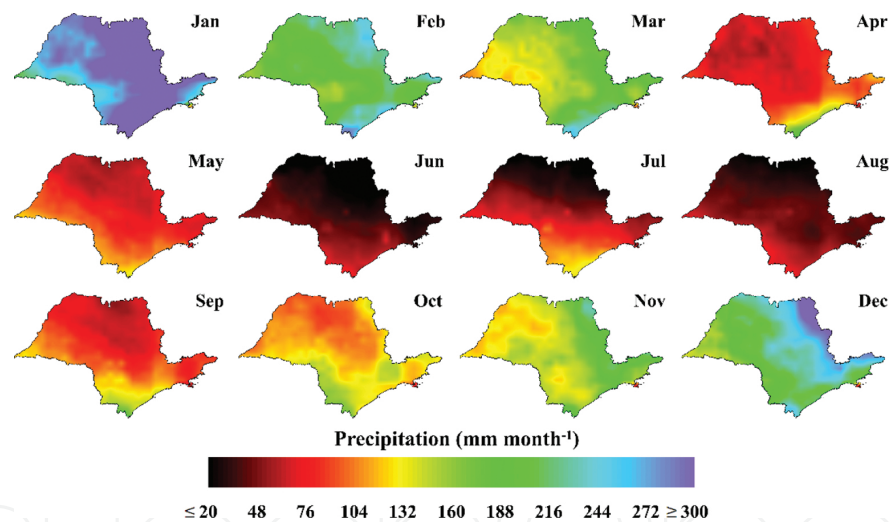

Figure 2. Spatial distribution of monthly average precipitation (mm month^{-1}) in SP for the period between 2000 and 2010.

Generally, it is noted that images from January to March and from October to December show higher precipitation as compared to April to September. This reflects the well-defined rainfall regime in SP: the rainy season (October to March) and the dry season (April to September) [30]. It is possible to note that in most of the year highest values of precipitation are located in the Coastal Plain and Serra do Mar regions. This dynamic is associated to frontal systems (cold fronts) and the South Atlantic Convergence Zone (SACZ), which occur during the year in SP and act mainly in the areas near the coast, as well as the fact that the Serra do Mar conditions the formation of orographic rainfall through the condensation of humid winds from the ocean [31]. In contrast, lower values of precipitation are observed

over the year in the Western Plateau region, where organized local convection is the main source of rainfall [32].

Figure 3 shows the monthly precipitation in SP between 2000 and 2010. Monthly precipitation ranged between 4.3 (August 2004) and 386.9 mm month^{-1} (January 2003), which indicates an absolute variation of 382.6 mm month^{-1}. On average, monthly precipitation between 2000 and 2010 was 128.9 mm month^{-1}.
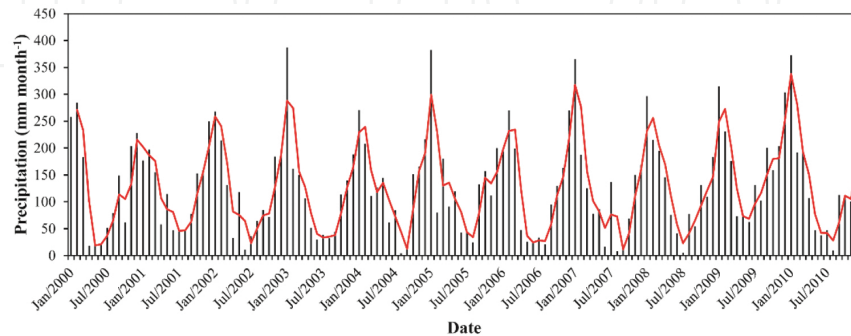

Figure 3. Monthly precipitation (mm month^{-1}) in SP between January of 2000 and December 2010. The red line represents the moving average of the time series (period = 2).

Average monthly precipitation ranged from 35.8 to 298.5 mm month^{-1}, where June is the driest month and January is the wettest. This result is observed in the January and June images shown in **Figure 2**. These two images differ significantly when compared to the other images, especially the image of January, since the image of June has some resemblance to the image of August. In June, it is possible to note that most of precipitation is lower than 48 mm month^{-1}, except in the Southern region, where values close to 76 mm month^{-1} were found. Regarding to the image of January, most of precipitation is higher than 300 mm month^{-1}, except in the western edge of the state, where values of ~216 mm month^{-1} were found.

Analysis of the dry season (April to September) and the rainy season (October to March) has revealed that the average monthly precipitation was, respectively, 64.5 and 193.2 mm month^{-1}. Therefore, average month precipitation in the rainy season was ~200% higher than the observed average in the dry season. Annual precipitation in São Paulo State ranged between 1403.5 and 2029.5 mm year^{-1}. In this sense, 2002 was the least rainy year, while 2009 was the most rainy year. Average annual precipitation was 1546.5 mm year^{-1}, with ~25% of that occurring in the months corresponding to the dry season and ~75% of the average annual precipitation in the months corresponding to the rainy season. Monthly precipitation in 2002 ranged between 10.4 (June) and 267.8 mm month^{-1} (January), while in 2009 monthly precipitation ranged from 62.4 (June) to 314.7 mm month^{-1} (January).

It is important to note that TRMM satellite estimates were not validated in this study. In this context, researches present in literature suggest relative errors ranging from ~5 [33] to ~25% [34]. Still, it is noted that the results regarding the precipitation regime in SP are consistent with several observation meteorological studies conducted in the state, such as [35, 36].

Figure 4 shows the spatial distribution of monthly average actual evapotranspiration (January to December) in São Paulo State between 2000 and 2010, derived from MOD16 algorithm.
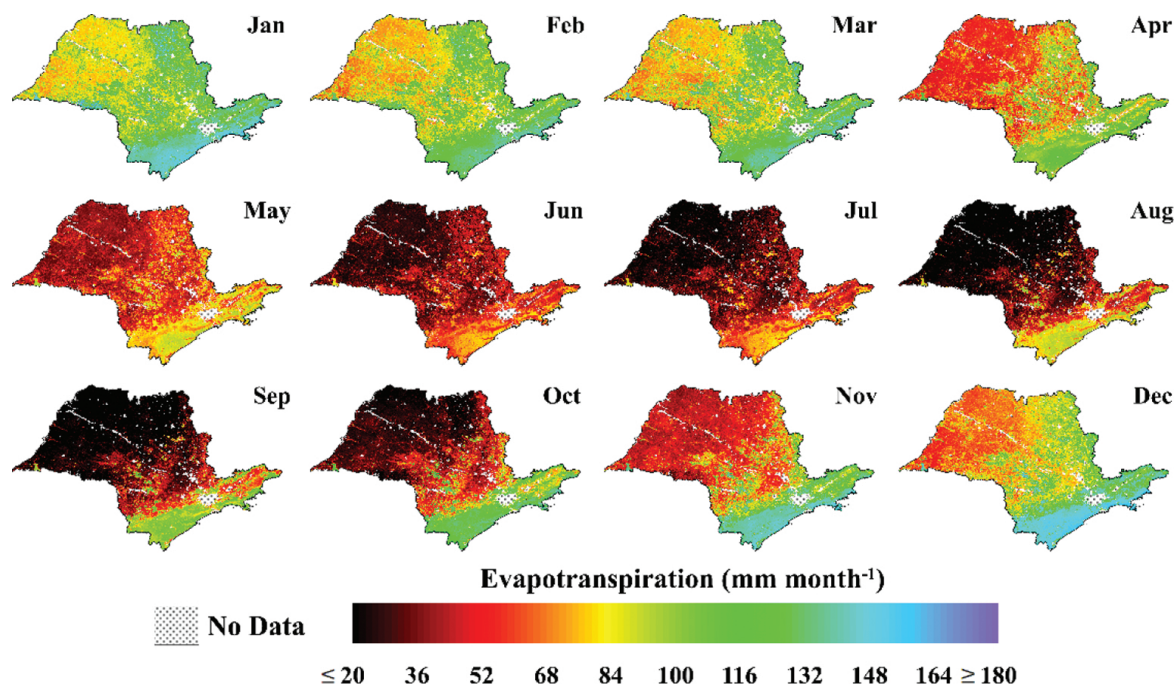

Figure 4. Spatial distribution of monthly average actual evapotranspiration (mm month^{-1}) in SP corresponding to the period between 2000 and 2010.

Visual inspection of **Figure 4** reveals a spatial and temporal pattern for evapotranspiration similar to the one found in precipitation (**Figure 2**). However, evapotranspiration images provide a better perception of subtle changes along the state. Generally, images corresponding to the rainy season have higher values for evapotranspiration when compared to images of the dry season. Evaporation depends on variation in solar radiation, local atmospheric circulation process, which regulates the precipitation system and air and soil moisture conditions, and vegetation conditions, which show considerable changes following the rainy or dry season [37]. Among these conditions, solar radiation stands out, whose incident amount depends, among other factors, on the season [38]. Therefore, this pattern is expected because highest incidence of solar radiation occurs during the rainy season [39]. It is also worth mentioning that throughout the year highest values of evapotranspiration are located in the southern and eastern SP, while lowest values are situated in the northern and western regions of the state.

Figure 5 shows monthly average actual evapotranspiration in SP between 2000 and 2010. Monthly evapotranspiration varied between 26.1 and 116.8 mm month^{-1}, representing an absolute variation of 90.7 mm month^{-1}. Accordingly, lowest monthly value was found in July 2000 and the highest in January 2003. Considering the period between 2000 and 2010, monthly evapotranspiration corresponded, on average, to 68.2 mm month^{-1}.
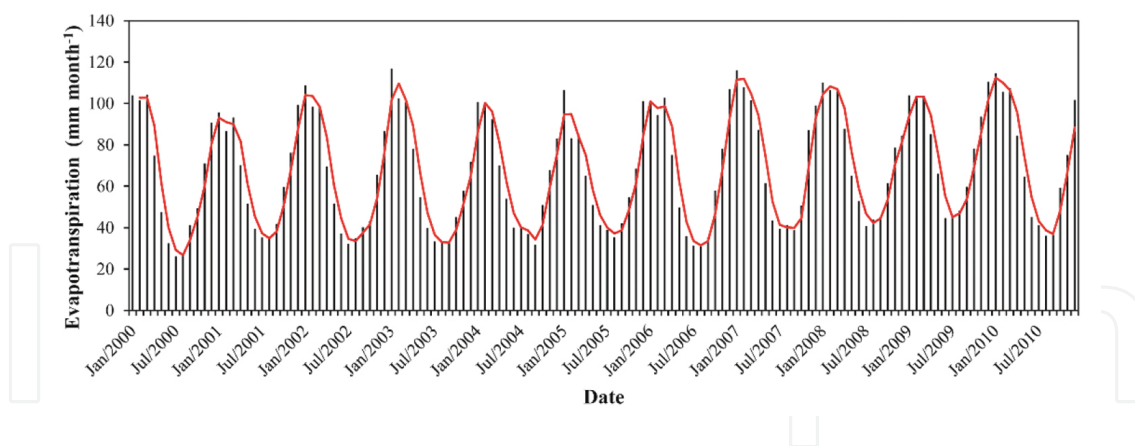
Figure 5. Monthly actual evapotranspiration (mm month^{-1}) in SP between January of 2000 and December 2010. The red line represents the moving average of the time series (period = 2).

The months of August and January presented, respectively, lowest and highest monthly average evapotranspiration (values of 36.6 and 107.1 mm month^{-1}). Relating precipitation and evapotranspiration, it denotes that August had the second lowest monthly average precipitation, while January had the highest monthly average precipitation.

Monthly average evapotranspiration in the dry season was 48.0 mm month^{-1}, while in the rainy season it corresponded to 88.3 mm month^{-1}, which shows an increase of ~84% in evapotranspiration during the wetter period of the year in São Paulo State. Annual evapotraspiration values ranged between 765.7 and 942.0 mm year^{-1}, with 2003 and 2009 presenting, respectively, lowest and highest estimates. In 2003, monthly evapotranspiration ranged from 32.7 (August) to 116.8 mm month^{-1} (January), while in 2009 monthly evapotranspiration ranged between 44.6 (June) and 110.4 mm month^{-1} (December). Regarding yearly average evapotranspiration, the estimate found for the period between 2000 and 2010 was 817.9 mm year^{-1}. On average, for the period between 2000 and 2010, evapotranspiration accounted for ~53% of precipitation in São Paulo State.

It should be noted that MOD16 algorithm estimates were not validated for this study. Ideally, validation process should be performed using surface measurements throughout SP in order to identify biases in the estimates found according to the conditions studied. However, there is a lack of such information for the study area, both the spatial and temporal perspective, which prevents this type of analysis. For comparison, [22], in a validation study for the MOD16 algorithm, found relative errors of 18–22% in tropical forest areas, 20% in seasonal flooding areas and 33% in agricultural areas. Finally, it should be noted that results found about the evapotranspiration regime in SP agree with the results from a modeling study using the Simple Biosphere Model (SiB2) performed by [40].

3.2. Precipitation and evapotranspiration in Atlantic Rainforest remnants between 2000 and 2010

Figure 6 shows the remnants of the Atlantic Rainforest in São Paulo State with area ≥ 100 ha, and the overlapping of the remnants mapped in São José do Rio Preto region (northwestern

SP) with a MODIS/Terra sensor image from June 27, 2010. It is possible to note that most of the remnants are located in South and East portions of the State, in contrast to the northern and western regions [16]. Yet, as observed in the highlighted image, polygons mapped by [5] are properly adjusted to MODIS images, which are the basis of the MOD16 algorithm used in this study.
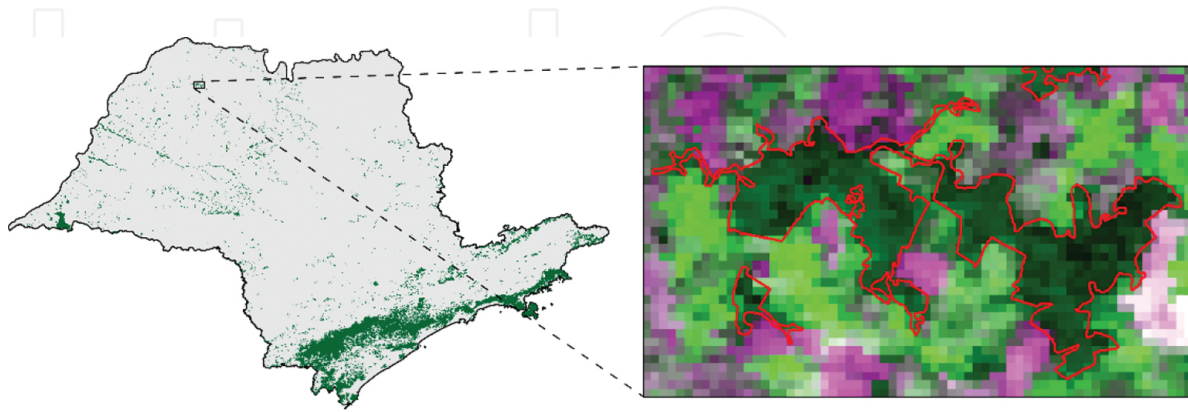

Figure 6. Atlantic Rainforest remnants in São Paulo State with an area equal or greater than 100 ha. Highlighted image shows the overlapping between remnants polygons mapped in São José do Rio Preto region and a MODIS/Terra sensor image (R1G2B1) from June 27, 2010.

For the period of 2011–2012, 25,554 polygons were mapped in São Paulo State, totalizing an area of ~2,421,538 ha. After the selection of the polygons with area ≥ 100 ha, 2054 were found, representing an area of ~1,914,331 ha. In here, it is important to mention that analysis related to precipitation and evapotranspiration were realized only for Atlantic Rainforest remnants with area equal to or greater than 100 ha.

Figure 7 shows precipitation (monthly and monthly average) in Atlantic Rainforest remnants between 2000 and 2010. It is possible to note a strong seasonality in Atlantic Rainforest remnants precipitation, similar behavior found in previous analysis for São Paulo State (Section 3.1). Monthly precipitation ranged between 11.7 and 460.1 mm month^{-1}, values found, respectively, in July 2008 and January 2010. Considering the entire period (2000–2010) monthly average precipitation was 114.7 mm month^{-1}. [41] observed, in Atlantic Rainforest areas in São Paulo State, monthly precipitation ranging between 1.5 and 347.3 mm month^{-1}. Moreover, during the period analyzed, monthly precipitation in Atlantic Rainforest remnants was, on average, ~12% higher than that estimated for SP.

Monthly average precipitation ranged from 49.6 (June) to 309.5 mm month^{-1} (January). In this sense, Donato et al. [41] estimated, for Atlantic Rainforest areas in São Paulo State, monthly average precipitation between 33.8 (August) and 272.0 mm month^{-1} (January), similar to those obtained in this study.

During the dry season, monthly average precipitation in remnants was 85.7 mm month^{-1}, while in the rainy season was 203.8 mm month^{-1}. Therefore, monthly average precipitation in the Atlantic Rainforest remnants was ~138% higher in the rainy season. Annual precipitation ranged from 1426.6 (2007) to 2185.4 mm year^{-1} (2009). Thus, annual precipitation showed an

absolute and relative variation of 758.8 mm year^{-1} and ~53%, respectively. In 2007, monthly precipitation fluctuated between 18.7 (June) and 268.2 mm month^{-1} (January), while in 2009 it ranged from 63.3 (June) to 298.6 mm month^{-1} (January). Annual average precipitation in Atlantic Rainforest remnants was 1737.0 mm year^{-1}. In addition, ~30% of the annual average precipitation occurred during the dry season, and ~70% was concentrated in the rainy season. Similar studies by [41, 42] found, for Atlantic Rainforest remnants areas in SP, annual average precipitation of 1784.0 and 1974.1 mm year^{-1}, respectively.

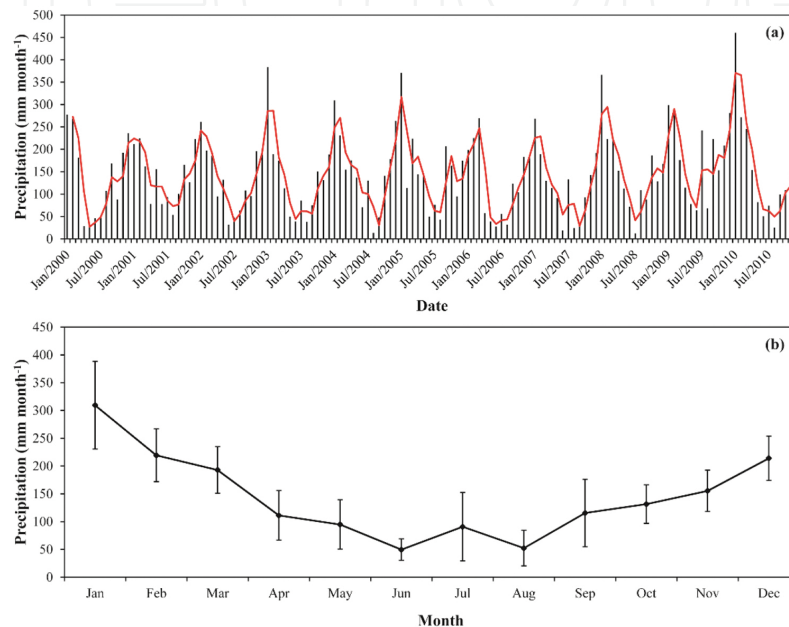**Figure 7.** Monthly (mm month^{-1}) (a) and monthly average (mm month^{-1}) (b) precipitation in Atlantic Rainforest remnants of São Paulo State between January 2000 and December 2010. In (a), the red line represents the moving average of the time series (period = 2), and in (b), vertical bars represent the standard deviation.

Figure 8 shows actual evapotranspiration (monthly and monthly average) in Atlantic Rainforest remnants between 2000 and 2010. It is possible to note the temporal variability of the values found, characterizing the seasonality of this parameter and presenting well-defined dry and rainy seasons, as mentioned in Section 3.1. Considering the period studied, monthly evapotranspiration oscillated between 55.3 and 144.3 mm month^{-1}. Accordingly, lowest value was found in July 2000, while the highest in December 2002. On average, considering the period between 2000 and 2010, monthly evapotranspiration was 104.03 mm month^{-1}. [43], considering an experimental microbasin located in an Atlantic Rainforest area in the municipality of Cunha, obtained monthly evapotranspiration values oscillating between 26.5 and 142.3 mm month^{-1}, similar to those obtained in the present study. It is worth mentioning that, considering the period analyzed, monthly evapotranspiration in Atlantic Rainforest remnants was, on average, ~52% higher than monthly evapotranspiration in SP.

Monthly average evapotranspiration ranged from 63.2 (June) to 139.3 mm month^{-1} (December). Comparing these results with monthly average precipitation, June was the month with lowest precipitation, while December was the third wettest month. In this context, [44], in a study

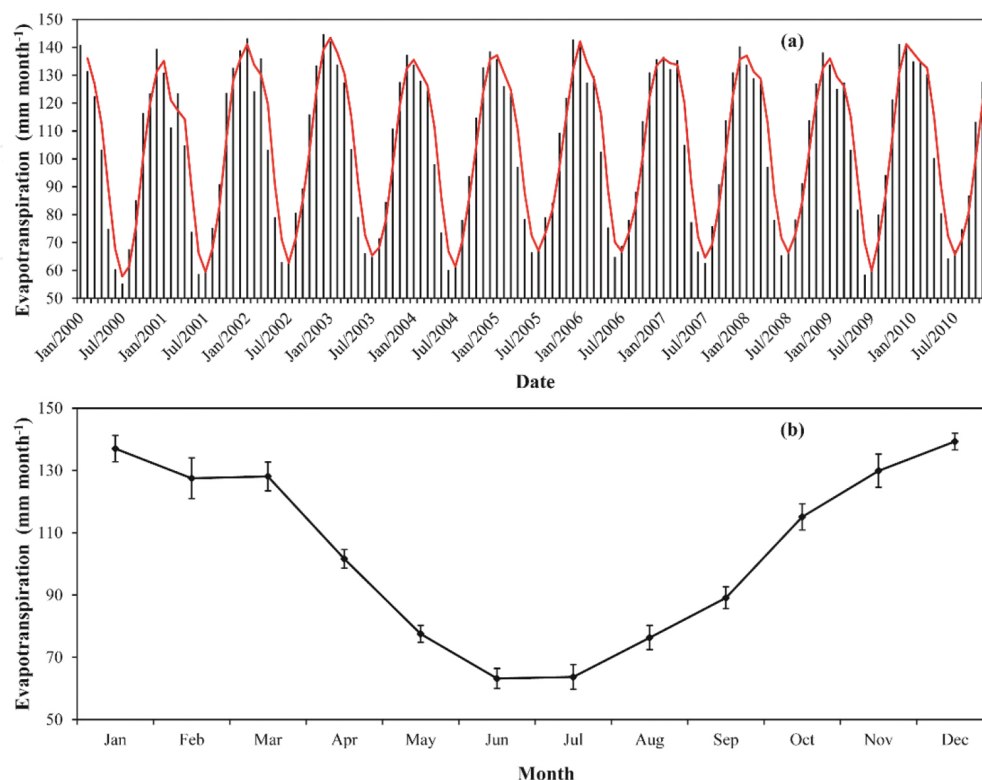conducted at the Serra do Mar State Park, found monthly average evapotranspiration between 35.8 (July) and 95.0 mm month^{-1} (January).

Figure 8. Monthly (mm month^{-1}) (a) and monthly average (mm month^{-1}) (b) actual evapotranspiration in Atlantic Rainforest remnants of São Paulo State between January 2000 and December 2010. In (a), the red line represents the moving average of the time series (period = 2), and in (b), vertical bars represent the standard deviation.

Monthly average evapotranspiration for the dry season was 78.6 mm month^{-1}, while during the rainy season was 129.5 mm month^{-1}. Considering these results, monthly average evapotranspiration in the Atlantic Rainforest remnants was ~65% higher in the rainy season when compared to the dry season. Annual evapotranspiration ranged from 1220.4 (2000) to 1275.2 (2002) mm year^{-1}, an absolute variation of 55 mm year^{-1} and relative variation of ~5%. Monthly evapotranspiration for 2000 and 2002 ranged, respectively, from 55.3 (July) to 140.7 mm month^{-1} (January), and from 62.5 (July) to 144.6 mm month^{-1} (December). Annual average evapotranspiration was 1248.3 mm year^{-1}, with dry and rainy season month representing, respectively, ~38 and ~62% of the total. Considering annual average, evapotranspiration represented ~72% of the precipitation in Atlantic Rainforest remnants, suggesting a low hydric production (~28%). Usually, evapotranspiration studies in tropical forests show values ranging, on average, from 1000 to 1400 mm year^{-1} [45]. Regarding Atlantic Rainforest in São Paulo State, [41] found annual average of 697.5 mm year^{-1} for evapotranspiration, ~44% lower than the result found in this study.

Figure 9 shows the continuous wavelet transform power spectrum for normalized time series of precipitation and evapotranspiration. In general, it is possible to observe that the main

oscillation mode in precipitation and evapotranspiration of Atlantic Rainforest remnants time series is concentrated between 8 and 16 months, showing, as previously mentioned, a strong seasonal or intraannual behavior.

For precipitation, maximum energy peak was observed between 10 and 14 months (seasonal mark), occurring between March 2001 and November 2009. In addition, less intense peaks of energy are highlighted for a period of 1.5 month (January 2003 and February 2003), 1–3 months (January 2005 to April 2005 and June 2009 to September 2009), and 5–7 months (January 2009 to December 2009), being the last period not statistically significant considering a 95% confidence interval. These less intense peaks of energy of 1.5 month, 1–3 months, and 5–7 months are related to high precipitation episodes, mainly in January 2003 (383.2 mm month^{-1}), in January 2005 (370.2 mm month^{-1}), and February, July and September 2009 (281.4, 242.5, and 223.3 mm month^{-1}, respectively). Yet, as previously mentioned, 2009 presented the highest values for annual precipitation. Therefore, these high values of precipitation could be related to the occurrence of frontal systems (cold fronts), the SACZ, and South American Low Level Jet (SALLJ). Cold fronts are very common in São Paulo State and cause intense and isolated rainfall in different regions of the state [32]. SACZ and SALLJ exert an important control in the frequency of extreme precipitation events in Southeastern Brazil, acting in intraseasonal and interannual scales [35]. It is important mentioning that the El Niño event contributes to the action of SACZ in São Paulo State, increasing the probability of intense rainfall in the state during the years that the phenomenon occurs [46].
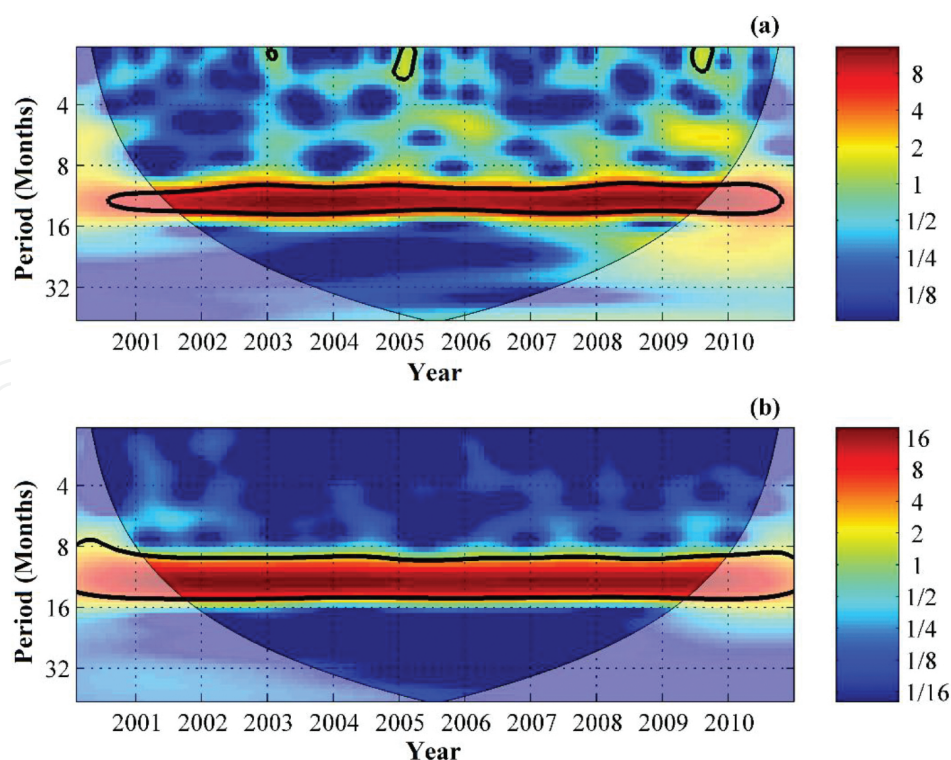

Figure 9. Continuous wavelet transform power spectrums for normalized time series of precipitation (a) and evapotranspiration (b). U-shaped curve represents the cone of influence, below which edge effects are important.

Regarding evapotranspiration, the maximum peak of energy is identified in the 9–15-month period (seasonal mark), occurring between January 2001 and December 2009. It is possible to observe less intense peaks of energy in the period of 5–7 months (January 2001 to March 2002, and December 2009 to March 2010); however, they are not statistically significant. Note that 2002 and 2009 showed the highest values of annual evapotranspiration. Therefore, the action of atmospheric systems, and their influence over meteorological variables (e.g., air temperature, wind speed, and air and soil moisture) [47], could have provided conditions that favored the increase of evapotranspirative processes in Atlantic Rainforest remnants considering the intraseasonal scale between 2001/2002 and 2009/2010 periods.

4. Conclusions

Combining TRMM satellite data and MOD16 algorithm enabled mapping the spatial distribution and evaluating precipitation and evapotranspiration in São Paulo State, as well as analyzing the temporal dynamics of these variables in Atlantic Rainforest remnants for the period between 2000 and 2010. Generally, the precipitation and evapotranspiration trends (considering both São Paulo State and forest remnants) revealed a strong seasonal pattern, with highest values concentrated in the rainy season (October to March) and lowest values in the dry season (April to September).

Regarding to São Paulo State, highest values of precipitation and evapotranspiration were found in southern and eastern regions, while lowest values were located in the northern and western portions of the state. The time series analysis showed that monthly averages for precipitation and evapotranspiration were, respectively, ~200 and ~84% higher during the rainy season when compared to the dry season. Considering annual averages, evapotranspiration corresponded to ~53% of precipitation in São Paulo State.

In regard to Atlantic Rainforest remnants, time series analysis showed that during the rainy season precipitation and evapotranspiration were, respectively, ~138 and ~65% higher than those observed during the dry season. In terms of annual averages, evapotranspiration accounted for ~72% of precipitation, indicating a low hydric production (~28%). Considering the entire period, monthly averages of precipitation and evapotranspiration were, respectively, ~12 and ~52% higher than the monthly averages for São Paulo State, which demonstrates the contribution of these remnants to the regional hydrologic regime. The higher amounts of precipitation are observed in the coastal region where most of the remnants are located and maybe there is an artifact, however if we analyze the evapotranspiration maps it is possible to note that the evapotranspiration is really low in the western part of Sao Paulo state due the presence of large areas of agriculture and pasture and a reduced number of forest remnants. Analysis of wavelet transform for precipitation and evapotranspiration time series in Atlantic Forest remnants showed that the main oscillation mode is concentrated between 8 and 16 months, revealing a seasonal or intra-annual behavior. It is important to note that the wavelets analysis allowed to conduct a more comprehensive evaluation of the behavior of precipitation and evapotranspiration through

time. It can be a useful tool to verify trends of temporal shifts in environmental parameters [48–53], which in its turn can affect the ecosystem services delivered by tropical forest remnants. In this sense, just to point out, the trends of temporal shifts in precipitation and evapotranspiration observed in our study were related, in general, to the SACZ, SALLJ, and El Niño.

Results found in this study demonstrated that the use of remote sensing was an important tool for analyzing hydrological variables in Atlantic Rainforest remnants, which can contribute to better understanding the interaction between tropical forests and the atmosphere, and for generating input data necessary for surface models coupled to atmospheric general circulation models. Accordingly, future studies should be performed to (i) validate MOD16 algorithm for Atlantic Rainforest conditions, (ii) analyze potential artifacts related to the spatial distribution of the land cover and environmental parameters, (iii) identify other phenomena that could be related to intraseasonal and interannual variations in precipitation and evapotranspiration occurred in Atlantic Rainforest remnants, (iv) analyze precipitation and evapotranspiration in specific forest formations of Atlantic Rainforest (e.g., dense ombrophylous forest, mixed ombrophylous forest, and seasonal semideciduous forest), (v) evaluate the differences of precipitation and evapotranspiration between forest remnants and different land use types (e.g., pasture, agriculture, urban areas, etc.), which can play an important role to understand more specifically what is the impact of land use changes in ecosystem services in tropical regions, and (vi) analyze the relationship between precipitation and evapotranspiration in Atlantic Rainforest remnants using other biophysical variables, such as surface albedo and vegetation indices.

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References

[1] Tabarelli M., Pinto L.P., Silva J.M.C., Hirota M.M., Bedê L. Challenges and opportunities for biodiversity conservation in the Brazilian Atlantic forest. Conservation Biology. 2005; 19(3):695–700. DOI: 10.1111/j.1523-1739.2005.00694.x

[2] Costa D.P., Faria C.P. Conservation priorities for the bryophytes of Rio de Janeiro State, Brazil. Journal of Biology. 2008; 30(2):133–142. DOI: 10.1179/174328208X300633

[3] Ribeiro M.C., Metzger J.P., Martensen A.C., Ponzoni F.J., Hirota M.M. The Brazilian Atlantic forest: how much is left, and how is the remaining forest distributed? Implications for conservation. Biological Conservation. 2009; 142(6):1141–1153. DOI: 10.1016/j.biocon.2009.02.021

[4] Morellato L.P.C., Haddad C.F.B. Introduction: the Brazilian Atlantic Forest. Biotropica. 2000; 32(4b):786–792. DOI: 10.1111/j.1744-7429.2000.tb00618.x

[5] SOS Mata Atlântica Foundation, National Institute for Space Research. Atlas dos Remanescentes Florestais da Mata Atlântica: Período 2011–2012 [Internet]. 2013 [Updated: 2013]. Available from: https://www.sosma.org.br/wp-content/uploads/2013/06/atlas_2011-2012_relatorio_tecnico_2013final.pdf [Accessed: 04/27/2016]

[6] Kronka F.J.N., Nalon M.A., Matsukuma C.K., Kanashiro M.M., Ywane M.S.S., Pavão M., et al. Forest inventory of the natural vegetation in São Paulo State. 1st ed. São Paulo: Instituto Florestal; 2005. 200 p.

[7] Swann A.L.S., Fung I.Y., Chiang J.C.H. Mid-latitude afforestation shifts general circulation and tropical precipitation. Proceedings of the National Academy of Sciences of the United States of America. 2012; 109(3):712–716. DOI: 10.1073/pnas.1116706108

[8] Ruhoff A.L., Paz A.R., Collischonn W., Aragão L.E.O.C., Rocha H.R., Malhi Y.S. A MODIS-based energy balance to estimate evapotranspiration for clear-sky days in Brazilian tropical Savannas. Remote Sensing. 2012; 4(3):703–725. DOI: 10.3390/rs4030703

[9] Oliveira G., Moraes E.C. Validation of net radiation obtained from MODIS/TERRA data in Amazonia with LBA surface measurements. Acta Aazonica. 2013; 43(3):353–364. DOI: 10.1590/S0044-59672013000300011

[10] Papadavid G., Hadjimitsis D. Adaptation of SEBAL for estimating groundnuts evapotranspiration, in Cyprus. South-Eastern European Journal of Earth Observation and Geomatics. 2012; 1(2):59–70.

[11] Kummerow C., Simpson J., Thiele O., Barnes W., Chang A.T.C., Stocker E., et al. The status of the Tropical Rainfall Measuring Mission (TRMM) after two years in orbit. Journal of Applied Meteorology. 2000; 39(2):1965–1982. DOI: 10.1175/1520-0450

[12] Mu Q., Heinsch F.A., Zhao M., Running S.W. Development of a global evapotranspiration algorithm based on MODIS and global meteorology data. Remote Sensing of Environment. 2007; 111(4):519–536. DOI: 10.1016/j.rse.2007.04.015

[13] Mu Q., Zhao M., Running S.W. Improvements to a MODIS global terrestrial evapotranspiration algorithm. Remote Sensing of Environment. 2011; 115(8):1781–1800. DOI: 10.1016/j.rse.2011.02.019

[14] Mishra A.K., Kumar R. Study of rainfall from TRMM Microwave Imager observation over India. ISRN Geophysics. 2012; 2012:1–7. DOI: 10.5402/2012/921824

[15] Labat D. Recent advances in wavelet analyses: Part 1. A review of concepts. Journal of Hydrology. 2005; 314(1):275–288. DOI: http://dx.doi.org/10.1016/j.jhydrol.2005.04.003

[16] Joly C.A., Speglich E. Biota/Fapesp program: a new paradigm on the study of conservation and biodiversity. Ciência e Cultura. 2003; 55(3):41–43.

[17] Bowman K.P., Collier J.C., North G.R., Wu Q., Ha E., Hardin J. Diurnal cycle of tropical precipitation in Tropical Rainfall Measuring Mission (TRMM) satellite and ocean buoy rain gauge data. Journal of Geophysical Research. 2005; 110(D21104):1–14. DOI: 10.1029/2005JD005763

[18] Yang S., Olson W., Wang J.J., Bell T.L., Smith E.A., Kummerow C.D. Precipitation and latent heating distributions from satellite passive microwave radiometry. Part II: evaluation of estimates using independent data. Journal of Applied Meteorology and Climatology. 2006; 45(5):721–739. DOI: 10.1175/JAM2370.1

[19] Huffman G.J., Adler R.F., Bolvin D.T., Gu G., Nelkin E.J., Bowman K.P., et al. The TRMM Multisatellite Precipitation Analysis (TMPA): quasi-global, multiyear, combined-sensor precipitation estimative at fine scales. Journal of Hydrometeorology. 2007; 8(1): 38–55. DOI: 10.1175/JHM560.1

[20] Cleugh H.A., Leuning R., Mu Q.Z., Running S.W. Regional evaporation estimates from flux tower and MODIS satellite data. Remote Sensing of Environment. 2007; 106(3):285–304. DOI: 10.1016/j.rse.2006.07.007

[21] Zhao M., Heinsch F.A., Nemani R., Running S.W. Improvements of the MODIS terrestrial gross and net primary production global data set. Remote Sensing of Environment. 2005; 95(2):164–176. DOI: 10.1016/j.rse.2004.12.011

[22] Ruhoff A.L. Remote sensing applied to the estimation of evapotranspiration in tropical biomes [thesis]. Porto Alegre: Federal University of Rio Grande do Sul; 2011. 166 p. Available from: http://hdl.handle.net/10183/32468

[23] Morales A.P. International agenda intensifies the growing of institutions in defense of the environment in Brazil. Ciência e Cultura. 2010; 62(4):6–7.

[24] Farinaci J.S., Batistella M. Variation on native vegetation cover in São Paulo: an overview of current knowledge. Revista Árvore. 2012; 36(4):695–705. DOI: 10.1590/S0100-67622012000400011

[25] Meyers S.D., Kelly B.G., O'Brien J.J. An introduction to wavelet analysis in oceanography and meteorology: with application to the dispersion of Yanai waves. Monthly Weather Review. 1993; 121(10):2858–2866. DOI: 10.1175/1520-0493(1993)121<2858:AITWAI>2.0.CO;2

[26] Massei N., Dupont J.P., Mahler B.J., Laignel B., Fournier M., Valdes D., et al. Investigating transport properties and turbidity dynamics of a karst aquifer using correlation, spectral, and wavelet analyses. Journal of Hydrology. 2006; 329(1–2):244–257. DOI: 10.1016/j.jhydrol.2006.02.021

[27] Alcântara E.H., Stech J.L., Lorenzzetti J.A., Novo E.M.L.M. Time series analysis of water surface temperature and heat flux components in the Itumbiara Reservoir (GO), Brazil. Acta Limnologica Brasiliensia. 2011; 23(3):245–259. DOI: 10.1590/S2179-975X2012005000002

[28] Torrence C., Compo G.P. A practical guide to wavelet analysis. Bulletin of American Meteorological Society. 1998; 79(1):61–78. DOI: 10.1175/1520-0477(1998)079<0061:APGTWA>2.0.CO;2

[29] Grinsted A., Moore J.C., Jevrejeva S. Application of the cross wavelet transform and wavelet coherence to geophysical time series. Nonlinear Processes in Geophysics. 2004; 11(5–6):561–566. DOI: 10.5194/npg-11-561-2004

[30] Genovez A.M., Zuffo A.C. Heavy rains in São Paulo State: existing studies and comparative analyses. Brazilian Journal of Water Resources. 2000; 5(3):45–58.

[31] Morais M.A., Castro W.A.C., Tundisi J.G. Climatology of cold fronts over the metropolitan region of São Paulo (MRSP) and their influence in the limnology of water supply reservoirs. Revista Brasileira de Meteorologia. 2010; 25(2):205–217.

[32] Alves L.M., Marengo J.A., Camargo H., Castro C. Onset of the rainy season over Southeast of Brazil: part 1—observacional studies. Revista Brasileira de Meteorologia. 2005; 20(3):385–394.

[33] Nóbrega R.S., Souza E.P., Galvíncio J.D. Analysis of precipitation derived from TRMM on a sub-basin in western Amazonia. Geography Journal (Recife). 2008; 25(1):6–20.

[34] Collischonn B., Allasia D., Collischonn W., Tucci C.E.M. Performance of TRMM satellite precipitation estimates over the Upper Paraguai. Brazilian Journal of Cartography. 2007; 59(1):93–99.

[35] Liebmann B., Charles J., Carvalho L.M.V. Interannual variability of daily extreme precipitation events in the State of São Paulo, Brazil. Journal of Climate. 2001; 14(2):208–218. DOI: 10.1175/1520-0442(2001)014<0208:IVODEP>2.0.CO;2

[36] Dufek A.S., Ambrizzi T. Precipitation variability in São Paulo State, Brazil, Theoretical and Applied Climatology. 2008; 93(3–4):167–178. DOI: 10.1007/s00704-007-0348-7

[37] Ruhoff A.L., Saldanha C.B., Collischon W., Uvo C.B., Rocha H.R., Cabral O.M.R. Multivariate analysis of evapotranspiration in cerrado and sugarcane areas. Brazilian Journal of Water Resources. 2009; 14(4):137–149.

[38] Fan Z., Thomas A. Spatiotemporal variability of reference evapotranspiration and its contributing climatic factors in Yunnan Province, SW China, 1961–2004. Climatic Change. 2013; 116(2):309–325. DOI: 10.1007/s10584-012-0479-4

[39] Giongo P.R. Mapping of the energy balance and daily evapotranspiration through remote sensing techniques [thesis]. Piracicaba: University of São Paulo; 2011. 122 p. Available from: http://www.teses.usp.br/teses/disponiveis/11/11143/tde-13092011-092028/es.php

[40] Martins C.A. Evapotranspiration estimation in the State of São Paulo with SiB2 biosphere model [dissertation]. São Paulo: University of São Paulo; 2011. 130 p. Available from: http://www.teses.usp.br/teses/disponiveis/14/14133/tde-24102011-182252/pt-br.php

[41] Donato C.F., Ranzini M., Cicco V., Arcova F.C.S., Souza L.F.S. Mass balance in small catchment in Atlantic Forest at Serra do Mar, Southeastern Brazil, Revista do Instituto Florestal. 2008; 20(1):1–11.

[42] Fujieda M., Kudoh T., Cicco V., Carvalho J.L. Hydrological processes at two subtropical forest catchments: the Serra do Mar, São Paulo, Brazil. Journal of Hydrology. 1997; 196(1):26–46. DOI: 10.1016/S0022-1694(97)00015-2

[43] Cicco V. Evapotranspiration determination by the methods of water and the chloride balances and the quantification of canopy interception in the Atlantic Forest: São Paulo, SP and Cunha, SP [thesis]. São Paulo: University of São Paulo; 2009. 138 p. Available from: http://www.teses.usp.br/teses/disponiveis/8/8135/tde-23112009-150138/pt-br.php

[44] Anido N.M.R. Hydrological characteristics of an experimental catchment for the identification of indicators of environmental monitoring [dissertation]. Piracicaba: University of São Paulo; 2002. 69 p. Available from: http://www.teses.usp.br/teses/disponiveis/11/11150/tde-10012003-151209/pt-br.php

[45] Bruijzeel L.A. Hydrology of moist tropical forests and effects of conversion: a state of knowledge review. 1st ed. Amsterdam: Free University Amsterdam/UNESCO; 1990. 224 p.

[46] Carvalho L.M.V., Jones C., Liebmann B . Extreme precipitation events in Southeast South America and large-scale convective patterns in the South Atlantic convergence zone. Journal of Climate. 2002; 15(17):2377–2394. DOI: 10.1175/1520-0442(2002)015<2377:EPEISS>2.0.CO;2

[47] Pereira A.R., Angelocci L.R., Sentelhas P.C. Agrometeorology: fundamentals and practical applications. 1st ed. Guaíba: Editora Agropecuária; 2002. 436 p.

[48]   Fu G., Yu J., Yu X., Ouyang R., Zhang Y., Wang P., et al. Temporal variation of extreme rainfall events in China, 1961–2009. Journal of Hydrology. 2013; 487: 48–59. DOI: 10.1016/j.jhydrol.2013.02.021

[49]   Chu Q., Lan A., Chen D., You P., Liu F., Xiao X. Analysis on temporal and spatial variation characteristics of potential evapotranspiration in Guizhou Province. Agricultural Science & Technology. 2014; 15(4):635. DOI: 10.1007/s00703-016-0442-4

[50]   Markovic D., Koch M. Stream response to precipitation variability: a spectral view based on analysis and modelling of hydrological cycle components. Hydrological Processes. 2015; 29(7): 1806–1816. DOI: 10.1002/hyp.10293

[51]   Wang H., Chen Y., Pan Y. Characteristics of drought in the arid region of northwestern China. Climate Research. 2015; 62(2): 99–113. DOI: 10.3354/cr01266

[52]   Zhang K. X., Pan S. M., Zhang W., Xu Y. H., Cao L. G., Hao Y. P., et al. Influence of climate change on reference evapotranspiration and aridity index and their temporal-spatial variations in the Yellow River Basin, China, from 1961 to 2012. Quaternary International. 2015; 380:75–82. DOI: 10.1016/j.quaint.2014.12.037

[53]   Villarreal S., Vargas R., Yepez E.A., Acosta J.S., Castro A., Escoto-Rodriguez M., et al. Contrasting precipitation seasonality influence evapotranspiration dynamics in water-limited shrublands. Journal of Geophysical Research: Biogeosciences.NM 2016; 121:494–508. DOI: 10.1002/2015jg003169