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Climatological Water Balance In The Municipality of Rio de Janeiro

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ABSTRACT

The lack of studies using the Climatological Water Balance (CWB) in the municipality of Rio de Janeiro (MRJ) motivated the present study. The climatic data of the Sistema Alerta Rio include information collected from 1997 to 2016. Thus, this study aimed to evaluate the spatial-temporal distribution of CWB, based on the identification of regions with water excess and deficit, using data from the Sistema Alerta Rio. The gaps were filled by regional weighting (rainfall) and multiple linear regression models (MLRM) – (air temperature). The CWB was applied to the years of 1997, 2015, and 2008/2009, which were considered as dry and wet years in the time series. From the results of the CWB calculated for each season of the Sistema Alerta Rio, water excess (EXC) and water deficit (DEF) were obtained at temporal and spatial scales. The Inverse of Square Distance (ISD) method was the most adequate in the spatialization of EXC and DEF. In 1997, considered a dry year in the MRJ, DEF was predominant. In 2015, the lowest DEF values were obtained at Rocinha station (South Region) and Grota Funda station (West Region). CWB results for the years 2008-2009 showed that EXC reached the maximum value of 1855 mm.year⁻¹ at Rocinha station and the minimum value of 503 mm.year⁻¹ at Penha station (North Region). The spatial results of the accumulated EXC and DEF showed that their distributions are related to the dynamics of multi-scale meteorological systems and the relief configuration of the municipality of Rio de Janeiro.

Keywords: cluster analysis, interpolation methods, multiple linear regression, water excess, water deficit.

Balanço Hídrico Climatológico Para o Município do Rio de Janeiro

RESUMO

A inexistência de estudos utilizando o Balanço Hídrico Climatológico (BHC) no município do Rio de Janeiro (MRJ) motivou o presente estudo. Os dados climáticos do Sistema Alerta Rio são de 1997 a 2016. Assim, este estudo teve como objetivo avaliar a distribuição espaço-temporal do CWB, com base na identificação de regiões com excesso e déficit hídrico, utilizando dados do Sistema Alerta Rio. Os dados climáticos passaram por preenchimento de falhas via ponderação regional (chuva) e modelos de regressão linear múltipla (MLRM) - (temperatura do ar). O BHC foi aplicado para os anos de 1997, 2015 e 2008/2009, considerados anos secos e úmidos na série temporal. Calculou-se o BHC para cada estação do Alerta Rio e, a partir disso foi obtido o excedente hídrico (EXC) e a deficiência hídrica (DEF), nas escalas temporal e espacial. O método Inverso da Distância ao Quadrado (IDQ) foi o mais adequado na espacialização do EXC e DEF. No ano de 1997, houve a predominância do DEF, sendo considerado um ano seco no MRJ. No ano de 2015 os menores valores de DEF foram obtidos nas estações Rocinha (Região Sul) e Grota Funda (Região Oeste). Os resultados do BHC para os anos de 2008-2009 mostram que o EXC atingiu o valor máximo de 1855 mm.ano⁻¹ na Rocinha (Região Sul) e o valor mínimo foi de 503 mm.ano⁻¹ na Penha (North Region). Os resultados espaciais dos EXC e das DEF acumuladas mostraram que as suas distribuições estão relacionadas à dinâmica dos sistemas meteorológicos de várias escalas e a configuração do relevo do MRJ.

Palavras-Chave: análise de agrupamento, métodos de interpolação, regressão linear múltipla, excedente hídrico e deficiência hídrica.

Introduction

The climatological water balance (CWB) was developed by Thornthwaite in 1948, to study

hydrographic basins in the United States, and modified by Mather in 1955 to be used as the basis for climatic classification. The method was later denominated

Thornthwaite-Mather Water Balance (1955). In this method, the water input is represented by the rainfall and the water output is represented by the evapotranspiration (ET). These data are used to estimate the actual evapotranspiration (AET), water deficit (DEF), water excess (EXC), and soil water storage (SWS). Several studies have applied this methodology; however, they addressed the water availability for residential and industrial supply, hydroelectric power generation, crops irrigation, urban drainage, and support for decision-making in urban planning (Rolim et al., 2007; Corte, 2015). This methodology is also applied in agrometeorological studies to define the crop with the best aptitude in the study area in climatic characterization (Rolim et al., 2007; Corte, 2015). However, in recent years, the use of CWB in urban areas has helped plan the soil use and occupation and the management of water resources, especially the EXC and DEF periods, subsidizing water supply projects (Willuweit & O'Sullivan, 2013, McDonald et al., 2014, CORTE, 2015). Buytaert & Bièvre (2012) used the difference between rainfall (R) and ET calculated by the CWB to evaluate water availability in the four large Andean metropolises (Bogotá, Quito, Lima, and La Paz). Their results revealed that the primary cause of the intensification of the water stress was the population growth. According to the authors, the population may increase the water demand by up to 50% by 2050. McDonald et al. (2014) state that as cities grow, the amount of water required to supply the population also grows. Urbanization affects global economic development, the rational consumption of natural resources, and the well-being of society. Water resources intended to supply cities are under continuous threat due to climate change and population growth. Thus, evaluating the impact of water resources is essential in public management (Buytaert & Bièvre, 2012). Corte (2015) used the CWB in an urban basin located in Santa Maria, state of Rio Grande do Sul. His results revealed the highest water excess close to the winter and the highest water deficit in August. Moraes (2007) applied the CWB in São José de Ubá, northwest region of the state of Rio de Janeiro, using an experimental micro basin to estimate the water balance and water availability. The author concluded that this region has annual water deficit, followed by a critical situation related to water storage for most of the year.

The monitoring of urban areas is crucial for the understanding of their influence on different environmental parameters and the climate (Imhoff et

al., 2010; Peres et al., 2018). Changes in the rainfall regime directly affect surface and subsurface water flows. They also increase the air temperature and the evapotranspiration, which causes less output and lower recharge of groundwater resources (Vörösmarty et al., 2000; Hunt & Watkiss, 2011; Buytaert & Bièvre, 2012). Cities are vulnerable to climate change. The global trend of urbanization and population growth demands larger volumes of water supply (Buytaert & Bièvre, 2012).

The Municipality of Rio de Janeiro (MRJ), located in the Southeast region of Brazil, is the 2nd largest metropolis in the country and occupies the 2nd position in the Gross Domestic Product (GDP) rank. The MRJ has densely populated areas, with a total population of 6,320,446 in 2010 and an estimated population of 6,661,359 inhabitants by 2020 (IBGE, 2017). Armond and Sant'Anna Neto (2017), Peres et al. (2018), and Sobral et al. (2018) carried out observational, numerical, and Remote Sensing (RS) studies using climatic data for both the state and the municipality of Rio de Janeiro. Armond and Sant'Anna Neto (2017) identified the meteorological systems that cause extreme rain events in the MRJ, and the Frontal Systems (FS) obtained 65% of the cases. Peres et al. (2018) evaluated the formation of the Urban Heat Island (UHI) and verified the intensification of the UHI in two different periods (1984-1999 and 2000-2015) via orbital products. Sobral et al. (2018) assessed the drought in Rio de Janeiro, and the metropolitan region of Rio de Janeiro experienced frequent droughts. Despite the importance of the MRJ, no studies on CWB have been reported for the region. Thus, this study aimed to evaluate the spatial-temporal distribution of CWB, based on the identification of regions with water excess and deficit, using data from the Sistema Alerta Rio.

Material and Methods

Study Area

MRJ has a total area of 1,224.56 km². The latitude ranges between 22°45'05"S and 23°04'10"S, and longitudes the longitude ranges between 43°06'30"W and 43°47'40"W. The altitude may exceed 1,000 m above sea level (asl) at the mouting ranges (Figure 1). According to the Köppen's classification, the climate of the region is Atlantic tropical ("Aw"). Summers are hot and humid, while winters are mild, with low rainfall records (Dereczynski et al., 2009). All stages of the study follow the flowchart (Figure 2).

Figure 1. Location of the 33 rainfall stations of Sistema Alerta Rio in the Municipality of Rio de Janeiro and its hypsometry (m).

Figure 2. Flowchart of the methodology used in the study.

Organization and treatment of the climate database of the Sistema Alerta Rio

The main objective of the Sistema Alerta Rio is to warn about heavy rains and landslides in the MRJ. The system is composed of a network of 33 rainfall stations along the regions of MRJ, which send real-time data every 15 minutes. This study considered the rainfall and air temperature data from 33 rainfall stations provided by the Sistema Rio Alerta database.

(<http://alertario.rio.rj.gov.br/download/>). Figure 1 shows the location of the 33 rainfall stations used in the study and their respective identifiers (ID).

Air temperature data are recorded every 15 minutes from seven surface weather stations (SWS). The stations and their respective ID are: Alto da Boa Vista (ID 16), Guaratiba (ID 20), Irajá (ID 11), Jardim Botânico (ID 28), Rio Centro (ID 19), Santa Cruz (ID 22) and São Cristóvão (ID 32) (Figure 3).

Figure 3. Distribution of the 7 meteorological stations in the municipality of Rio de Janeiro.

To improve the quality of the rainfall data of the Sistema Rio Alerta, the gaps were filled using the analysis of the mean, maximum, and minimum rainfall values of MRJ. This analysis aimed to identify gross errors contained in the time series. The irregularities were verified, and then the data were evaluated and compared with the reference stations, selected by the proximity and geographical characteristics.

The consistency analysis was carried out by calculating the monthly mean (M) of the selected stations and the standard deviation (SD). After obtaining the values of these statistical parameters, the acceptable minimum and maximum limits for each month were established. Any value above the maximum limit and below the minimum limit is considered as a discrepant value and therefore requires the gaps to be filled.

The limits Eqs.(1) and (2) are:

$$L_{\min} = M - (4 \times DP) \quad (1)$$

$$L_{\max} = M + (4 \times DP) \quad (2)$$

Where $L_{\min}$ is the Minimum Limit, $L_{\max}$ is the Maximum Limit, M is the Arithmetic Mean of rainfall (mm), and SD is the standard deviation of rainfall (mm).

The Regional Weighting Method (Tucci et al., 2000) was used to complete the series based on the data available from three nearby stations, which are in the same climatological region. After filling the gaps, its consistency should be analyzed. The Regional Weighting method is given by Eq. 3:

$$Y_c = \frac{1}{3} \left[\frac{X_1}{X_{m1}} + \frac{X_2}{X_{m2}} + \frac{X_3}{X_{m3}} \right] Y_m \quad (3) \quad \text{Where } Y_c$$

is the estimated temperature/rainfall in station Y ; X_1 , X_2 and X_3 are the temperatures/rainfall corresponding to the month to be completed; X_{m1} , X_{m2} , and X_{m3} are the mean temperatures/rainfall of three nearby stations; and Y_m is the mean temperature/rainfall of the station Y .

Estimate of the mean air temperature

To fill the temperature gaps of the time series of the MRJ, the respective coefficients of the multiple linear regression model (MLRM) were obtained based on the monthly mean temperature (T_m , °C), latitude and longitude, and altitude of 12 stations from 1997 to 2016. The mean monthly temperatures were estimated based on the MLRM, using the latitude, longitude and altitude of the meteorological stations.

The MLRM was adjusted to databases of the observed monthly average temperature (Table 1). The 12 stations of the Sistema Rio Alerta initially had gaps from 1997 to 2003, which were completed with T_m values from nearby stations. For the 12 stations that did not have data between 1997 and 2016, the gaps were filled based on the coefficient of regression for the estimation of their annual monthly average.

Table 1. Stations used as the basis for MLRM application, followed by identifiers (ID), latitude and longitude (°) and altitude (m).

ID	Stations	Latitude (°)	Longitude (°)	Altitude (m)
1	Vidigal	-22.99	-43.23	85
4	Tijuca	-22.93	-43.22	340
6	Copacabana	-22.99	-43.19	90
11	Irajá	-22.83	-43.34	20
12	Bangu	-22.88	-43.47	15
16	Jardim Botânico	-22.97	-43.22	0
19	Barra/Riocentro	-22.98	-43.41	0
20	Guaratiba	-23.05	-43.59	0
22	Santa Cruz	-22.91	-43.68	15
26	Campo Grande	-22.90	-43.56	30
28	Alto da Boa Vista	-22.97	-43.28	355
32	São Cristóvão	-22.90	-43.22	25

The MLRM was used to evaluate the relation between the T_m , which is the dependent variable, and the independent variables latitude, longitude, and altitude, according to Eq. 4:

$$T_m = A_m + B_m \phi + C_m \beta + D_m Z \quad (4)$$

Where T_m refers to the estimated value of the average temperature of the month m ($m = 1, 2, 3, \dots, 12$); ϕ , β , and Z refer to, respectively, latitude, longitude, and altitude; A_m , B_m , C_m , and D_m are the regression coefficients.

To evaluate the statistical significance of MLRM, the T_m data were subject to analysis of variance at the 95% significance level, by the F and Student t -tests, using the R software version 3.4.2 (R DEVELOPMENT CORE TEAM, 2017). The existence of a significant relation between the dependent variable and the independent or explanatory variables was evaluated by the F_{cal} test, according to the following hypotheses:

H_0 : $B_m = C_m = \dots = K_n = 0$ (the relation between the variables is not linear);

H_1 : at least one $B_m \neq 0$. The statistic of the test is given by Eq. (5):

$$F_{cal} = \frac{QM_{Reg}}{QM_{Res}} \quad (5)$$

In which QMR_{eg} and QMR_{es} are the regression and the residual mean square.

For $F_{cal} \geq F_{tab}$, H_0 is rejected for a significant p-value $\alpha < 0.05$;

$F_{cal} \leq F_{tab}$, H_0 is accepted for a non-significant p-value $\alpha > 0.05$.

The Student t -test was used to evaluate the significance between the dependent and independent variables, which was evaluated by the t_{cal} test, according to the following hypotheses:

H_0 : $B_m = C_m = \dots = K_n = 0$ (coefficients are not important in the model);

H_1 : $B_m \neq 0$ (coefficients are important in the model)

where, for $t_{cal} \geq t_{tab}$, H_0 is rejected for a non-significant p-value $\alpha < 0.05$;

$t_{cal} \leq t_{ab}$, H_0 is accepted for a significant p-value $\alpha > 0.05$.

Calculation of the Climatological water Balance

The CWB of each station was calculated based on the rainfall and temperature data. The CWB analysis considered the periods of 1997-2015 (dry years) and 2008-2009 (wet years), the periods were identified in the analysis of rainfall and air temperature data. The CWB is an alternative to estimate the mean water storage in the soil based on the natural water supply to the soil (rainfall) and the atmospheric demand (ETP), and with an appropriate available water capacity (AWC).

This study adopted the following basic premises: soil and topography do not interfere with the transformation of rainfall (P) into real evapotranspiration (ET_r) and water filling in the soil; the rainfall distribution (P) is uniform throughout the month, the total water demand by the plant is equal to the reference evapotranspiration ET_0 , and thus, ET_0 represents the climatological water demand; the P rainfall is the only form of water input, and thus, P is the climatological water supply (Rolim et al., 2007; Corte, 2015). The mean or normal monthly P and ETR are required as input data. In this study, available water capacity (AWC) is assumed as 100 mm. Based on the data described, Thornthwaite-Mather Water Balance (1955) provides monthly estimates of the ETR, DEF, EXC; estimates of the accumulated difference between P and ET_0 (NEG-AC) and soil water storage (SWS).

Potential evapotranspiration (ETP) was estimated by the Thornthwaite Method based on Eqs. (6), (7) and (8):

$$ETP = Fc \times 16 \times \left(10 \times \frac{T}{I} \right)^a \quad (6)$$

$$a = 67.5 \times 10^{-8} \times I^3 - 7.71 \times 10^{-6} \times I^2 + 0.01791 \times I + 0.492 \quad (7)$$

where ET_p = potential evapotranspiration (mm.month⁻¹); T = mean air temperature (°C); Fc = correction factor in function of the latitude and month, computed, and I = annual thermal index, given by:

$$I = \sum_{i=1}^{12} \left(\frac{T_i}{5} \right)^{1.51} \quad (8)$$

The interpolation method Inverse of Square Distance (ISD) was applied using the ArcGIS software, version 10.3, applied to the parameters DEF and EXC of the MRJ.

Results and Discussion Temporal

In Figure 4, DEF was predominant in some stations in the MRJ in 1997, except in January. The phenomenon El niño worked in the state of Rio de Janeiro (SRJ), of SPI (Standardized Precipitation Index) and RDI (Reconnaissance Drought Index) drought indices - (Sobral et al., 2018; Oliveira Júnior et al., 2018), intensified this parameter as it caused high temperatures and drought, influencing the CWB results. The cumulative value of 635.7 mm.year⁻¹ was recorded in 1997, and the highest accumulated annual DEF occurred at Penha station (635.7 mm.year⁻¹), according to Dereczynski et al. (2009) and Zeri et al. (2011), the Penha station located in the North Zone of the MRJ has the lowest records of rainfall and high temperatures. Similar and the lowest accumulated annual DEF occurred at the Rocinha station (185.6 mm.year⁻¹), with lowest rainfall records and the highest temperatures, featured for located in the south of the MRJ, close to the coast, and the Tijuca massif. In the latter, the active meteorological systems move from south to north, transporting the humidity from the sea to the continent. When reaching the Tijuca massif, the humid air rises and increases the volume of rainfall (Dereczynski et al., 2009; Terrassi et al., 2020). The annual EXC was 89.6 mm.year⁻¹ at Ilha do Governador (ID 8), mainly in January. This same month had the highest EXC concentration in all regions of the MRJ due to the higher rainfall, which influenced the EXC, except for Rocinha station, which recorded the highest EXC in January, September, and October (Figure 4). The results showed a large water output in 1997, expressed by high DEF values and low recharges.

In March 1997, the Climanálise Bulletin recorded rainfall lower than the average due to the lower frequency of FS in the Southeast region. In July 1997, the rainfall was lower than the average in the coast of Rio de Janeiro (CLIMANALISE, 2017). Dereczynski et al. (2013) state that the amount of rainfall associated with extreme rainfall events has increased in recent years, especially in the frequency and amount projected until the end of the 21st century, with longer dry periods and shorter wet seasons. Regarding the temperature, a heating trend is observed, with a variation between 2°C and 5°C higher than the average.

Figure 4. Parameters of the CWB (DEF and EXC, mm) in the MRJ, at Vidigal (a), Rocinha (b), Ilha do Governador (c), Penha (d), Recreio dos Bandeirantes (e), and Grota Funda (f) stations, in 1997.

In 2015, the El Niño caused severe drought conditions in the Southeast of Brazil, being the most critical period of the water crisis in the region (Marengo & Alves, 2015) and, therefore, influencing the distribution of DEF and EXC (Figure 5). Penha and Ilha do Governador stations, representative of the lowland region and the leeward of Tijuca massif, had no EXC, and their DEF values were $947.7 \text{ mm}\cdot\text{year}^{-1}$ and $1065.8 \text{ mm}\cdot\text{year}^{-1}$, respectively. These high values affect vegetation growth, evidencing the need for crop irrigation, urban afforestation, and reforestation in the municipality (Terrassi et al., 2020; Freitas et al., 2020). The lowest DEF values were recorded at Rocinha ($61.2 \text{ mm}\cdot\text{year}^{-1}$) and Grota Funda ($96.1 \text{ mm}\cdot\text{year}^{-1}$) stations due to the effects of the maritimity associated with the relief. January had DEF peaks, which were caused by

the high ETP resulting from the high temperatures and low rainfall volumes, except for Grota Funda station, which had EXC. The maximum EXC was recorded at Rocinha ($461.9 \text{ mm}\cdot\text{year}^{-1}$), especially in November, with $204.5 \text{ mm}\cdot\text{year}^{-1}$. The highest ETP value was observed at Ilha do Governador station, with $1865 \text{ mm}\cdot\text{year}^{-1}$, followed by Penha, with $1639.69 \text{ mm}\cdot\text{year}^{-1}$. Grota Funda station had the lowest ETP value ($1259.67 \text{ mm}\cdot\text{year}^{-1}$) – (Figure 5). ETP increases in function of the temperature. Meireles et al. (2014) state that temperatures are lower in a location with vegetation on the surface, where water is available for the most time in the soil, and the energy is partitioned between latent heat (used to evaporate some of this water) and sensible heat (related to surface heating).

Figure 5. Parameters of CWB (DEF and EXC) in the MRJ, at Vidigal (a), Rocinha (b), Ilha do Governador (c), Penha (d), Recreio dos Bandeirantes (e), and Grota Funda (f) stations, in 2015.

In Figure 6, the CWB results for 2008-2009 indicate that DEF reached a maximum of 302.17 mm.year⁻¹ at Penha station and the minimum at Rocinha station (3.11 mm.year⁻¹). EXC reached the maximum of 1855.16 mm.year⁻¹ at Rocinha station and a minimum of 503.06 mm.year⁻¹ at Penha station. In December 2009, intense rains resulted in the maximum EXC values in all seasons, reaching 338 mm.year⁻¹ at Ilha do Governador station. ETP reached the maximum value (2401.69 mm.year⁻¹) at Vidigal and the minimum value (2069.55 mm.year⁻¹) at Rocinha (Figura 6). According to the Climanalise Bulletin, the storms that

occurred in December caused serious disturbances to the population of the Southeast Region of Brazil. The most tragic ones, which resulted in death and material loss in Rio de Janeiro, especially in the city of Angra dos Reis-RJ, were mainly associated with the increase of humidity convergence in the center of Brazil (CLIMANÁLISE, 2017). This convergence was reinforced by the formation of a low-pressure center adjacent to the coast and by the flow associated with the Bolivian High (BH) and the cyclonic vortices in the mid and upper troposphere, common in Southeastern Brazil (Lima et al., 2009).

Figure 6. CWB (DEF and EXC) parameters in the MRJ, in the years 2008 and 2009, at Vidigal (a), Rocinha (b), Ilha do Governador (c), Penha (d), Recreio dos Bandeirantes (e), and Grota Funda (f) stations.

These results show that the highest EXC occurred in the summer, due to the higher rainfall at this time of the year (Brito et al., 2016; Terrasi et al., 2020). The influence of the orography is remarkable in this season and favors the occurrence of local rainfall, such as the occurrence of squall lines (SL) and mesoscale convective systems (MCS), which happens at a lower magnitude during the spring. Also, the sea/land breeze and valley/mountain circulations are more intense in the summer; they interact with FS and South-Atlantic Convergence Zone (SACZ) and thus generate and intensify rainfall in the state of Rio de Janeiro (Lima et al., 2009; Zeri et al., 2011; Brito et al., 2016; Oliveira Júnior et al., 2019).

Spatial

Figures 7 and 8 show that the highest EXC and the lowest DEF were recorded in the surroundings of the

MRJ massifs, in the SE/SW directions, due to high rainfall rates, resulted from the interaction between meteorological systems and the relief (Brito et al., 2016; Terrasi et al., 2020), and the low temperatures, which contributed to the highest EXC. Araújo (2010) observed an abrupt change in the air temperature at Pedra Branca, Gericinó, and Tijuca massifs (18-20°C) when compared with the rest of the municipality (21-23°C). Moraes et al. (2005) observed, in the spatial distribution of the temperature close to the surface in MRJ, that the highest temperatures coincided with the urban occupation of the RMRJ, especially in North Region. This fact indicates the formation of UHI in the region. Dereczynski et al. (2009) reported that in the lowland areas, rainfall is always lower than the total rainfall observed near the MRJ hills. The minimum rainfall was recorded in the extreme north of the

municipality, where the Irajá (ID 11) and Penha (ID 9) stations are located.

From 2008 to 2009, DEF values were lower than in 1997 and 2015 due to the regular rainfall in the MRJ. DEF values were higher in the lowlands, in the urbanized region, and the leeward of the coastal massifs in North Region and West Region, with values higher than 400 mm. According to the Climanálise Bulletin, in 2008, most of the country registered rainfall values higher than the historical average. At the beginning of January, the formation of unstable areas and the SACZ phenomenon led to heavy rainfall in several municipalities in Southeast Brazil (Lima et al., 2009). The occurrence of heavy rainfall in other months was mainly due to the SF, the action of troughs in the medium and high levels of the atmosphere, and the action of the Low-Level Jet (LLJ) and SACZ. Again, January 2009 recorded rainfall higher than the historical average. The main meteorological systems that caused the intense rainfall were BH and SACZ (Oliveira Júnior et al., 2019). In March, SACZ contributed to above-average rainfall in areas of Southeast Brazil. EXC was higher in 2015 than in 1997 and was concentrated in three regions of the MRJ: Tijuca massifs, Pedra Branca, and Mendanha (Figure 1). From 2008 to 2009, EXC values were higher, with intense rainfall. In December 2009, the highest EXC values were observed at Tijuca and Pedra Branca massifs, on the slope that faces the sea. Dereczynski et al. (2009) and Terassi et al. (2020) found similar results when studying three rainfall maxima associated with the three mountain ranges of MRJ: the first, near Serra da Carioca (southeast); the second, near Serra do Mendanha (north), and the third, near the Serra Geral de Guaratiba (southwest), near Grota Funda station.

Table 2 shows the average ETP values of the study period. Most of the stations had ETP values above 100 mm, except for Tijuca (ID 4) and Alto da Boa Vista (ID 28), both near the Tijuca massif. Highlights for Av. Brasil/Mendanha (ID 29), Anchieta (ID 24), Irajá (ID 11) and Ilha do Governador (ID 8) stations with higher ETP values (>130mm).

ID	Stations	ETP (mm)
1	Vidigal	105.25
2	Urca	108.81
3	Rocinha	100.06
4	Tijuca	92.56
5	Santa Teresa	104.78
6	Copacabana	105.38
7	Grajaú	114.27
8	Ilha do Governador	140.23
9	Penha	121.91
10	Madureira	125.34
11	Irajá	136.39
12	Bangu	128.41
13	Piedade	121.82
14	Jacarepaguá/Tanque	116.63
15	Saúde	124.67
16	Jardim Botânico	115.41
17	Barra/Barrinha	110.56
18	Jacarepaguá/Cidade de Deus	118.09
19	Barra/Riocentro	114.93
20	Guaratiba	107.19
21	Est. Grajaú/Jacarepaguá	111.61
22	Santa Cruz	124.74
23	Grande Méier	124.75
24	Anchieta	132.70
25	Grota Funda	110.20
26	Campo Grande	123.52
27	Sepetiba	111.74
28	Alto da Boa Vista	89.16
29	Av. Brasil/Mendanha	130.96
30	Recreio dos Bandeirantes	110.57
31	Laranjeiras	113.69
32	São Cristóvão	123.70
33	Tijuca/Muda	117.87

Table 2. Annual average ETP values (mm) of MRJ stations in the period 1997-2016.

Figure 7. Spatial distribution of DEF (mm) in 1997 (a), 2015 (b), and 2008-2009 (c).

Figure 8. Spatial distribution of EXC (mm) in 1997 (a), 2015 (b), and 2008-2009 (c).

Conclusions

The Multiple Linear Regression Models adjusted for the databases of the observed average monthly temperatures indicate that the variables latitude, longitude, and altitude are necessary to represent the spatial variability of the minimum temperature in the MRJ. MLRM explained most of the spatial variability of the T_{min} for the study region and revealed that altitude is the variable that most influences the variation of the air temperature in the MRJ.

The CWB carried out at the Sistema Rio Alerta stations for the wet period (2008-2009) and the dry period (1997 and 2015) shows that the highest DEF values were registered from June to August, as a result of the strong action of South Atlantic Subtropical Anticyclone (SASA) and the influence of local systems. January concentrates the highest EXC, with higher intensity in the south, due to physiographic factors. The highest ETP values occur in December and January when the temperature is higher in the municipality of the Rio de Janeiro.

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