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UPDATE OF CLIMATOLOGICAL NORMAL AND KÖPPEN CLIMATE CLASSIFICATION FOR THE MUNICIPALITY OF BOTUCATU-SP

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1 RESUMO

O clima é observado há milhares de anos ao longo do desenvolvimento humano, e seu conhecimento é fundamental para as práticas agrícolas. A classificação climática é uma tarefa difícil devido ao período de dados necessários para sua identificação, no mínimo 30 anos de medidas registradas, conforme recomenda a Organização Mundial de Meteorológica. O objetivo desta pesquisa foi identificar as normais climáticas dos elementos do clima e atualizar a classificação climática do município de Botucatu - SP, utilizando o método proposto por Köppen (1918) e adaptado por Setzer (1966). Os elementos analisados foram a precipitação pluviométrica, umidade relativa do ar e temperatura média do ar. Foram utilizados dados diários da estação meteorológica local, no período de 1991 a 2020. As normais climatológicas foram identificadas com temperatura média do ar de 21,34°C, umidade relativa média do ar de 70% e precipitação média anual de 1500 mm, com ocorrência média de precipitação em 107 dias ao ano. Analisando os dados da nova normal climática segundo Köppen, o clima de Botucatu - SP foi identificado com Aw, diferentemente das classificações anteriores, com verões quentes e úmidos (maior temperatura e precipitação) e invernos frios e secos (baixa temperatura e precipitação).

Palavras-Chave: Classificação climática de Köppen, Normal climatológica, Temperatura e Precipitação, Mudanças climáticas.

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UPDATE OF THE CLIMATE STANDARD AND CLIMATE CLASSIFICATION OF KÖPPEN FOR THE BOTUCATU-SP MUNICIPALITY

2 ABSTRACT

The climate has been observed for thousands of years throughout human development, its knowledge is fundamental for agricultural practices. Climate classification is a difficult task due to the period of data required for its identification, at least 30 years of recorded measurements, as recommended by the World Meteorological Organization. The objective of this research is to identify the climatic normals of the elements of the climate and to update the climatic classification of the municipality of Botucatu - SP, using the method proposed by Köppen (1918) and adapted by Setzer (1966). The elements analyzed were rainfall, relative humidity and average air temperature. Daily data from the local meteorological station were used, from 1991 to 2020. The climatological normals were identified with an average air temperature of 21.34°C, an average relative humidity of 70% and an average annual precipitation of 1500 mm, with average occurrence of precipitation in 107 days of the year. Analyzing the data of the new climatic normal according to Köppen, the climate of Botucatu - SP was identified with Aw, unlike the previous classifications, with hot and humid summers (higher temperature and precipitation) and cold and dry winters (low temperature and precipitation).

Keywords: Köppen climate classification, Climatological normal, Temperature and precipitation, Climate change.

3 INTRODUÇÃO

Climate can be considered one of the determining factors within the spatial dynamics of the distribution and dissemination of living beings across territories, as it directly affects the soil and consequently the entire biome within it, as well as its potential for land use and agricultural production (SILVA FILHO *et al.*, 2021). In this scenario, climatology consists of the study of climate, the variation of its elements and their influence on human activity, the environment, health and social well-being. Knowledge of the variation in elements is fundamental for agro-climatic zoning, which can be used to identify whether a certain crop has the capacity to adapt to a given region, considering climatic elements (INMET, 2022).

The climate of a region can be determined by factors such as latitude, altitude, continentality, and vegetation. As the climate of a place is determined by a series of factors, there is a wide variety of climates spread across the Earth's surface. Although no two locations have identical climates, it is possible to define regions in which the climate is relatively uniform between different locations. The process of identifying regions with similar climates is called a climate classification model (YNOUE *et al.*, 2017).

In this sense, climate studies are based on meteorological observations and measurements carried out in a given region, such that when characterizing the climate of this region, profiles of rainfall regime, air temperature, relative air humidity, atmospheric pressure, wind and solar

radiation enable climate classification (INMET, 2022).

Climatic classification aims to define areas or regions with relatively homogeneous/similar biogeographic characteristics (ALMEIDA, 2016). One of the classic models for climate classification was created by Köppen in 1918 to identify the climate in a simplified way. Köppen (1918) believed that natural vegetation is the best indicator to express the characteristics of the climate of a given location. The model made great progress in identifying regions across the globe through the study of vegetation associated with measurements of air temperature and rainfall (ALMEIDA, 2016; YNOUE *et al.*, 2017). This model has been used for more than a century as a reference for climate classification. Some adaptations to the original model were made by other authors over time for specific locations (CARDOSO; MARCUZZO; BARROS, 2014).

To classify the climate of a location, it is necessary to have several years of meteorological data. However, due to the large period of time needed, there are still few meteorological databases that meet this requirement, considering the various technical and maintenance problems related to meteorological station operations. There is also the issue of periodic calibration of the sensors, which is not always properly carried out (FRANCO *et al.*, 2022).

Climatological data, as well as most natural variables, tend to have a normal statistical distribution. In the normal statistical distribution, the largest number of observations in a sample (or population) are close to the mean, while values far from the mean have few observations. Therefore, when mentioning a climatic series over a long period, it is common to use the term "climatological normal" (VAREJÃO-SILVA, 2006).

According to the World Meteorological Organization (WMO, 2023), a period of 30 years of data is necessary to identify the climatological normal of a given location and consists of the average values (monthly and annual) of the climate elements (air temperature (°C), relative air humidity (%) and precipitation (mm)) in a defined period. Botucatu's climatological normal has been studied and published in the past (SMAABC, 2002; ROLIM *et al.*, 2007; CUNHA; MARTINS, 2009; ALVES *et al.*, 2014; ROSSI *et al.*, 2018). Studies on climate change demonstrate the importance of monitoring climate variability and its impacts on the economy, environment, health and natural disasters. According to the IPCC AR 6 (2021) bulletin, the study and identification of the climate (and its changes) is essential for maintaining local anthropogenic activities (INMET, 2022). Climate change has already been identified in regions close to the study region, as demonstrated by the work of Alvares, Sentelhas and Dias (2022), in the municipality of Piracicaba – SP.

Given the importance of having knowledge about the climate of a location and its agronomic impact and considering the effects caused by climate change, this work aimed to i) identify the monthly and annual climatological normals of air temperature, relative humidity air and precipitation over the last 30 years, following the WMO (2023) pattern for the period from 1991 to 2020; and ii) carry out the updated Köppen classification (1918) for the municipality of Botucatu - SP.

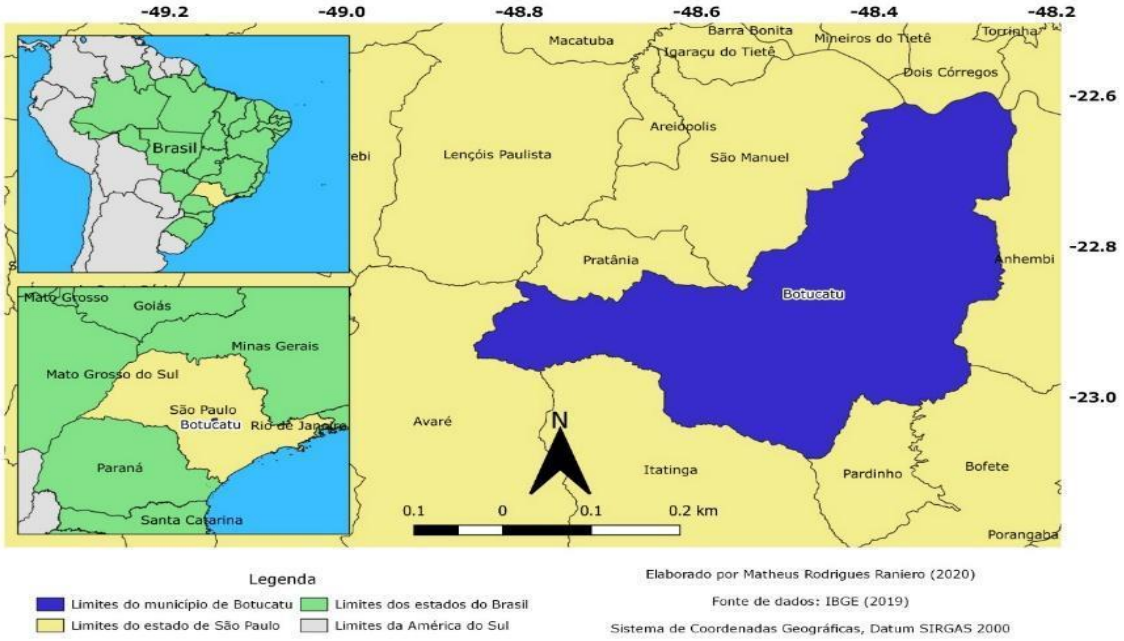
4 MATERIALS AND METHODS

4.1 Location and climate

The study was carried out using the historical data series from the Meteorological Station of the Department of Rural Engineering and Socioeconomics of the Faculty of Agricultural Sciences of the Universidade Estadual Paulista "Júlio de Mesquita Filho" (UNESP) of Botucatu - São

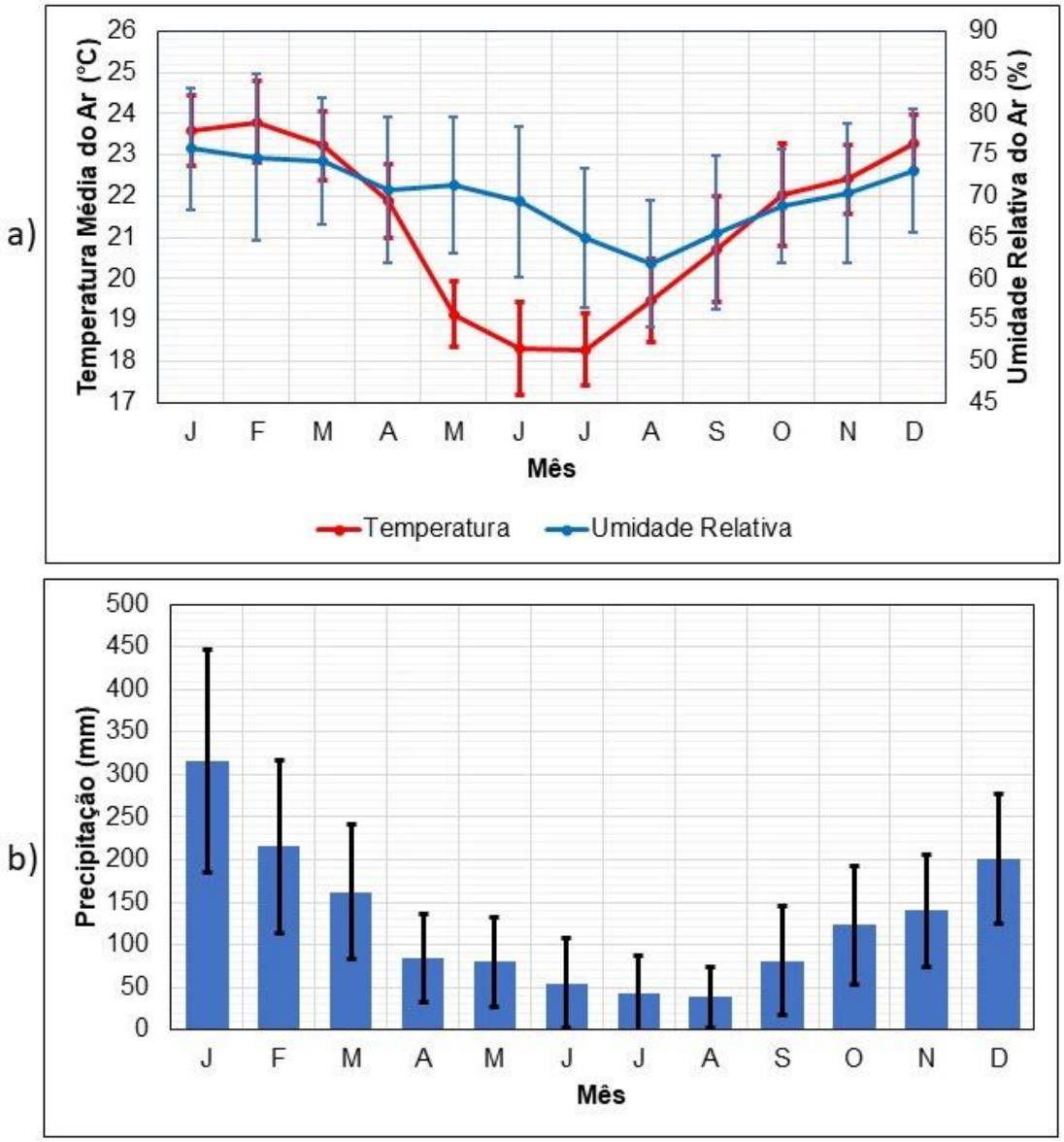
Paulo – Brazil (22°54'S, 48°27' W is 786 m). Botucatu (Figure 1) is a municipality of approximately 149 thousand inhabitants in a territorial area of 1,482.642 km², with the Cerrado and Atlantic Forest biomes (IBGE, 2022). The municipality is located close to two large dams (Barra Bonita and Jurumirim) and is approximately 221 km away from the Atlantic Ocean (ROSSI *et al.*, 2018).

Figure 1. Municipality of Botucatu -SP



The historical series from 1991 to 2020 presents monthly values of temperature and relative humidity (Figure 2a) and the average accumulated precipitation values (Figure 2b). The hottest months occur in summer, with an average maximum temperature of 23.80°C in February, a maximum relative humidity of 75.76% in January and a maximum precipitation of 310.37 mm in January. The minimum values occur in winter, with average temperatures of 18.28°C in July, with a minimum relative humidity of 61.86% and minimum precipitation of 38.76 mm in August.

Figure 2. Temperature, relative humidity and precipitation from 1991 to 2020 for Botucatu - SP



Source: Author (2023)

4.2 Köppen classification of the region of the municipality of Botucatu

The Köppen classification for the municipality of Botucatu, according to (SMAABC, 2002; ROSSI *et al.*, 2018), in relation to the Climatological Normal 1981-2010, is identified as Cwa, mesothermal (subtropical and temperate) with hot and rainy summers and dry and cold winters.

Studies carried out by Rolim *et al.* (2007), Cunha and Martins (2009) and Alves *et al.* (2014) classified Botucatu's climate as Cfa, which characterizes a hot temperate (mesothermal) and humid climate in all seasons.

In Figure 3, it is possible to see the climate classification of neighboring municipalities of Botucatu-SP (and the entire state of São Paulo). Many locations are classified as having Aw or Cwa climates

in the region close to Botucatu. The municipality of Botucatu is located in a region separating two homogeneous climate regions within the state: the northwest, with Aw predominance; and southeast, with a predominance of Cwa. It is worth remembering that Figure 3 was prepared based on meteorological stations spread across the state, and most municipalities had their classification carried out with data extrapolated from these stations.

Figure 3. Köppen climate classification for the state of São Paulo

Source: SMAABC (2002)

4.3 Data Acquisition Instruments

Data measured over 30 years from automatic (EMA) and conventional (EMC) meteorological stations were used. At EMA (Figure 4a), temperature and relative humidity were measured by a *Campbell Scientific* HC2S3 sensor. Precipitation was measured by the *Campbell Scientific TB4 Rain Gage digital rain gauge.* Data were recorded by a *Campbell Scientific* CR1000 Datalogger. At EMC (Figure 4b), the analog nature of the equipment needed that measurements be routinely carried out by meteorological observers, following WMO standards (2023). The maximum and minimum air temperatures were measured by *R. FUESS thermometers,* and the relative humidity was measured with a *Salmoiraghi instrument*. Precipitation was measured using the IR *Ville de Paris model rain gauge (Figure 4c).*

Figure 4. Automatic and conventional meteorological station at Lageado farm - UNESP in Botucatu – SP

Source: Author (2023)

4.4 Concurrent Data Analysis

The data obtained by EMC were from the period 1971 to 2016. The EMA began operating in 2015 and remains in operation until the present day (2023). To unify the databases, a study was carried out by Franco *et al.* (2022) with the aim of comparing data from conventional and automatic sources. The authors developed models that made it possible to estimate data for the automatic station in a period prior to its activation.

4.5 Identification of the Climate Normal

To identify climate normals, daily data on minimum, average and maximum air temperature, relative air humidity and rainfall were used. Using daily data, the average value of each month was calculated for air temperatures (minimum, average and maximum) and relative air humidity. For rainfall, the sum of days (accumulated value) was calculated, and the number of days in that precipitation was greater than 1 mm each month. After identifying the values for each month, the mean and standard deviation between the months were calculated.

4.6 Köppen Climate Classification Methodology

The Köppen Classification (1918) was based on the distribution and quantity of climate elements, which include air temperature and rainfall. These elements constitute the criteria for separating climate types. This classification underwent adaptations by other authors. Setzer (1966) simplified the classification (Table 1) by creating classification criteria (keys) in a simpler and more direct way adapted for Brazil (CARDOSO; MARCUZZO; BARROS, 2014).

Table 1. Key to Köppen's climate classification (1918) simplified by Setzer (1966) for Brazil.

Normal average temperature of the coldest month	Normal average temperature of the hottest month	Total rainfall of the driest month (Pms)	Total annual rainfall (P)	Type of climate according to Köppen (Humid Climates)		Symbol
>= 18°C	>= 22°C	>= 60 mm		Tropical	No dry season	**Af**
		< 60 mm	< 2500 - 27.27. Pms		dry winter	**A W**
			>= 2500 - 27.27. Pms	Tropical with excessive rainfall		**Am**
< 18°C	< 22°C	< 30 mm	Subtropical	Warm		**Cwa**
				Seasoned		**Cwb**
	>= 22°C	>= 30 mm		Warm	No dry season	**CF**
	< 22°C			Seasoned		**Cfb**

Source: Cardoso; Marcuzzo; Barros (2014)

In the classification, five basic climate groups were described (Table 2), identified by the capital letters A, B, C, D, and E. The groups are subdivided into other groups, which are based on the seasonal distribution of precipitation and air temperature characteristics (ALMEIDA 2016; YNOUE *et al.*, 2017).

Table 2. Köppen climate classification groups

Groups	Fundamental Types
A	Af - tropical rainy jungle climate
	Aw - tropical savannah climate
B	BS - semiarid skewers climate
	BW - desert (arid) climate
W	Cs - humid temperate climate (with dry summer)
	Cw - humid temperate climate (with dry winter)
	Cf - humid temperate climate (no dry season)
D	Dw - cool woodland climate with dry season (taiga)
	Df - woodland climate without dry season (taiga)
AND	ET - tundra climate (barren land)
	EF - climate of perpetual ice and no possibility of vegetation (glacial)

Source: Vianello and Alves (2012)

5 RESULTS AND DISCUSSION

5.1 Climatological Normal

Table 3 contains the average values and standard deviations of air temperature, relative humidity, the average value of monthly accumulated precipitation, the highest recorded daily precipitation and its year of occurrence, and the average number of days that precipitation occurred in each month. The last line presents the annual values of air temperature and relative humidity, the annual accumulated value of precipitation, the highest rainfall recorded in 24 hours, the year in which the highest rainfall occurred and the number of annual rainy days for the period. from 1991 to 2020.

Table 3. Climatic normal of temperature, relative humidity and precipitation for the municipality of Botucatu - SP from 1991 to 2020

Month	T	UR	P Monthly	P Max 24 h	Year	Number of P Days
	°C	%	mm	Mm		Days
Jan.	23.58 ±0.85	75.76 ± 7.35	315.14 ±131.12	238.05	2011	17
Feb.	23.80 ±0.85	74.26 ± 10.10	215.13 ±215.13	284.00	2020	14
Sea.	23.22 ±0.99	74.26 ± 7.71	161.91 ±79.69	113.19	1992	11
Apr.	21.88 ±0.84	70.67 ± 8.84	83.39 ±52.01	64.53	2009	6
May	19.12 ±0.89	71.38 ± 8.30	79.69 ±52.40	102.93	1993	6
Jun.	18.31 ±0.79	69.95 ±8,51	54,84 ±52,32	87,10	2012	5
Jul.	18,28 ±1,12	64,95 ±8,51	41,85 ±44,65	61,47	2019	3
Ago.	19,47 ±1,86	61,87 ±7,68	38,60 ±35,66	64,73	2008	3
Set.	20,71 ±1,02	65,61 ± 9.32	80.72 ±63.85	68.93	2000	7
Out.	22.03 ±1.29	68.84 ± 6.89	123.03 ±69.92	75.38	2011	9
Nov.	22.41 ±1.25	70.40 ± 8.41	140.01 ±66.13	66.98	2003	11
Dec.	23,29 ±0.84	73.14 ± 7.46	200.15 ±76.36	87.79	2009	14
Yearly	21.34	70.07	1,534.47	284.00*	2020**	107

Legend: T = Average air temperature; RH = Relative air humidity, P monthly = Monthly accumulated precipitation; P Max. 24 h = highest daily rainfall recorded; No. Days of P = number of days of precipitation.
* Maximum precipitation occurred and ** Year in which the highest amount of precipitation occurred in the historical series.

Table 4 presents the values of climatic normals for maximum and minimum air temperature, daily maximum and minimum values and year of occurrence. The months with the highest temperature occur in summer with a maximum temperature above 28°C, with the highest temperature recorded being 39.19°C in 2020. The months with the lowest temperature occur in winter, reaching less

than 15°C. Looking at the extreme measures and their years of occurrence, some high peaks were observed in the period from 2010 to 2020. During this period, historical records were recorded for maximum and minimum temperatures.

Table 4. Climate normal of maximum, minimum temperature and year of occurrence of extreme values in the municipality of Botucatu - SP from 1991 to 2020

Month	Tmax	Tmin	Absolute Tmax	Year	Absolute Tmin	Year
	(°C)	(°C)	(°C)		(°C)	
Jan.	28.34 ± 1.34	19.87 ± 0.64	35.70	2015	15.35	2002
Feb.	28.65 ± 1.30	20.00 ± 0.76	36.02	2012	14.98	1992
Sea.	28.12 ± 1.14	19.46 ± 0.68	34.45	2012	13.36	2011
Apr.	26.79 ± 1.06	18.03 ± 0.92	33.08	2012	8.32	2016
May	23.80 ± 0.86	15.51 ± 1.02	32.40	2010	6.88	2018
Jun.	23.12 ± 1.47	14.54 ±1,00	30,93	2010	3,59	1994
Jul.	23,53 ±1,17	14,13 ±0,88	29,95	2010	2,69	1994
Ago.	25,21 ±1,31	14,77 ±1,20	35,82	2010	4,68	2011
Set.	26,50 ±1,89	16,04 ± 1.06	37.50	2020	7.03	2002
Out.	27.77 ± 1.76	17.40 ± 1.23	39.19	2020	8.84	2014
Nov.	27.88 ± 0.87	18.00 ± 1.16	35.23	2006	10.65	2014
Dec.	28.46 ± 0.90	19,16 ± 0.86	34.65	2012	11.73	2011
Yearly	26.51	17.24	39.19*	2020**	2.69*	2012**

Legend: Tmax = average of maximum air temperatures; Tmin = average minimum air temperatures; Absolute Tmax = maximum daily air temperature; Tmin Absolute = minimum daily air temperature.
* Maximum and minimum air temperature and ** Year of occurrence of the highest and lowest air temperature in the historical series

5.2 Climate Classification

Following the classification criteria defined by Köppen (1918) and adapted by Setzer (1966) for the Brazilian climate, the variables used by the model were average air temperature, average accumulated precipitation for each month and average annual accumulated precipitation values. The model is divided into 4 stages (Table 1): analyzing the average air temperature of the coldest month, average air temperature of the hottest month, precipitation volume of the driest month and total annual precipitation volume. In view of the interpretation of the aforementioned model, it is clear that:

1 - The historical series showed the lowest average temperature of 18.28°C recorded in July during the winter period. Discarding groups B, D and E.

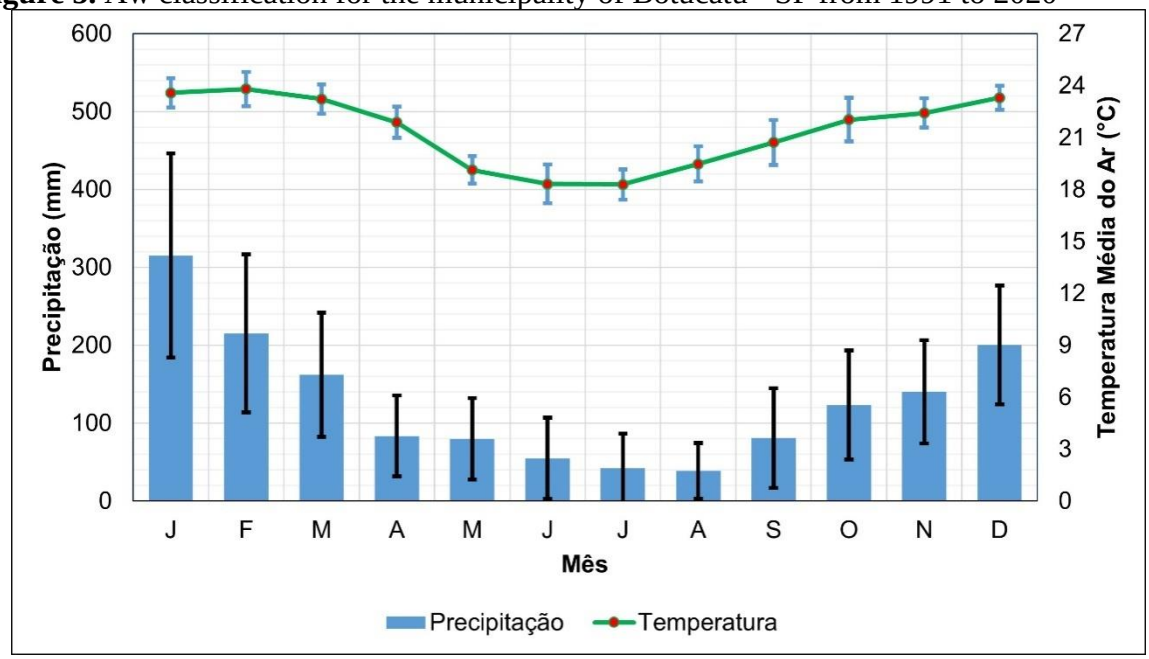
2 - The highest average temperature in the series occurred in February, 23.80°C during the summer.

3 - The volume of the greatest dry period occurred in winter and August, with an average volume of 38.60 mm, eliminating group C.

4 - The average volume of annual accumulated precipitation was 1,534.47 mm, which, according to the aforementioned criteria, identifies the climate of Botucatu - SP as Aw according to the Köoppen classification, referred to as a savanna climate, tropical with rain in summer and winter dry. This means that the classification made with the 1991-2020 series results in a different type of climate than that previously found by other researchers (citation?).

Figure 5 presents the graph with the climatic temperature and precipitation normals from 1991 to 2020, representing the Aw climate for the municipality of Botucatu – SP after the new classification. The highest temperatures and volume of precipitation occur in summer, with a monthly average minimum temperature of 19.77°C, an average temperature of 23.45°C and a maximum temperature of 28.37°C. The average precipitation varies between 160 and 315 mm accumulated per year. month. The period of drought and lower temperature occurs in the winter month with monthly average values of minimum temperature of 14.48°C, average temperature of 19.21°C and maximum temperature of 25.08°C, and the volume of precipitation varies between 38 and 80 mm.

Figure 5. Aw classification for the municipality of Botucatu - SP from 1991 to 2020



Source: Author (2023)

The classification of climates present in the territory of the state of São Paulo, carried out by Setzer (1966), indicates that Botucatu was in the Cwa classification range (subtropical dry winter climate) (MARTINELLI, 2010), referring to average values of precipitation and temperature, which date back to before 1966. Cunha and Martins (2009), using historical series from 1971 to 2006, classified Botucatu's climate as Cfa (subtropical climate with hot summer), according to the Köppen model, with an annual average of 20. 3°C, average minimum temperature of 17.1°C in July, average maximum temperature of 23.1°C in February. For precipitation, the rainiest month, on average, is January (246.2 mm), and the driest month is August (36.1 mm).

Research carried out by Rolim *et al.* (2007) and Alves *et al.* (2014) identified the climate of Botucatu as Cfa. It is also possible to find authors who use the classification for Botucatu as Cwa (SMAABC, 2002; ROSSI *et al.*, 2018).

Considering the updated classification of the climate of the city of Botucatu to Aw (tropical savanna climate), it is clear that changing the class from Cwa to Aw does not change the dry winter classification. Citations on the Cfa classification for Botucatu (CUNHA *et al.*, 2009; ROLIM *et al.*, 2007; ALVES *et al.*, 2014) consider that the climate does not have a dry season, which in fact does not match the nature of the data (Figure 6) due to the reduced amount of precipitation in the winter months.

The Aw classification also implies a change from a subtropical climate (Cwa) to a tropical climate, and due to the other specificities of total rainfall and normal average temperature, Botucatu's climate classification becomes tropical savannah. The constant updating of climate classifications is an urgent demand to better identify the relationships between climate and agricultural production, among other demands, especially in the face of climate change. Data referring to the current climatological normal (1991-2020) show an increase in the normal average temperature and total rainfall in the driest month, as well as total annual rainfall.

According to Rolim (2007), the climates in the interior of the state of São Paulo Aw, Cwa and Cwb are influenced by

altitude. The Cwa climate lost many areas in the central plateau to the detriment of other types of climate. This loss occurs because in many regions, the temperature of the coldest month was greater than 18°C, favoring the Af, Aw and Am climates.

A study carried out by Alvares, Sentelhas and Dias (2022) identified that the climate in the municipality of Piracicaba – SP (81 km away from Botucatu) is changing. Data collected at the Luiz de Queiroz College of Agriculture (Esalq/USP) show that between 1916 and 2016, the average temperature in the municipality registered an increase of 0.9°C, and the average air temperature recorded between 1917 and 1946 was 21.4°C. During the period from 1987 to 2016, the temperature rose to 22.3°C. This small change changed the municipality's climate classification from Cfa to Aw. Data from climate databases in the interior of the state of São Paulo and South America point to a strong trend toward tropicalization in the region.

A change of every half degree (0.5°C) makes a large difference in terms of climate impact. The consequences are an increase in the occurrence of storms, drought, heat waves, and drastic changes in precipitation patterns, among others. Extreme drought and high precipitation events that occur every 10 years could occur two to three times in the same period if the planet is 2.0°C warmer. Extreme heat events that occurred every 50 years may occur 14 times in the same period. If the planet's average temperature increases by 4.0°C (compared to the period 1850 - 1900) before 2100, the number of extreme weather events in some locations could become nine times more frequent (IPCC AR 6, 2021).

6 CONCLUSION

Botucatu's climate is characterized by hot, rainy summers and cold, dry winters. The climatological normals identified in the period from 1991 to 2020 indicate average minimum temperatures of 17.24°C, an average of 21.34°C and an average maximum of 26.51°C. Relative air humidity has an average value of 70% throughout the year, with annual accumulated precipitation of approximately 1,500 mm, with precipitation occurring, on average, on 107 days of the year. Applying the Köppen method, the climate of Botucatu - SP was identified as Aw, due to the average temperature of the coldest month (18.28°C) being above 18°C. The result of this classification was different from that found by other authors in previous periods. In 2020, in February, the highest rainfall in the historical series occurred, 284 mm daily, and in October, the highest maximum air temperature recorded was 39.19°C.

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