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CLIMATE ANALYSIS AS STATISTICAL SUBSIDIES FOR DISCUSSION ON CLIMATE CHANGE AND COFFEE PRODUCTION: THE CASE STUDY OF CAMPINAS-SP

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1 RESUMO

A ocorrência e intensidade de eventos climáticos extremos podem impossibilitar a produção cafeeira em algumas áreas do estado de São Paulo. O estudo analisou estatisticamente as tendências das precipitações e das temperaturas no período de 1990 a 2020, para Campinas-SP. As análises foram realizadas para as estações de verão e inverno. Para observação das tendências das séries temporais, foram realizados os testes estatísticos de Mann-Kendall, Pettitt e índices de temperatura: *Summer Days* (SU); e precipitação: *Consecutive Dry Days* (CDD). Identificou-se tendência no aumento das temperaturas máximas e mínimas, e diminuição das precipitações para ambas as estações do ano. O índice SU apresentou maior quantidade de dias com temperaturas acima de 25°C. Vale destacar que o valor de alfa é 0,05, o que indica que a significância dos dados é alta, com chance de 5% do método estatístico estar incorreto. No inverno, as maiores temperaturas máximas concentraram-se no mês de agosto, e as menores temperaturas mínimas no mês de julho. Para a precipitação, o índice CDD apontou maior concentração de dias com precipitação menor ou igual a 1mm entre 2010 e 2020. Evidenciaram-se alterações significativas nos padrões de temperatura e precipitação, as quais podem ser decisivas na produção cafeeira do município.

Palavras-chave: Estatística Climatológica, Temperatura, Precipitação, Aquecimento Global, Café.

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2 ABSTRACT

The occurrence and intensity of extreme weather events may make coffee production impossible in some areas of the state of São Paulo. This study statistically analyzed rainfall and temperature trends from 1990 to 2020 for Campinas-SP. The analyses were carried out for the

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summer and winter seasons. To observe the trends of the time series, Mann–Kendall and Pettitt statistical tests and temperature indices were performed: summer days (SUs) and precipitation consecutive dry days (CDDs). A trend was identified in terms of increasing maximum and minimum temperatures and decreasing precipitation for both seasons of the year. The SU index showed a greater number of days with temperatures above 25°C. It is worth noting that the alpha value is 0.05, which indicates that the significance of the data is high, with a 5% chance of the statistical method being incorrect. In winter, the highest maximum temperatures occurred in August, and the lowest minimum temperatures occurred in July. For precipitation, the CDD index showed a higher concentration of days with precipitation less than or equal to 1 mm between 2010 and 2020. Significant changes were evident in temperature and precipitation patterns, which could be decisive in the municipality's coffee production.

Keywords: Climatological Statistics, Temperature, Precipitation, Global Warming, Coffee.

3 INTRODUCTION

Over the last few decades, several studies have shown the occurrence of significant changes in temperature and precipitation patterns in different parts of the world (VILLA *et al.*, 2022; TORRES *et al.*, 2022). In particular, in relation to coffee-growing areas, these changes can both make production unfeasible and increase cultivation problems, such as decreased quality (BESSADA *et al.*, 2018) and increased disease (ALFONSI *et al.*, 2019).

The results of changes in global climate patterns are compiled and made available to the public through reports issued by the Intergovernmental Panel on Climate Change (IPCC) with the aim of providing support for the discussion of their probable anthropogenic origins and potential measures to adapt and mitigate, climate change (IPCC, 1992, 2007, 2014). The latest report released by the Panel (IPCC, 2021) presented the results of studies focusing on the regional changes that have been occurring around the world, and such results allow a greater understanding of the possibilities for action by public policy makers. Changes in climate patterns generate impacts in different social sectors, such as industry (UHLIG; GOLDEMBERG; COELHO, 2008), energy generation (WALTER, 2007), urban planning (LIMA; ZANELLA, 2011), human health (FERNANDES; HACON; NOVAIS, 2021) and agricultural and animal production (TORRES *et al.*, 2022; MANICA *et al.*, 2022). Therefore, improving knowledge about the impacts that climate change has been causing on a regional scale helps public policy makers to implement more precise measures to adapt and mitigate climate change

In this context, studies applied to climate, which have a methodological essence of statistics, have gained representation in the scientific literature by enabling a better understanding of current climate dynamics. For example, studies in Brazil have been carried out on climate using meteorological stations that sought to characterize the dynamics of precipitation and temperature in the states of Santa Catarina (VIANNA *et al.*, 2017), São Paulo (BLAIN; PICOLI; LULU, 2009), Mato Grosso (GARCIA *et al.*, 2011), Amazonas (CORRÊA *et al.*, 2016) and Rio Grande do Norte (LIMA *et al.*, 2012). However, several studies also report the difficulty of working with data from meteorological stations due to errors in reading climate phenomena, which compromises the reliability of data for long periods of time (HAWKINS; SUTTON, 2009; RIBEIRO *et al.*, 2016), making it difficult to perform statistical tests with larger series and obtain more scientifically assertive results.

In addition to climate data correction techniques widely used in research (BABA; VAZ; COSTA, 2014; JARDIM; SILVA, 2022), there is the possibility of using mathematical and statistical models that generate a wide network of points with different meteorological variables. The models and comparative studies between data provided by meteorological stations and data generated by models show low correlations for precipitation data compared to the NASA power model (TORRES *et al.*, 2022; TORRES, 2022). Nevertheless, there are different orbital models, and each one tends to better project a certain climate variable (BENDER; SENTELHAS, 2015). Thus, the temporal and spatial consistency of data, as well as their similarity with reality, represents a methodological challenge for climate studies.

Another methodological aspect related to the study of climate change is the application of the data. For coffee farming, for example, understanding the interactions between climate and coffee plantations, considering the specific characteristics of each producing region, can be a complex and comprehensive task. However, this information makes important contributions to addressing the climate issue in coffee production.

The municipality of Campinas has national economic relevance, being an area of study in social fields, such as public security (CAICEDO-ROA *et al.*, 2019) and sociospatial segregation (ROLNIK *et al.*, 2015), as well as natural aspects, regarding pedological (LOMBARDI NETO; MOLDENHAUER, 1992) and climate studies (CASTELLANO; NUNES, 2012). Campinas has a wide agricultural and industrial production, with support from large research and development centers such as the State University of Campinas (UNICAMP) and the Campinas Agronomic Institute (IAC). Historically, the municipality has a relationship with dryland coffee farming that dates back to the 19th century, when the municipality became one of the major centers of coffee production and wealth generation in the state (FERRÃO, 2015; BARBOSA; FERRÃO, 2020).

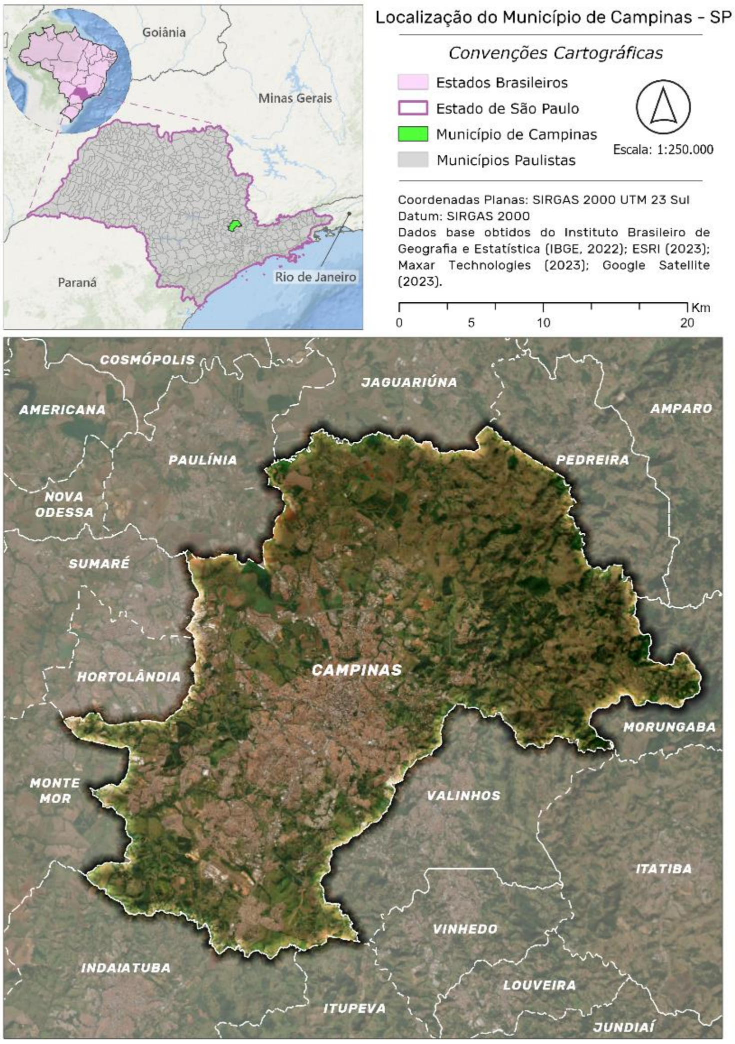
Based on these assumptions, the present work aims to evaluate the possibility of using temperature and precipitation data from the *NASA Power Project satellite model* for climate studies in Campinas. Considering that, statistical correlation tests were carried out between data from the *NASA Power Project satellite model* and data from the CIIAGRO meteorological station. As a secondary objective, changing trends in the temperature and precipitation series of the study area were evaluated, as well as changes in the frequency and intensity of days with high temperatures and days with low precipitation, possibly impacting the coffee crop. The relevance of understanding changes through statistical tests quantitatively supports the discussion on the speed of climate change at the local level. In this sense, it also provides sustain for decision-making on appropriate resilience strategies by the private sector and public.

4 MATERIALS AND METHODS

4.1 Study area

The study was conducted in the municipality of Campinas (latitude 22°53'20” S and longitude 47°04'40” W), which has an altitude of 689 m (Figure 1), in Southeast Brazil. According to data from the Brazilian Institute of Geography and Statistics (IBGE), the municipality has approximately 1 million and 200 thousand inhabitants (IBGE, 2019).

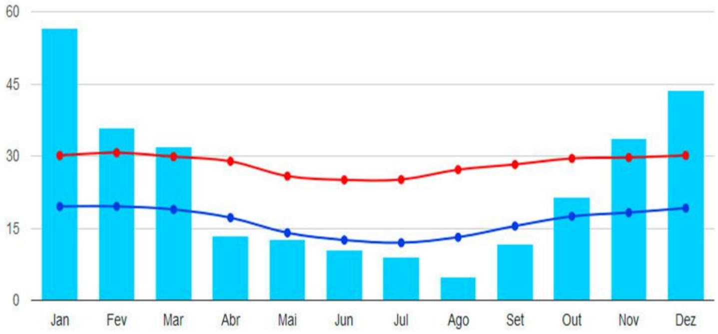
Figure 1. Location of the study area.



Source: Authors (2023).

According to the Köppen classification, the Campinas region has a hot subtropical climate with dry winters (Cwa), characterized by hot and rainy summers, in which the average annual precipitation is 1350 mm, the maximum temperature in summer reaches 30°C, and the minimum temperature in winter is 11°C (DOBBERT, 2015). Figure 2 represents the climatological normal for the municipality of Campinas for the maximum/minimum temperature and precipitation variables based on the period from 1990 to 2022.

Figure 2. Climogram of the municipality of Campinas (1990-2022).



Source: CEPAGRI (2023).

Regarding coffee production, a symbol of regional prosperity, it is important to describe that coffee cultivation is only viable under specific climatic conditions. The phenological development of plants and the management of the species occurs within a specific range of temperature and precipitation. Then, extreme events and changes in climatic characteristics can be decisive in the growth of this crop (TORRES *et al.*, 2022).

4.2 Validation of climate data

The climate data used in this research come from the *NASA Power Project model* (www.power.larc.nasa.gov), which provides a set of surface meteorological data estimated from satellite information and models (SAYAGO *et al.*, 2020) in a regular and continuous grid without gaps (SPARKS, 2018). NASA data are generated on a ½-degree by 2/3-degree global grid and subsequently crosslinked by bilinear interpolation to a global grid of half-degree longitude by arc latitude (SAYAGO *et al.*, 2020).

For the study area, information was obtained from a single model grid (corresponding to the coordinates of the municipality of Campinas), from which the variables of maximum temperature, minimum temperature and precipitation were considered on a daily scale for the period from 1990 to 2020, for the summer and winter seasons.

During summer and winter seasons of the Integrated Agrometeorological Information Center to perform statistical validation tests for the NASA Power Project model, were used data observed from the meteorological station, located in Campinas during the same evaluation period, which covers 30 years, corresponding to the weather stations., were used.

Validation was carried out through the calculation of bias (equation 1), which indicates the average tendency of the simulation to be greater or less than the observed data (GUPTA; SOROOSHIAN; YAPO, 1999), and the mean squared error (RMSE) (equation 2), which is related to the standard deviation of errors (AVILLA-DIAZ *et al.*, 2020).

$$MBE = \frac{1}{N}\sum_{t=1}^{N}\left(I(t) - \hat{I}\,(t)\right) \qquad (1)$$

$$RSME = \sqrt{\frac{1}{N}\sum_{t=1}^{N}\left(\hat{I}(t) - I(t)\right)^2} \qquad (2)$$

Where I(t) is the irradiance measured at time t, Î(t) is the predicted irradiance value (by the model) at time t and N is the number of data points in the set.

4.3 Statistical tests

After the comparison calculations, tests were executed to analyze the trends in the time series. The nonparametric test, designed by Mann (1945) and later adapted by Kendall (1975), checks the value of the historical series in relation to the other values, always following a sequential ordering process, which counts the number of times the remaining terms are greater than the analyzed value. This test is based on the rejection or acceptance of a null hypothesis (H0), which denies or confirms the existence of a trend in the historical series analyzed with a certain level of significance (95% for this study).

The Mann–Kendall test can only be applied if the series is serially independent; this test was applied in this study for the summer (December to March) and winter (June to September) periods from 1990 to 2020. The goal for using this test wasunderstand changes in temperature and precipitation patterns in these two seasons, which present striking and antagonistic characteristics of temperature and precipitation.

The Mann–Kendall trend test is calculated using equations 3 and 4 (HIRSCH; SLACK, 1984):

$$S = \sum_{c=1}^{n-1} \sum_{d=c+1}^{n} sign\ (x_d - x_c) \qquad (3)$$

Knowing that:

$$sign\ (x_d - x_c) = \begin{cases} +1, x_{d\,>\,x_c} \\ 0, x_d = x_c \\ -1, x_{d\,<\,x_c} \end{cases} \qquad (4)$$

In addition, x_c and x_d refer to the data points at positions *c* and *d*, respectively, and n is the size of the data series. The significance level, *Z*, is calculated by equations 5 and 6:

$$Var\ (S) = (n(n-1)(2n+5) - \sum_{c=1}^{n} t_c(c)(c-1)(2c+5))/18 \qquad (5)$$

$$Z = \begin{cases} S - 1/\sqrt{Var(S)}, & S > 0 \\ 0, & S < 0 \\ (S+1)/\surd(Var(S)\ ), & S = 0 \end{cases} \qquad (6)$$

In this case, *tc* accumulates to *t*, and *c* denotes the interaction time. For this test, the significance level is set at 95%, which also indicates that the absolute value of *Z* must be greater than or equal to 1.96 (YANG *et al.*, 2020).

The Mann-Kendall test returns a list of components, including Kendall's tau, which represents the statistical result obtained, a value that will be evaluated to understand the presence of a trend in the time series data. (EL-SHAARAWI; NICULESCU, 1992).

From the observation of a trend using the Mann–Kendall test, the Pettitt test (1979) was applied with the aim of characterizing the period in which there was an abrupt change in the time series, without restrictions on the probability distribution (ZHANG; LU, 2009). The statistical method is calculated by equation 7:

$$U_{t,r} = \sum_{i=1}^{t} \sum_{j=t+1}^{T} sign\ (x_i - x_j) \quad 1 \leq t < T \qquad (7)$$

Where x_i and x_j are data points in the time series of T, while $U_{t,T}$ is the statistical variable. With this, the possible point of abrupt change K_t is calculated from equation 8.

$$K_t = \max\ |U_{t,T}| \qquad (8)$$

The corresponding significance probability p associated with K_t is calculated by equation 9:

$$p = 2\exp((-6K_t^2)/(T^3 + T^2)) \qquad (9)$$

After identifying the trends presented in the data series, calculations of extreme values were generated using two indices, one referring to temperature and the other one, to precipitation:

i) Index *Number of Summer Days Index* (SU): temperature index of summer days, which counts days with a temperature greater than 25°C (or greater than the value stipulated by the user). In the present work, calculations were carried out at temperatures above 25°C, 34°C and 37°C.

ii) *Consecutive Dry Days Index* (CDD): a precipitation index that indicates consecutive dry days, adjusted to the climatic reality of the study region (hot, rainy summers and dry winters). Days with precipitation less than or equal to 1 mm/day were identified for the entire data series, including summer and winter seasons.

The extreme temperature (SU) and precipitation (CDD) indices were calculated following the methods of Zhang *et al*. (2005) and Haylock *et al*. (2006), which were executed using *RClimdex*, software developed by the Canadian Meteorological Service (ZHANG; YANG, 2004).

5 RESULTS AND DISCUSSION

5.1 Validation of climate data

Among the databases, the tests show a greater correlation between the maximum and minimum temperature data and lower correlations for precipitation. The relationship between the model and the data observed throughout the analysis period is noted. Table 1 presents the bias value (MBE) and the mean squared error (RMSE) for the climatic variables studied in the summer and winter months, demonstrating that the model is capable of reproducing the minimum temperature better than the maximum temperature.

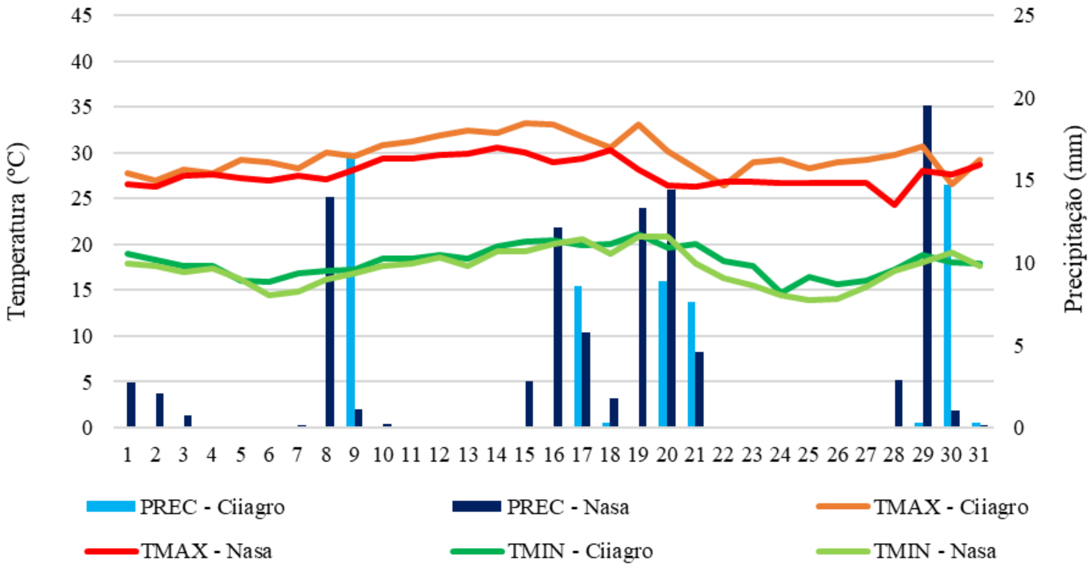
Table 1. Bias (MBE) and error (RMSE) values for the maximum and minimum temperatures and precipitation in the study area.

INDEXES	TMAX	TMIN	PREC
SUMMER			
RSME	2.79	1.48	13.13
MBE	-1.22	-0.40	-0.41
WINTER			
RSME	2.79	1.96	7.46
MBE	0.27	-0.87	0.42

Source: Authors (2023).

In this context, the greatest variability was observed in precipitation values and during the summer months, considered the rainy period in Campinas. The volumes observed at the CIIAGRO meteorological station in the winter months, but mainly in the summer, were lower than those indicated in the NASA model, demonstrating its tendency to overestimate precipitation. Figure 3 illustrates, as an example, the month of March 2020, corresponding to the summer period, in which it is possible to observe the variations between the two databases for the maximum/minimum temperature and precipitation variables.

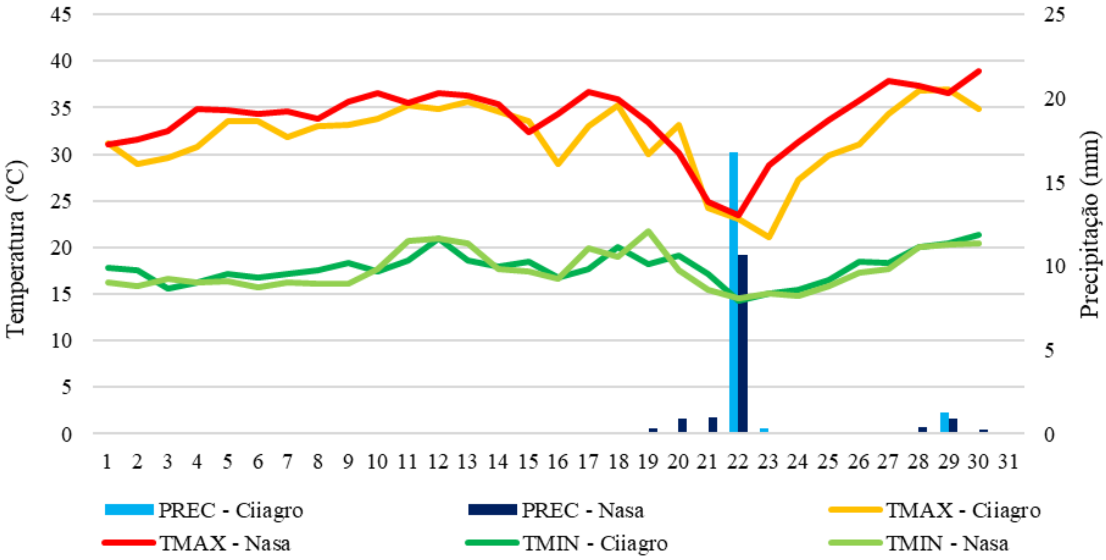
Figure 3. Variation between maximum temperature (TMAX), minimum temperature (TMIN) and precipitation (PREC) during a summer month (March 2020), considering data from CIIAGRO and NASA.



Source: Prepared by the authors (2023).

Figure 4 illustrates the month of September (2020), which corresponds to winter. It is possible to observe that the variations between the CIIAGRO and NASA values do not have major differences compared with the values obtained for the summer months (Figure 5), especially for the precipitation variable.

Figure 4. Variation between maximum temperature (TMAX), minimum temperature (TMIN) and precipitation (PREC) during a winter month (September 2020), considering data from CIIAGRO and NASA.



Source: Prepared by the authors (2023).

Thus, the results of the MBE and RMSE tests suggest good correlation between the NASA and CIIAGRO databases, with the NASA model being able to represent the temperature and precipitation of the study area. Although the precipitation variable showed greater variations in the summer months, the model was able to reproduce the seasonality and average behavior of the analyzed variable, allowing us to conclude that there was good coherence between both bases for the precipitation variable. The maximum and minimum temperature variables showed greater correlations, reinforcing the feasibility of using data from the NASA model, which implies the possibility of using this model for other studies on climatology (TORRES *et al*., 2022; TORRES, 2022).

These results are very useful for climate studies in the municipality of Campinas because they statistically validate the use of a more complete, coherent and useful database.

5.2 Pettitt tests

The Mann–Kendall tests (Table 2) showed a trend of change in the three series studied, with the maximum and minimum temperatures showing an increasing trend and precipitation showing a decreasing trend. The Pettitt test for the summer period (Table 2) revealed a greater increase in the maximum temperature than in the minimum temperature. Taking into account the average before the year in which the homogeneity of the series broke with the year after, there was an increase of 1.0°C for the maximum temperature and 0.6°C for the minimum temperature. For precipitation, there is a decreasing trend evidenced by the difference between the data before and after the year of break in the homogeneity of the series (2009), with a negative value of -1.3 mm for the summer period of the historical series analyzed.

Table 2. Results of the Mann–Kendall and Pettitt tests for the summer season.

Meteorological variable	Kendall's Tau	Value before the break year	Breaking year	Value after the break year	Trend Value
Maximum temperature	0.077	28.0°C	2011	29.0°C	1.0°C
Minimum temperature	0.089	18.6°C	2009	19.2°C	0.6°C
Precipitation	-0.086	7.1 mm	2009	5.8 mm	-1.3 mm

Source: Prepared by the authors (2023).

Pettitt tests (**Table 3**) revealed an increasing trend similar to that found in the summer season, with maximum temperatures showing a greater increase than minimum temperatures and precipitation showing a decrease. The increase in the maximum temperature was 1.6°C, and the increase in the minimum temperature was 0.9°C. Precipitation showed a downward trend of -1.2 mm/day for the winter period.

Table 3. Results of the Mann–Kendall and Pettitt tests for the winter season.

Meteorological variable	Kendall's Tau	Value before the break year	Breaking year	Value after the break year	Trend Value
Maximum temperature	0.145	25.2°C	2001	26.8°C	1.6°C
Minimum temperature	0.103	12.4°C	2011	13.3°C	0.9°C
Precipitation	-0.107	2.5 mm	2000	1.3 mm	-1.2 mm

Source: Prepared by the authors (2023).

Even with both seasons showing a trend of increasing temperatures and decreasing precipitation, it is possible to observe that winter showed greater increasing trends, reaching 1.6°C for maximum temperatures and 0.9°C for minimum temperatures.

For precipitation, both seasons show decrease values above 1.0 mm/day, with summer showing a decrease of 1.3 mm/day and winter 1.2 mm/day (difference of just 0.1 mm /day between seasons).

In this sense, the increase in temperature and the decrease in precipitation during the summer and winter seasons can have significant impacts on coffee production in Campinas. In summer, higher temperatures can lead to thermal stress in coffee plants, resulting in lower productivity and quality of the beans (DAMATTA, 2004). Furthermore, a lack of rainfall can lead to a reduction in the availability of water for irrigation, which can further aggravate the effects of heat on crops (CAMARGO, 2010).

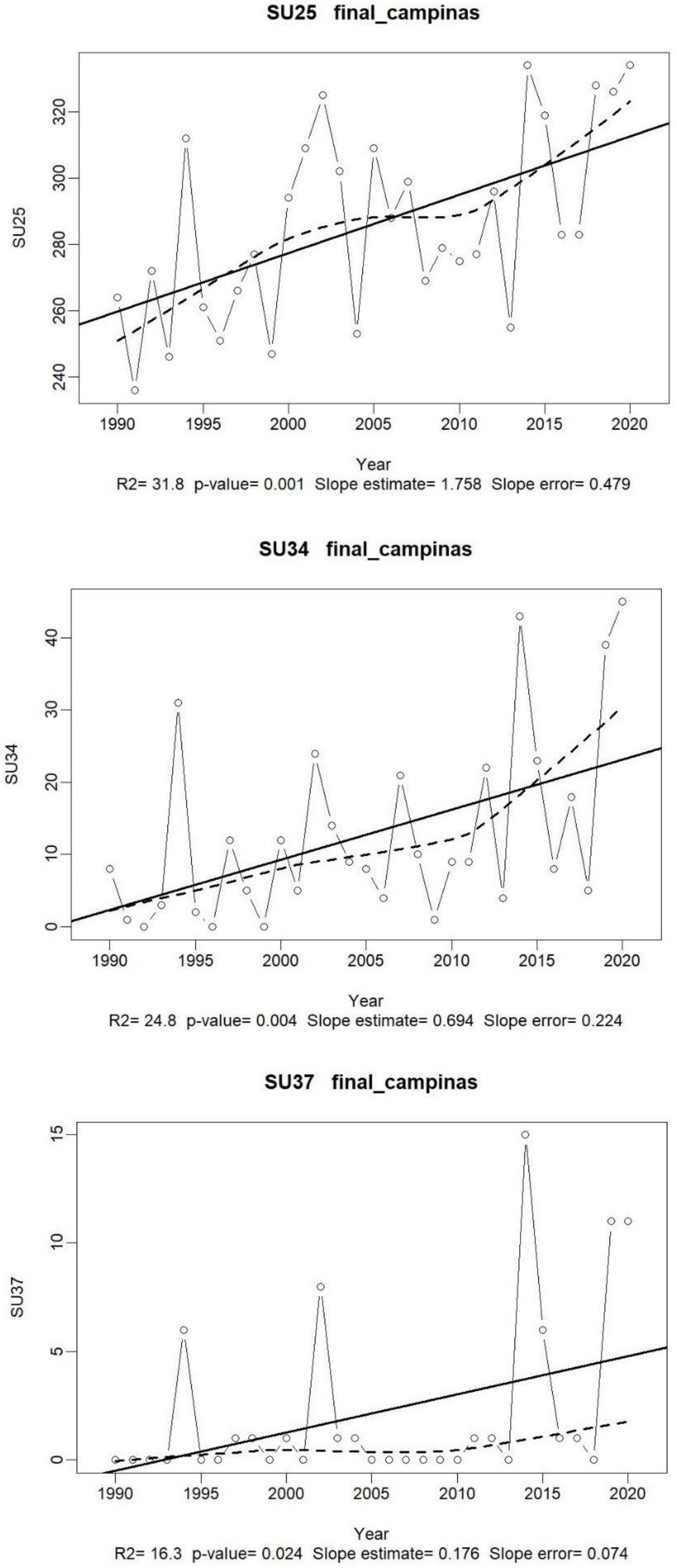
In winter, reduced rainfall can affect crop development during the crucial fruit growth phase, as the lack of water during this period compromises grain formation, leading to lower production and reducing the yield of coffee crops (DAMATTA, 2004; FAGAN et al., 2011). Moreover, changes in rainfall behavior can favor the emergence of pests and diseases, causing additional damage to crops (ALFONSI *et al.*, 2019).

5.3 Climate indices

The results of the SU (Figure 5) and CDD (Figure 6) indexes for the study area corroborate the trend of increasing temperature and decreasing precipitation found in the Mann–Kendall and Pettitt trend tests. The SU index resulted in the occurrence of 334 days with a temperature above 25°C between 2014 and 2020. A temperature above 34°C was predominant in 2020, when there were 45 days with a temperature equal to or greater than this temperature (34°C) in Campinas. In 2014, 43 days with a temperature higher than that mentioned were recorded. Finally, when considering days with a temperature greater than 37°C, 2014, 2019 and 2020 were the years with the highest number of days above this temperature, totaling 15 days in 2014 and 11 days in 2019 and 2020. Furthermore, for all temperatures used in the SU index, there was an increasing trend within the analyzed period.

Seasonally, the days with the highest maximum temperature during winter were concentrated in the month of August, while the days with the lowest minimum temperature were found in July. In the summer months, the month with the highest maximum temperature (above 25°C) was December, and in that same month, the lowest minimum temperatures were also found.

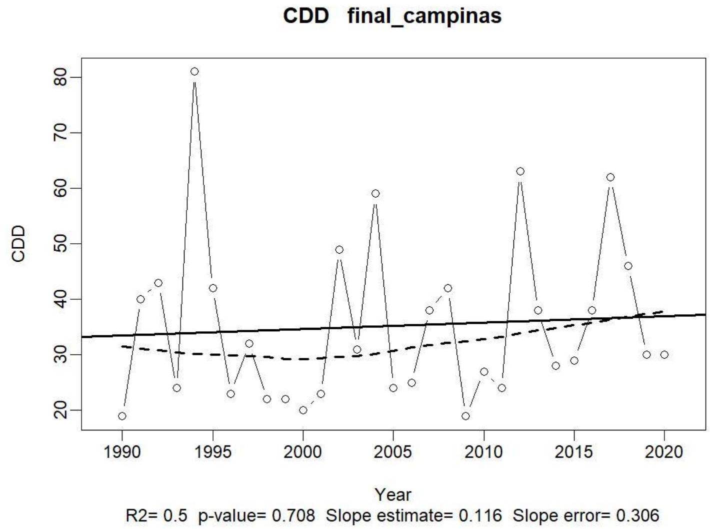
Figure 5. The index *Numer of Summer Days* (SU) represents the upward trend in temperature records above 25, 34 and 37°C.



Source: Authors (2023).

For the CDD (Figure 6), the year 1994 had the greatest number of dry days in sequence, totaling 81 days, followed by the years 2012 and 2017, with 63 and 62 consecutive days, respectively, with precipitation less than or equal to 1 mm. It is worth mentioning that 1994 was considered a dry year with heavy frost, which had a negative impact on agricultural production in the state of São Paulo (MORICOCHI *et al.*, 1995).

Figure 6. The CDD shows the trend of consecutive days with precipitation less than or equal to 1 mm.



Source: Prepared by the authors (2023).

In this way, the index results more accurately detail the occurrence of extreme events within the historical data series, which, according to the Mann–Kendall and Pettitt tests, already show clear trends. Therefore, with an increase in the occurrence of climate extremes, strategies that seek to adapt coffee plantations with a focus on sustainable management practices, which also aim to mitigate climate change, are recommended. More efficient irrigation systems (HO *et al.*, 2020), coffee varieties more adaptable to climate change conditions (PETEK; SERA; FONSECA, 2009) and agroforestry systems (COLTRI *et al.*, 2019) are some of the most recommended possibilities within the scientific literature for adaptation and mitigation of climate change in coffee production.

6 CONCLUSION

The present study demonstrated the occurrence of changes in temperature trends (maximum and minimum) and precipitation within the period from 1990 to 2020 for the summer and winter seasons in the municipality of Campinas.

The results suggest good correlation values between the NASA and CIIAGRO databases, with the NASA model being able to represent the temperature and precipitation of the study area.

Pettitt tests revealed that there was an increase in temperature (maximum and minimum) throughout the entire historical data series analyzed, as well as a tendency toward a decrease in precipitation. The trend is most evident for the maximum temperature variable, which increased by 1.6°C in winter. For precipitation, the most significant decrease was in the summer season, at -1.3 mm.

The extreme indices showed an increase in consecutive dry days with precipitation below 1 mm/day and an increase in days with temperatures above 25°C. The indices occur most frequently in the years that make up the last decade of the historical series (2010 to 2020). The analysis showed that winter days are becoming hotter, especially in August, and summer days have presented higher temperatures.

Thus, the relevance of climate change adaptation measures in Campinas is supported by the results that highlight an increase in temperature and a decrease in precipitation. If these trends intensify, the municipality runs the risk of facing water shortages, causing economic losses for both industry and agriculture, in addition to negative impacts on the well-being of the population due to thermal discomfort. Specifically, with regard to coffee production, this sector could be severely affected by climate change, making coffee cultivation difficult and hindering the development of agricultural tourism. The factors mentioned increase the reasons for implementing mitigation and adaptation measures in the municipality.

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