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Analysis of climate change scenarios using CMIP6 models in Pernambuco, Brazil

Análise dos cenários de mudanças climá icas usando modelos CMIP6 em Pernambuco, Brasil

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ABSTRACT

Monitoring the effects of climate change is essential due to the ongoing increase in extreme drought and flood events, primarily driven by changes in key variables such as precipitation and temperature. In this study, data from eight Coupled Model Intercomparison Project Phase 6 (CMIP6) models were used to assess temperature and precipitation anomalies in the state of Pernambuco, Brazil, for the period 2041 to 2100, considering two different climate scenarios (SSP245 and SSP585). The projected data were compared with WorldClim historical climatological data between 1970 and 2000. Due to the significant spatial variability of annual precipitation in Pernambuco, ranging from 400 to 2,200 mm, the state was evaluated considering its territory in total and also in two distinct climatic regions (Sertão/Agreste and Zona da Mata). An increase in temperature is projected, even in the least pessimistic scenario (SSP245) with an increment of 1.64°C from 2041 to 2060. During the same period, an increase of 2.10°C is expected in the SSP585 scenario. For the period from 2081 to 2100, the models indicate increases of 2.45 and 4.53°C, respectively. Precipitation will decrease in all scenarios and regions of Pernambuco, with a reduction of up to 227.24 mm year^{-1} in the Zona da Mata between 2081 and 2100 in the SSP585 scenario. These potential changes pose imminent threats to water resources, agriculture, biodiversity, and the population, demanding proactive measures from policymakers and stakeholders to mitigate these effects.

Keywords: temperature; precipitation; climate variability; shared socioeconomic pathways; water resources.

RESUMO

Monitorar os efeitos das mudanças climáticas é essencial devido ao aumento contínuo de eventos extremos de seca e inundação, impulsionados principalmente por alterações em variáveis-chave como precipitação e temperatura. Neste estudo, dados de oito modelos do Projeto de Intercomparação de Modelos Acoplados Fase 6 (CMIP6, sigla em inglês) foram utilizados para avaliar anomalias de temperatura e precipitação no Estado de Pernambuco, no período de 2041 a 2100, considerando dois cenários climáticos distintos (SSP245 e SSP585). Os dados previstos foram comparados com dados climatológicos históricos do WorldClim, entre 1970 e 2000. Devido à significativa variabilidade espacial da precipitação anual em Pernambuco, que varia de 400 mm a 2.200 mm, o estado foi avaliado considerando o seu território na totalidade e também em duas regiões climáticas distintas (Sertão e Agreste e Zona da Mata). O aumento de temperatura está previsto, mesmo no cenário menos pessimista (SSP245), com incremento de 1,64°C, de 2041 a 2060. No mesmo período, é esperado um aumento de 2,10°C no cenário SSP585. Para o período de 2081 a 2100, os modelos indicam aumentos de temperatura de 2,45 e 4,53°C, respectivamente. A precipitação diminuirá em todos os cenários e regiões de Pernambuco, com uma redução de até 227,24 mm ano^{-1} na Zona da Mata entre 2081 e 2100 no cenário SSP585. Essas mudanças potenciais representam ameaças iminentes aos recursos hídricos, à agricultura, à biodiversidade e à população, exigindo medidas proativas por parte de formuladores de políticas e demais partes interessadas, com o intuito de mitigar esses efeitos.

Palavras-chave: temperatura; precipitação; variabilidade climática; *shared socioeconomic pathways*; recursos hídricos.

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Introduction

Monitoring climate change effects is imperative due to the continued increase in extreme drought and flood events, driven mainly by changes in key variables such as precipitation and temperature, which significantly impact the water and energy balance (Kamruzzaman et al., 2021). This is even more important when considering that, like many other regions in the world, Brazil has been severely affected by temperature increases and changes in the hydrological cycle in recent decades, and the same is expected for the coming years (Andrade et al., 2021; Dantas et al., 2022; Ballarin et al., 2023).

Climate change poses a multitude of risks, with particularly severe implications for semi-arid regions. This is notably true for a significant portion of the Northeast Brazil region (NEB), including the state of Pernambuco, where approximately 80% of the territory is classified as semi-arid (Araujo et al., 2021). Droughts are natural climatic phenomena that have a global impact on human and environmental activities and can be considered one of the most costly and widespread natural disasters (Nandgude et al., 2023).

In the NEB, droughts are recurrent and have severe negative repercussions on social and economic activities, and on the availability of water resources, affecting thousands of people. Starting in 2012, the NEB faced the most impactful drought in decades, which extended until 2018 and caused various socioeconomic damages (Marengo et al., 2022). Furthermore, there are flash flood and landslide events, which have intensified in Pernambuco in recent years, resulting in the deaths of dozens of citizens in the most affected areas (Marengo et al., 2023).

The Intergovernmental Panel on Climate Change (IPCC), established in 1998 by the United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO), is the primary international scientific body responsible for assessing climate change (Silveira et al., 2013). The main objective of the IPCC is to enhance the understanding of past, present, and future climate changes, whether resulting from natural, unforced variability, or in response to changes in radiative forcings, all within the context of multiple models (Eyring et al., 2016).

In this context, Global Climate Models (GCMs) are essential for assessing the impact of climate change (Kamruzzaman et al., 2021). Taking into consideration the physical processes and interactions within each climatic subsystem (biosphere, atmosphere, hydrosphere, cryosphere, and land surface), GCMs aim to project the future state of the climate. These models, developed by various institutions that always apply the same physical principles but may use slightly different assumptions, are run over large historical or future periods and are driven by natural forcings (e.g., solar irradiance and volcanic aerosols) and anthropogenic emissions that alter greenhouse gas (GHG) concentrations, leading to changes in radiative forcing (Cos et al., 2022).

Brazil, considering the NEB (in which Pernambuco is included), has already been extensively assessed in terms of climate change. However, previous assessments primarily considered the models from the Coupled Model Intercomparison Project Phase 5 (CMIP5), which was released in 2013. These studies had already indicated the possibility of the effects of climate change, including temperature increase and reduced precipitation (Silveira et al., 2013; Guimarães et al., 2016; Andrade et al., 2021). More recently, with the release of the Sixth Assessment Report (AR6) of the IPCC, there has been greater availability and utilization of the CMIP6 (phase 6) data, which represents a new generation of the models compared to their predecessors. CMIP6 coordinates activities for the intercomparison of independent models and their experiments, which have adopted a common infrastructure to collect, organize, and distribute model outputs from running common sets of experiments.

The main difference between CMIP5 and CMIP6 is the future scenario. CMIP5 projections are available based on 2100 values of radiative forcings for four Representative Concentration Pathways (RCPs) of GHG. In contrast, CMIP6 uses Shared Socioeconomic Pathways (SSPs) with the assumptions of the CMIP5 scenarios (Kamruzzaman et al., 2021). Hence, the traditional RCPs are now referred to as SSPs, even though their underlying framework is quite similar, enabling comparisons between them.

The assessment of potential climate change impacts aligns with the National Water Security Plan (PNSH, in Portuguese) (ANA, 2019), which outlines actions to be undertaken to ensure water supply for current and future generations. In this context, the objective of this study was to evaluate the impact of climate change in the state of Pernambuco using different models and scenarios from CMIP6, identifying regions with a higher likelihood of being affected.

Material and methods

Study area

The study was conducted in the state of Pernambuco, located in the Northeast region of Brazil (NEB), with an approximate area of 98,938 km^2. Based on its physical characteristics, the state is divided into five mesoregions: the Metropolitan Region of Recife, Zona da Mata, Agreste, Sertão Pernambucano (of Pernambuco), and Sertão do São Francisco (Souza et al., 2018). According to Silva et al. (2022), the lowest rainfall indices occur in the mesoregions of Sertão Pernambucano, and Sertão do São Francisco, with annual averages ranging from 400 to 800 mm, especially in Sertão do São Francisco, where rainfall is even scarcer. The Agreste region already has a higher average, ranging from 600 to 1,000 mm, while in Zona da Mata and Metropolitan Region of Recife, the values range from 1,000 to 2,200 mm.

To assess the impact of climate change in Pernambuco, specifically precipitation, the state was divided into two main regions: Zona da Mata and Sertão/Agreste (Figure 1). Since precipitation varies significantly between these two climatically distinct regions, the purpose of this division was to provide a more detailed evaluation of future precipitation variations.

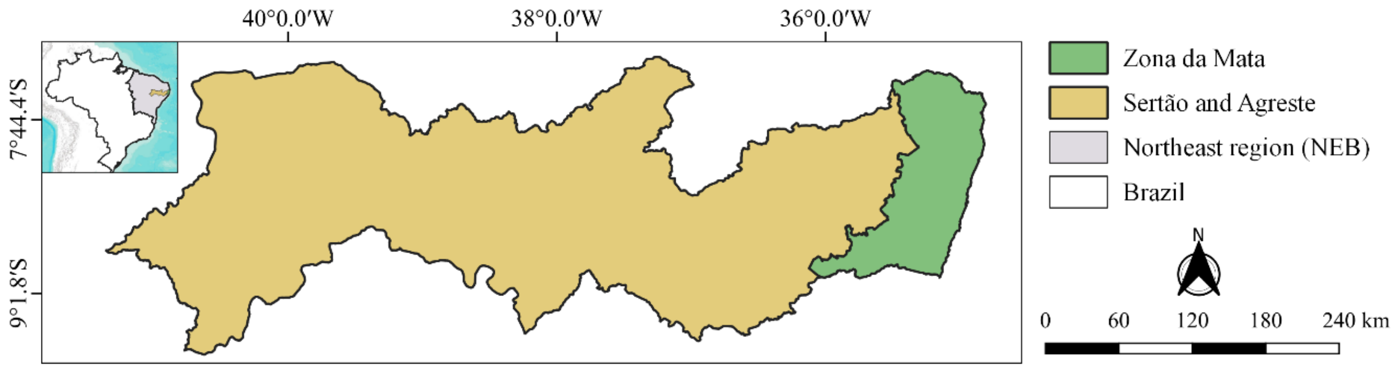


Figure 1 – Pernambuco state with a focus on the two regions used for climate change assessment.

In addition to this distinction, the state was evaluated in its entirety regarding precipitation and temperature variations, aiming at a better understanding and a higher level of detail in detecting these changes.

Coupled Model Intercomparison Project Phase 6 climate data

For the climate change projections, eight CMIP6 models were used, as described in Table 1. The data derived from CMIP6 are the results of simulations from different GCMs with a historical scenario (based on historical observations) and future scenarios that combine SSPs with future radiative forcing scenarios RCPs based on updated emission trend data within a scenario matrix framework (Wu et al., 2021).

Data of the eight models were obtained from WorldClim (https://worldclim.org/data/cmip6), already corrected for bias, based on surface data. WorldClim, which is a high-resolution global climatic and meteorological database, started to provide this data in a more straightforward manner. These data can be used for spatial mapping and modeling purposes and are provided for research and related activities. In addition to the bias correction, the CMIP6 data used were also downscaled. In this case, data with a spatial resolution of 30 seconds (~1 km^2) were employed.

Only the SSP245 and SSP585 scenarios were selected, representing intermediate and high GHG emission conditions. These scenarios are equivalent to the previous RCP 4.5 and RCP 8.5 from CMIP5. Data from the eight models were aggregated, and then an average value was obtained for the state of Pernambuco. Integrating as many models as possible is intended to minimize assessment uncertainties. For the evaluation of future climate change scenarios, only data from 2041 to 2100 were considered, divided into 20-year periods (2041–2061, 2061–2080, and 2081–2100). Historical data from the period 1970 to 2000 were used as a reference database for comparison (Fick and Hijmans, 2017).

The SSP245 scenario represents a "middle-of-the-road" outlook, constituting an intermediate scenario. In this case, it is assumed that environmental systems are experiencing some level of degradation.

Table 1 – Global Circulation Models used and their respective institutions or agencies and countries of origin.

Model	Institution/Country
BCC-CSM2-MR	*Beijing Climate Center China* (China)
CanESM5	*Canadian Earth System Model 5nd generation* (Canada)
CNRM-CM6-1 CNRM-ESM2-1	*Centre National de Recherches Meteorologiques / Centre Européen de Recherche et de Formation Avancée en Calcul Scientifique* (France)
IPSL-CM6A-LR	*L'Institut Pierre-Simon Laplace* (France)
MIROC6 MIROC-ES2L	*Japan Agency for Marine-Earth / Atmosphere and Ocean Research Institute, National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology / RIKEN Center for Computational Science* (Japan)
MRI-ESM2-0	*Meteorological Research Institute Earth System Model version 2* (Japan)

BCC-CSM2-MR: Beijing Climate Center Climate System Model version 2 – Moderate Resolution; CanESM5: Canadian Earth System Model version 5; CNRM-CM6-1: Centre National de Recherches Météorologiques Climate Model version 6.1; CNRM-ESM2-1: Centre National de Recherches Météorologiques Earth System Model version 2.1; IPSL-CM6A-LR: Institut Pierre-Simon Laplace Climate Model version 6A, Low Resolution; MIROC6: Model for Interdisciplinary Research on Climate version 6; MIROC-ES2L: Model for Interdisciplinary Research on Climate Earth System version 2 for Long-term simulations; MRI-ESM2-0: Meteorological Research Institute Earth System Model version 2.0.

On the other hand, SSP585 is the scenario driven by fossil fuels, and it is the most pessimistic. In this context, social and economic development is based on intensified exploitation of fossil fuel resources, with a high percentage of coal and energy-intensive lifestyles worldwide. Therefore, in this setting, it is expected that the effects of climate change will be more intense (Tebaldi et al., 2021).

Surface precipitation data

Precipitation data obtained from the network of the National Institute of Meteorology (INMET) were used for comparison with historical data from the CMIP6, for some points. Although the WorldClim data already have bias correction, this comparison aimed to verify the similarity of the series. As the WorldClim data are purely climatological, climatologies were also calculated from the daily precipitation data of INMET stations, in order to compare the two series.

Evaluation strategy

Climate change assessment was carried out using data from CMIP6 for eight models. The models were individually processed within a Geographic Information System (GIS) environment, and then average values of precipitation and temperature were calculated for the state of Pernambuco. These data were evaluated through maps and graphs, with future data (2041–2100) compared to historical data (1970–2000) to identify positive or negative anomalies. The anomalies were calculated by subtracting the value of the climate model from the value of the reference climatology (historical data). In the case of precipitation, the relative anomalies were calculated following Jayawardhana and Chathurange (2020), according to Equation 1:

$$Anomaly_{m,y} = \left(\frac{Projected - Reference}{Reference}\right) x\ 100 \quad (1)$$

Where:

$Anomaly_{m,y}$: represents the monthly or yearly precipitation anomalies.

Projected denotes the climatic data from different scenarios.

Reference: represents the historical reference data.

The assessments were conducted for the entire state, and for precipitation, which exhibit significant spatial variability, and data were also analyzed considering the different regions, shown in Figure 1.

Climate change assessments considered data for precipitation and temperature, with the primary goal of demonstrating how these variables are expected to change by the end of the century in the two scenarios evaluated. The assessment, for the three different periods (short, medium, and long term), was carried out considering the absolute and relative differences in relation to historical climatological data, as was also performed by Andrade et al. (2021) in the state of Pernambuco.

Results and discussion

Temperature anomalies

In the state of Pernambuco, there is a noticeable trend of increasing temperature over the decade, based on the CMIP6 data, both in the moderate GHG scenario (SSP245) and the more pessimistic one (SSP585). As estimated, the impact will be higher in the more drastic scenario, with the most significant intensity at the end of the century (2081–2100), where a temperature increase of up to 5°C is projected throughout the state, especially in the semiarid region (Figure 2).

In the SSP245 scenario, there is already a noticeable trend of temperature rise, even in the period from 2041–2060, with an average increase of 1.64°C compared to the baseline historical data (1970–2000).

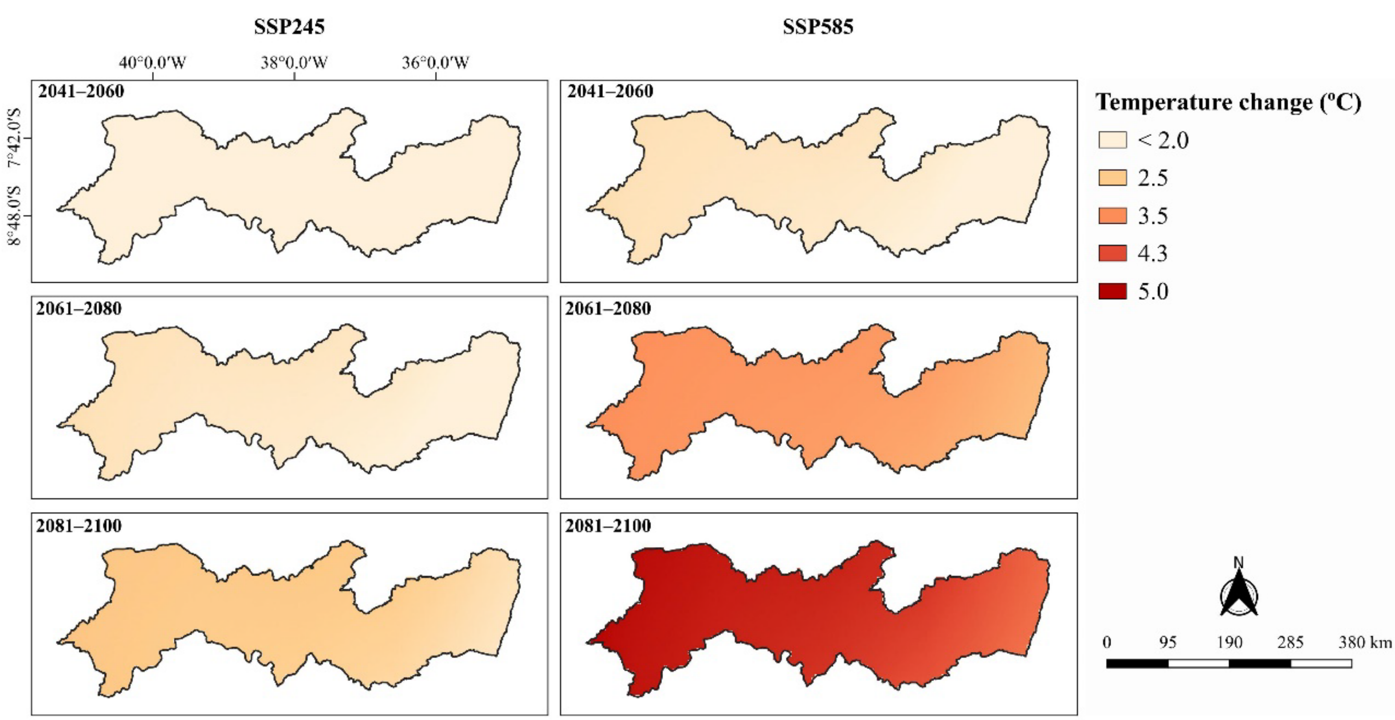


Figure 2 – Temperature increases in the state of Pernambuco from 2041 to 2100, based on the Coupled Model Intercomparison Project Phase 6 models for the SSP245 and SSP585 scenarios.

During the same period, the SSP585 scenario predicts an increase of 2.10°C (Figure 3). As the assessment periods progress until 2100, there is a clear trend of higher temperature elevation, as evidenced in the graphs. From 2081–2100, the expected rise is 2.46°C in SSP245 and 4.53°C in SSP585. In all cases, the average temperature is consistently higher in SSP585, and this difference is expressed through the variation (in degrees Celsius) relative to historical values, as represented by the vertical bars in Figure 3.

Based on the obtained results, Almazroui et al. (2021) observed that in tropical regions such as NEB, the average annual temperature increases in the mid-century period between 1.0–1.8°C in SSP245 and 1.2–3.0°C in SSP585. For the end of the century, other future scenarios exhibit substantially higher warming, ranging between 1.7–3.0°C in SSP245, and 2.8–5.0°C and over in SSP585. Similar results, with increasing temperature rise until 2100, were also found by Andrade et al. (2021) when evaluating different CMIP5 models in a basin partially located in Pernambuco, in a climate transition zone. Ballarin et al. (2023) also detected a temperature increase trend in NEB, in the same scenarios considered in this study, with greater emphasis on the distant future (1970–2100), highlighting the need for adopting efficient strategies to deal with the climate crisis.

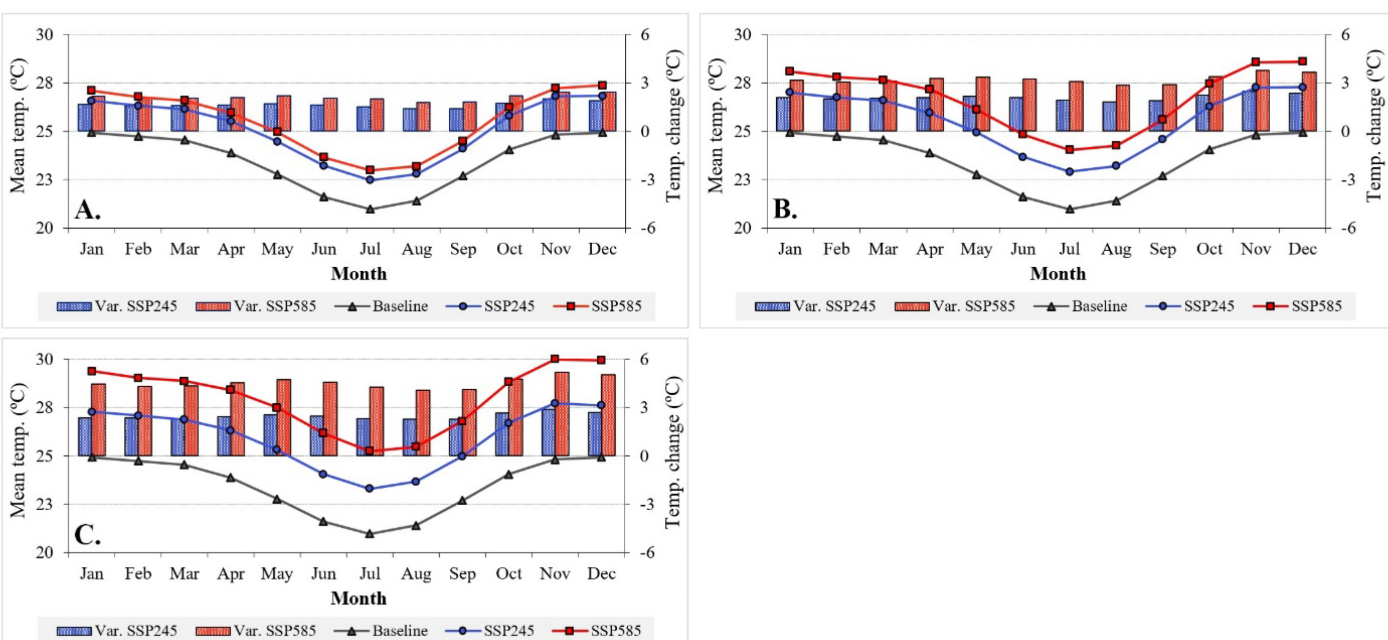
According to the baseline historical data (1970–2000) from CMIP6 models with bias corrected by WorldClim (Figure 4), the average temperature in Pernambuco is 23.44°C, with the lowest temperatures recorded in the Agreste region. Comparable findings were discovered by Santos et al. (2022). Therefore, an increase in temperatures of up to 5°C by the end of the century, in addition to significantly affecting the comfort of people and animals, would have a range of consequences that would influence the entire state. Global temperature rise, for example, would contribute to rising sea levels along the coast of Pernambuco over the years. Additionally, it would lead to increased frequency and intensity of floods and droughts, the expansion of vectors for endemic diseases, changes in hydrological regimes (due to changes in precipitation), agricultural losses, and threats to biodiversity, among other harmful impacts (Santos et al., 2013).

Studies with CMIP5 had already indicated temperature elevation as the primary consequence of climate change in the NEB, including Pernambuco, leading to alterations in the rainfall pattern as well (Silveira et al., 2013; Guimarães et al., 2016; Andrade et al., 2021). Studies conducted for South America also showed the same temperature behavior for the NEB, indicating that temperatures are projected to remain between 1 and 5°C above historical records, depending on the scenario considered (Almazroui et al., 2021; Reboita et al., 2022).

Precipitation anomalies

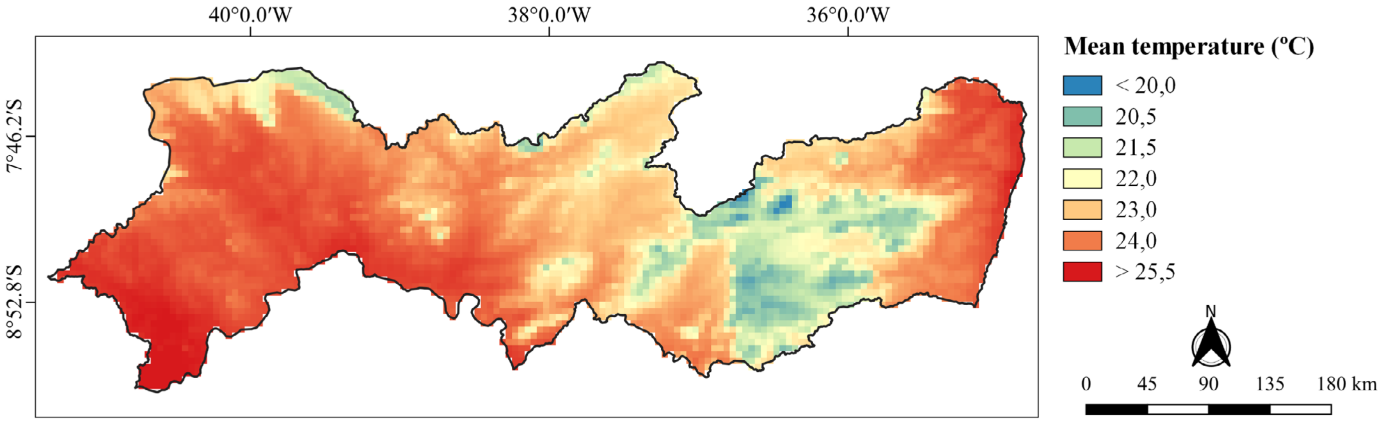
Pernambuco state

As previously mentioned, Pernambuco exhibits significant spatial variability in the precipitation pattern from the semi-arid region towards the coast (Figure 5). This substantial annual variation, ranging from <400 to >2,000 mm (Silva et al., 2022), leads to the evaluation of the state in a spatially segregated manner concerning precipitation change trends.

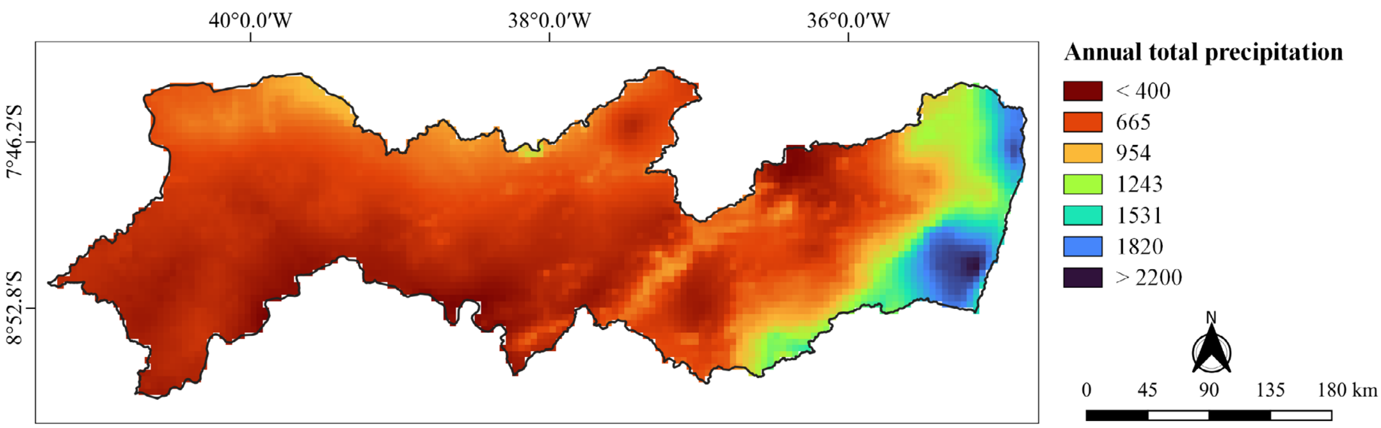


Temp.: temperature; Var.: temperature change in °C.

Figure 3 – Average temperature (baseline) and temperature change in Pernambuco, based on the Coupled Model Intercomparison Project Phase 6 models for the SSP245 and SSP585 scenarios, during the periods (A) 2041–2060, (B) 2061–2080, and (C) 2081–2100.



Source: WorldClim 2 (Fick and Hijmans, 2017).
Figure 4 – Annual average temperature in Pernambuco based on historical data (1970–2000).

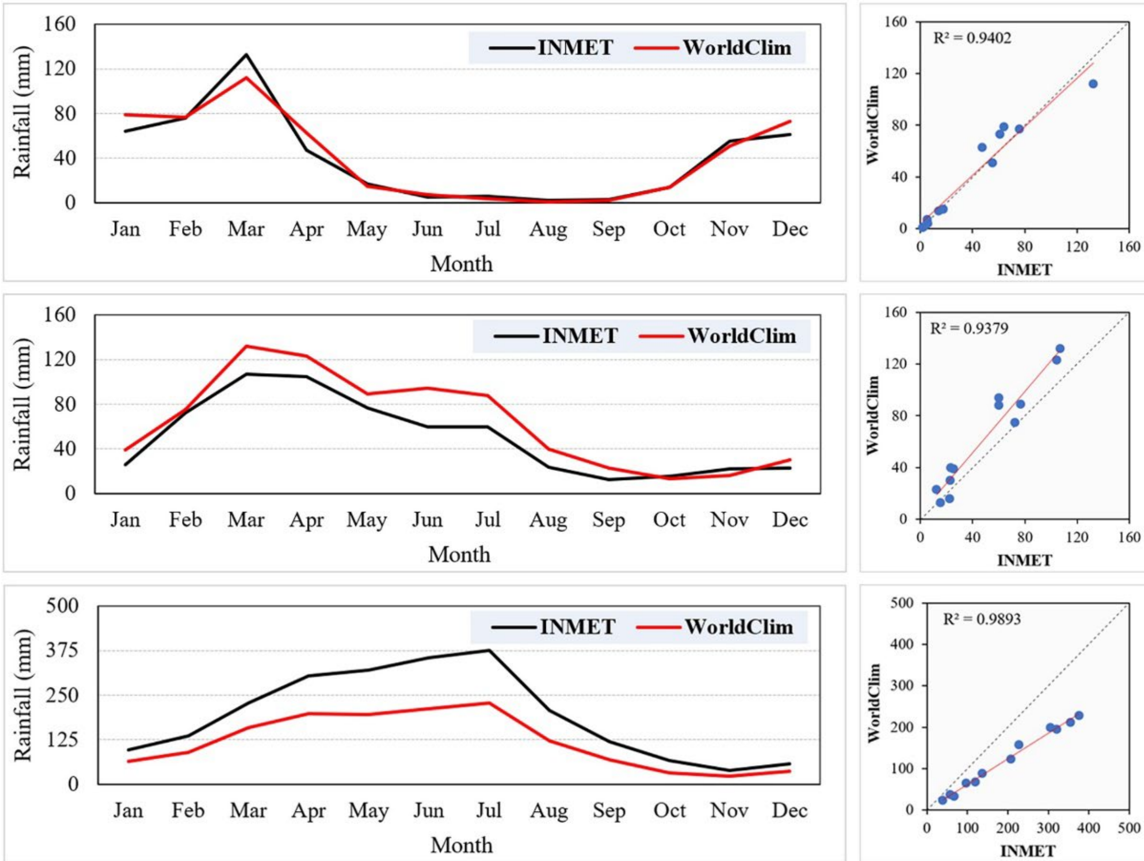


Source: WorldClim 2 (Fick and Hijmans, 2017).
Figure 5 – Annual total precipitation in Pernambuco based on historical data (1970–2000).

Consequently, to ensure a better level of detail in assessments, the state was evaluated in two ways: 1. Spatially, considering its entire territory, which allows for the visualization, through maps, of how precipitation variation will occur until the end of the century; and 2. Precipitation averages for the Sertão/Agreste and Zona da Mata, separately, as these two regions will respond with different intensities to climate-induced precipitation changes, based on CMIP6.

Before the assessments, some comparisons with historical precipitation data from the WorldClim and INMET database, obtained from pluviometric stations, were conducted to confirm if the interpolated data from WorldClim aligned well with in situ measurements. Based on the observations from comparisons made at three stations (Petrolina, Pesqueira, and Recife) located in different mesoregions of Pernambuco, there is noticeable satisfactory agreement between the two series (Figure 6). However, along the coast, WorldClim tends to underestimate precipitation based on historical data. This condition is also observed when using other data sources, such as orbital remote sensing products, exemplified by the Tropical Rainfall Measuring Mission (TRMM) satellite, which underestimated precipitation along the coast (Soares et al., 2016). Therefore, these are physiographic limitations in the state itself that hinder the accurate precipitation estimate in this area. Nevertheless, it is still evident that the series exhibits the same seasonal variation, with a similar temporal dynamic.

Just as with air temperature, precipitation is expected to undergo significant changes over the years, especially in the Zona da Mata, where a more pronounced reduction in rainfall regimes is anticipated, with declines of up to 300 mm year^{-1} in SSP585 scenario, during the period from 2081–2100 (Figure 7). The more pronounced reduction in this region may be related to the annual precipitation volume itself. Given that it is an area with high accumulations, exceeding 2,200 mm, it is expected that models predict a greater decline in precipitation. In the Sertão and Agreste regions, decreases will occur with less intensity and will be more homogeneous.



Source: WorldClim 2 (Fick and Hijmans, 2017).
INMET: National Institute of Meteorology; R^2: coefficient of determination.
Figure 6 – Comparison between precipitation series from National Institute of Meteorology and historical series from WorldClim of three municipalities in Pernambuco

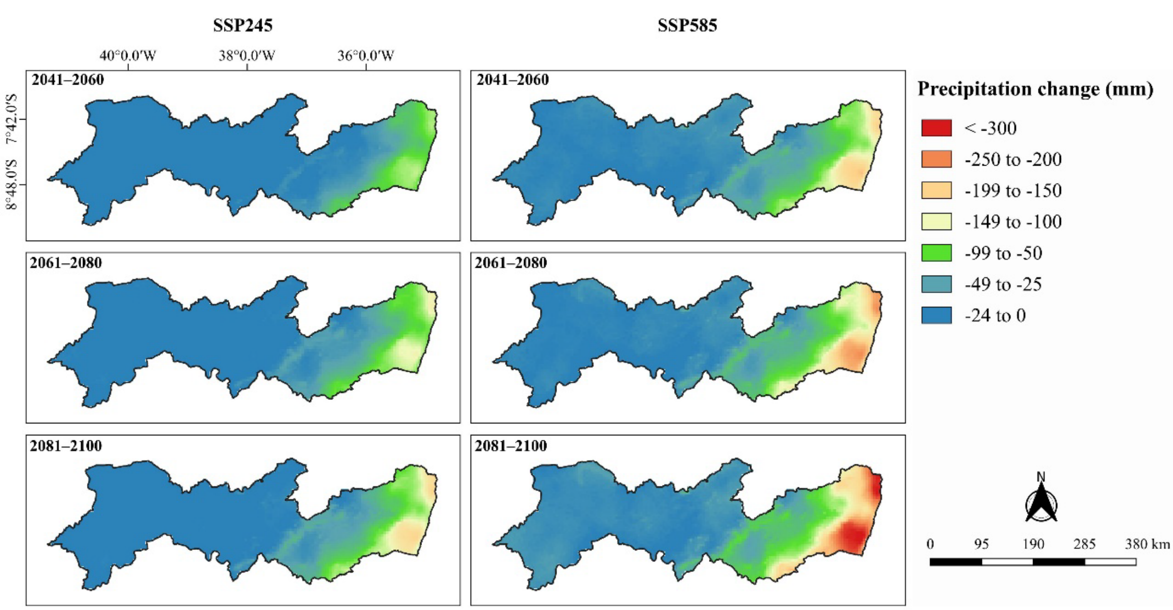


Figure 7 – Precipitation anomalies for Pernambuco until the end of the century, based on the Coupled Model Intercomparison Project Phase 6 models for the SSP245 and SSP585 scenarios.

It is important to note that the anomaly map follows a similar pattern to historical average precipitation (Silva et al., 2022), with a greater reduction in precipitation recorded in areas with higher rainfall indices. Nevertheless, even in the intermediate scenario (SSP245) and for the upcoming years (2041–2060), a reduction in precipitation is already noticeable.

Bezerra et al. (2021), assessing annual precipitation in Pernambuco from 1987 to 2019, detected a trend of reduced precipitation in the Zona da Mata of up to 204 mm year^{-1}. Considering CMIP6 data (Figure 7), this same trend, with quite similar values, was also confirmed in all evaluated periods and scenarios. Dantas et al. (2022), evaluating 16 CMIP6 models in the NEB, also detected a more pronounced reduction in precipitation along the coast, which includes Pernambuco. In areas located within the semi-arid region, this reduction was less pronounced.

The 2024 report on the impact of climate change on water resources in Brazil by the National Water and Basic Sanitation Agency (ANA, 2024) noted that hydrographic regions in the North, Northeast, and parts of the Central-West may face increased water scarcity due to decreasing water availability. This trend could worsen with rising GHG and temperatures, potentially reducing water availability by up to 40% by 2040 in major Brazilian hydrographic regions.

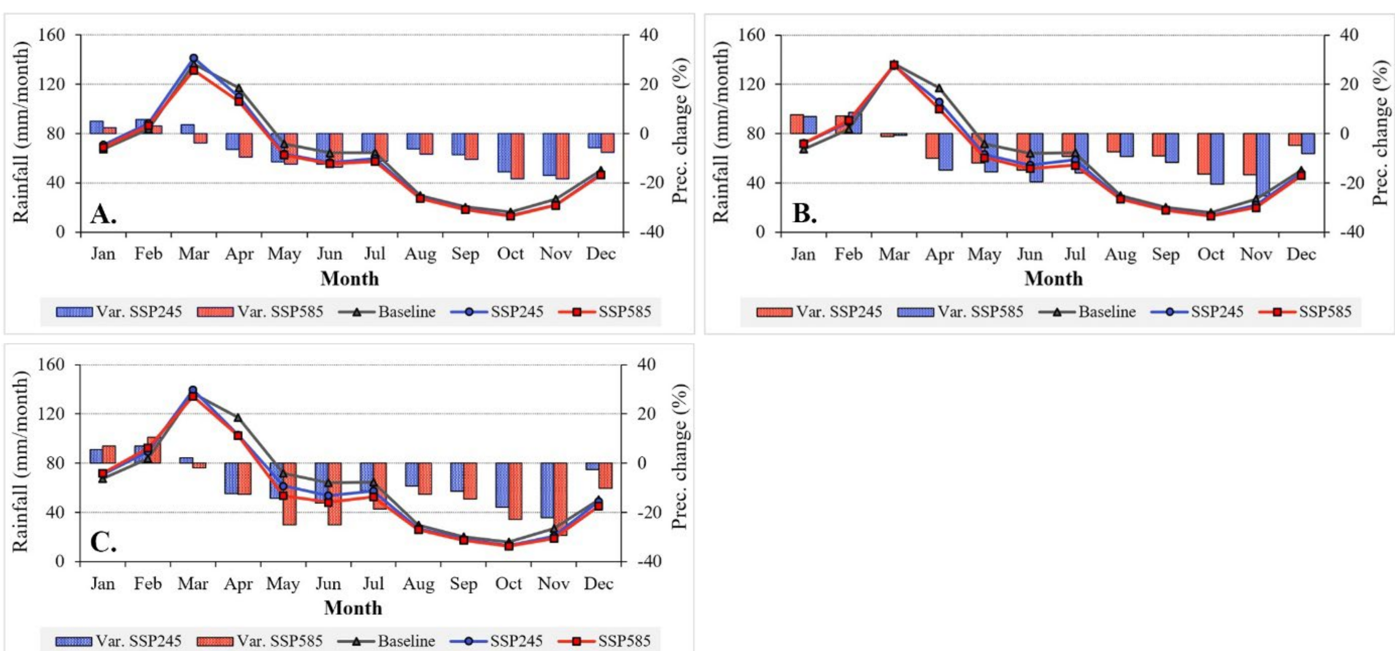
In terms of average values for the entire state, a reduction in precipitation is projected for all scenarios, as shown in Figure 8, especially from April onwards, when this reduction is more pronounced. In some months, such as January and February, the opposite is observed, with a slight increase in precipitation volumes. However, these values are not sufficient to compensate for the projected declines in rainfall for the other periods of the year.

Data from Figure 8 can be better visualized in Table 2, which expresses how precipitation is expected to reduce compared to the historical reference (1970–2000) value. It is evident that the SSP585 scenario is the most alarming, with a reduction of up to 73.15 mm year^{-1} in the period from 2081–2100, when precipitation is projected to decrease from 747.68 to 674.53 mm. Obviously, as it considers average values for the entire state, these values may not be as representative, given the significant spatial variability with which climate changes are expected to affect Pernambuco. Therefore, it is necessary to analyze the data for the Zona da Mata and Sertão/Agreste separately.

Table 2 – Changes in projected precipitation for Pernambuco until the end of the century, based on Coupled Model Intercomparison Project Phase 6 models for the Shared Socioeconomic Pathway 245 and the Shared Socioeconomic Pathway 585 scenarios.

Period	Annual precipitation			Precipitation change (mm)	
	Historical	SSP245	SSP585	SSP245	SSP585
2041–2060	747.68	718.44	694.17	-29.24	-53.51
2061–2080	747.68	707.95	688.09	-39.73	-59.59
2081–2100	747.68	702.38	674.53	-45.30	-73.15

SSP245: Socioeconomic Pathway 245; SSP585: Shared Socioeconomic Pathway 585.



Var.: precipitation change in %; Prec.: precipitation.

Figure 8 – Precipitation anomalies in the state of Pernambuco, based on the Coupled Model Intercomparison Project Phase 6 models for the SSP245 and SSP585 scenarios, during the periods (A) 2041–2060, (B) 2061–2080, and C: 2081–2100.

Zona da Mata Pernambucana

To obtain data separately for the Zona da Mata and Sertão/Agreste, all images containing precipitation data from the CMIP6 models were processed in a GIS (Quantum GIS). Data were clipped using a shapefile of the two distinct regions and then average values were calculated for each area. The average estimated precipitation data until the end of the century, in the SSP245 and SSP585 scenarios, for the different periods, are represented in Figure 9. As anticipated, a more pronounced change in future trends is observed when considering only the Zona da Mata region, with a reduction in precipitation of up to 227.24 mm $year^{-1}$ in SSP585 by the end of the century. Even in the most optimistic scenario analyzed (SSP245, from 2041 to 2060), reductions of over 200 mm $year^{-1}$ are already predicted. The highest precipitation variations (vertical bars) are expected for the rainier periods (March to August), confirming that CMIP6 models tend to predict greater effects of GHG on precipitation under more intense rainfall conditions.

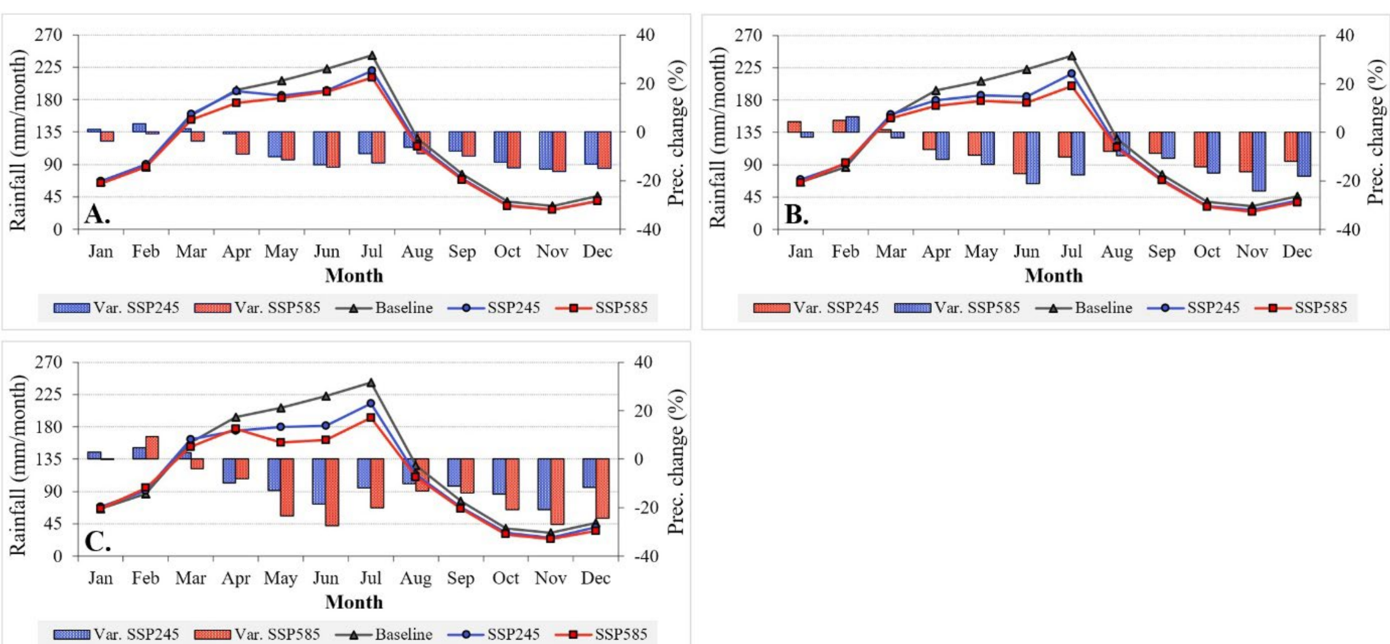
According to historical data (1970–2000), the average annual precipitation over the Zona da Mata is 1,492.61 mm. Throughout the different analyzed periods, precipitation tends to decrease significantly within the two scenarios. From 2041 to 2060, for example, a reduction of 97.10 and 148.97 mm is expected in SSP245 and SSP585, respectively. Two decades later, between 2081 and 2100, this reduction worsens to 143.82 and 227.24 mm, respectively (Table 3). Over the following century, the trend would be, within this context, for even further reduction, provided that measures to mitigate the attenuating effects of the GHG are not adopted.

Medeiros et al. (2022), evaluating different versions of CMIP in Brazil, also detected, with CMIP6, a decrease in precipitation in different areas of the NEB (including Pernambuco) with more pronounced reductions along the coast (Zona da Mata Pernambucana). The authors also revealed that the number of consecutive dry days is predicted to increase, as well as the occurrence of more extreme rainfall events, which makes the region more vulnerable to disasters such as floods and landslides. In addition, Seboia et al. (2020) emphasized that in low-latitude regions, such as the NEB, the total volume of precipitation events is expected to decrease, while their intensity is expected to increase over the next century.

Table 3 – Changes in projected precipitation for the *Zona da Mata* of Pernambuco until the end of the century, based on Coupled Model Intercomparison Project Phase 6 models for the Shared Socioeconomic Pathway 245 and the Shared Socioeconomic Pathway 585 scenarios.

Period	Annual precipitation			Precipitation change (mm)	
	Historical	SSP245	SSP585	SSP245	SSP585
2041–2060	1492.61	1395.51	1343.64	-97.10	-148.97
2061–2080	1492.61	1373.78	1313.22	-118.83	-179.39
2081–2100	1492.61	1348.79	1265.37	-143.82	-227.24

SSP245: Socioeconomic Pathway 245; SSP585: Shared Socioeconomic Pathway 585.



Var.: precipitation change in %; Prec.: precipitation.

Figure 9 – Precipitation anomalies in the *Zona da Mata* of Pernambuco, based on Coupled Model Intercomparison Project Phase 6 models for the SSP245 and SSP585 scenarios, during the periods (A) 2041–2060, (B) 2061–2080, and (C) 2081-2100.

Sertão and Agreste of Pernambuco

Since Sertão and Agreste represent approximately 80% of the territory of Pernambuco, these areas exhibit a behavior similar to the overall state average in terms of predicted precipitation anomalies until the end of the century (Figure 10). Despite this, lower historical precipitation is observed in this region, and there is a declining trend for the future. This region already has lower rainfall indices, with a historical average (1970–2000) of 657.97 mm year^{-1}. Nevertheless, a decrease in rainfall is expected, with a decline of up to 60.34 mm year^{-1} for SSP585 during the period 2081–2100. Although it may seem small when compared to the Zona da Mata, it is important to emphasize that, proportionally, the values are comparable. Being a region where rainfall is already scarce, a reduction of this magnitude can significantly aggravate drought events, which are already recurrent and intense (Marengo et al., 2017; Rossato et al., 2017; Souza et al., 2018).

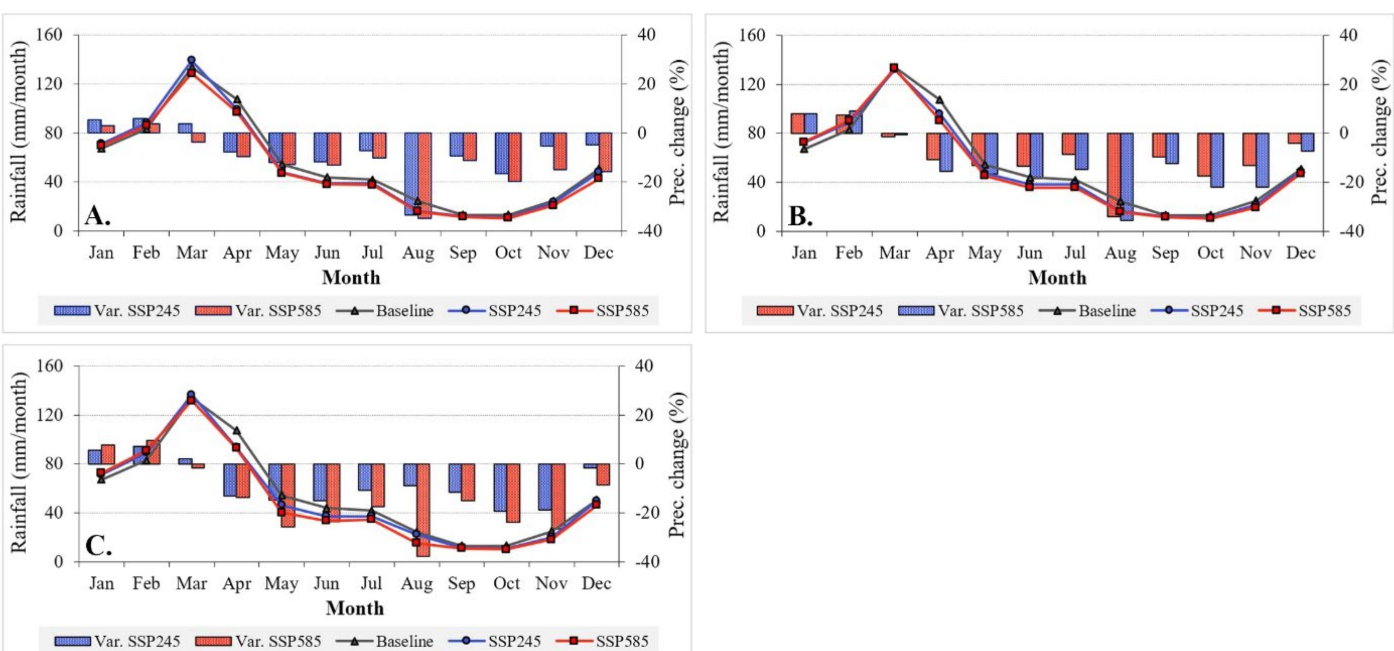
Medeiros et al. (2022) also identified that, in this region of the state, changes in annual precipitation volume will be less significant than in the Zona da Mata Pernambucana. Table 4 shows the expected precipitation values for each period in both scenarios, along with the variation compared to the historical reference series.

In general, climate change impacts are already evident in Brazil (Ballarin et al., 2023), including the Northeast region (Dantas et al., 2022) in which Pernambuco is located (Andrade et al., 2021). As the decades progress, these implications are expected to become even more intense (Marques et al., 2024). One of the significant impacts of climate change, with rising temperatures and reduced precipitation, is the increase in areas susceptible to desertification (Silva et al., 2023). The Center for Strategic Studies and Management (CGEE, 2016) identifies parts of the states of Alagoas, Bahia, Espírito Santo, Maranhão, Minas Gerais, Paraíba, Pernambuco, Piauí, Rio Grande do Norte, and Sergipe, as well as the entire state of Ceará, as areas susceptible to desertification in Brazil. There are still other risks associated with climate change, as emphasized by Kunreuther et al. (2013), such as global socio-economic development being threatened, in addition to water availability and agricultural production, besides changes in sea levels and heatwaves in parts of the world. All of this underscores the need to select public policies, which should be an ongoing exercise in an attempt to mitigate imminent risks. In this sense, Marengo et al. (2021) indicated that the improvement of knowledge and monitoring of early warning risks, dissemination and communication, and disaster preparedness must be mandatory.

Table 4 – Changes in projected precipitation for the *Sertão/Agreste* regions of Pernambuco until the end of the century, based on the Coupled Model Intercomparison Project Phase 6 models for the Shared Socioeconomic Pathway 245 and the Shared Socioeconomic Pathway 585 scenarios.

Period	Annual precipitation			Precipitation change (mm)	
	Historical	SSP245	SSP585	SSP245	SSP585
2041–2060	657.97	633.47	606.24	-24.50	-51.73
2061–2080	657.97	622.43	607.77	-35.54	-50.20
2081–2100	657.97	625.79	597.63	-32.18	-60.34

SSP245: Socioeconomic Pathway 245; SSP585: Shared Socioeconomic Pathway 585.



Var.: precipitation change in %; Prec.: precipitation.
Figure 10 – Precipitation anomalies in the *Sertão/Agreste* regions of Pernambuco, based on the Coupled Model Intercomparison Project Phase 6 models for the SSP245 and SSP585 scenarios, during the periods (A) 2041–2060, (B) 2061–2080, and (C) 2081–2100.

Conclusions

This study presents an evaluation of prospective climate change effects in Pernambuco, Brazil, utilizing CMIP6 models. The findings indicate a noteworthy temperature increase, especially in the SSP585 scenario, projected up to 5°C by the end of the century. This warming trend emphasizes the importance of promptly addressing its implications across various sectors.

Precipitation anomalies, particularly in the Zona da Mata, reveal a discernible reduction in rainfall, more pronounced in the SSP585 scenario. Spatial variability underscores vulnerability, with the Zona da Mata facing a more severe decline than the semi-arid Sertão/Agreste. These changes threaten water resources, agriculture, and biodiversity, demanding proactive measures from policymakers and stakeholders.

Underscoring the critical need for adaptive and mitigative strategies in addressing impending climate change impacts in Pernambuco, the projected changes in temperature and precipitation emphasize the urgency of robust early warning systems, comprehensive disaster preparedness initiatives, and targeted public policies. Ensuring water security, safeguarding agriculture, and preserving the well-being of the population require concerted efforts to navigate evolving climate conditions.

Considering these findings, this study contributes valuable insights to the scientific discourse on climate change impacts, providing a basis for informed decision-making. Complexities of climate variables necessitate continuous monitoring, research, and adaptive measures. Pernambuco stands at a critical juncture, demanding concerted efforts to foster resilience and sustainable development amid an uncertain climatic future.

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Authors' contributions

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