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ASSESSMENT OF CLIMATIC VARIABILITY FROM PRECIPITATION AND TEMPERATURE DATA USING THE MONTECARLO SIMULATION METHOD FOR THE ZAPATOSA SWAMP COMPLEX

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Abstract: This study evaluates climate variability in the La Zapatosa Complex (CCZ) using Monte Carlo simulation and SARIMA models, with the objective of projecting changes in precipitation and temperature between 2022 and 2040, based on a quantitative and stochastic methodology. The results, obtained from the analysis of 13 climate and weather stations, indicate an annual decrease of 1.40% in precipitation and an increase of 0.96°C in temperature. These trends pose critical risks to water sustainability, biodiversity and regional food security. It is concluded that it is urgent to implement adaptation measures, such as efficient water resource management and crop diversification, to mitigate the impacts of climate change in the CCZ.
Keywords: climate variability; Monte Carlo Simulation; SARIMA models; La Zapatosa Complex; adaptation to climate change.

INTRODUCTION

The Cienagoso de la Zapatosa Complex (CCZ) is the largest continental freshwater wetland system in Colombia, with between 30,000 and 40,000 ha in summer and up to 70,000 ha in the rainy season (Mi-nambiente, 2018). This complex includes around 1900 interconnected marshes interconnected with each other by means of streams, and for this reason it has been declared a Regional District of Integrated Management (DRMI) and recognized as a RAMSAR site. It is also home to an unusual wealth of ecosystems ranging from gallery forests to flooded grasslands that support countless species, many of them endemic or endangered, and play a key role in local climate regulation and the regional hydrological cycle.

It is home to a remarkable biodiversity: 807 species of vascular plants (15 endemic such as *As-trocaryum malybo* and *Clavija latifolia*) and 368 plants useful for medicine, construction and handicrafts. The fauna includes 39 mammals such as the nocturnal monkey (Aotus griseimembra) and the jaguar (*Panthera on-ca*, VU), 208 birds including the endemic chavarri *(Chauna chavaria*), and 51 reptiles such as the crocodile *(Crocodylus acutus*, EN). The 25 amphibians include the poison dart frog *(Dendrobates truncatus*, en-demica), and 45 fish, including critical species such as the bocachico (*Prochilodus magdalenae*). This ecosystem is vital for fishing and local traditions.

The municipalities of Curumaní, Chiriguaná, Chimichagua and Tamalameque, in Cesar, along with El Ban-co, in Magdalena, depend directly on its waters for productive activities such as fishing and, of course, for domestic supply. It also provides essential ecosystem services such as water supply, flood regulation, and sediment retention, which are the backbone of rural well-being in this region.

Despite its ecological and social relevance, there is limited availability of quantitative studies that characterize the climate variability of strategic ecosystems in Colombia, such as the CCZ, particularly with robust methodological approaches that integrate stochastic models and long-term simulations. Recent research has emphasized the need to move towards localized analyses in tropical wetlands that consider the impact of climate change on key meteorological variables (Fatichi et al., 2016; IPCC, 2014), underscoring the urgency of generating baseline information to guide adaptation and mitigation decisions in highly vulnerable contexts.

Consistent with the above, the risk of climate change and its impacts have generated effects on the most vulnerable regions and ecosystems, among which the CCZ stands out. Therefore, this project is highly relevant because it can be a framework for the protection of a natural system that not only hosts a wide variety of species, but also contributes significantly to the environmental balance and the well-being of local communities. However, rising temperatures and changes in precipitation patterns have put the structure and functioning of this complex ecological system at risk.

Regional projections indicate that, in the CCZ, an increase in temperature accompanied by a decrease in precipitation is expected, which could significantly affect water availability, agricultural productivity and biodiversity. Previous studies have shown the high vulnerability of wetlands to climate variability, highlighting the need for robust analytical tools to forecast future scenarios and thus support decision-making in water resource management and adaptation to environmental changes.

The main motivation for this research lies in the urgent need to generate accurate and localized information on climate variability in the CCZ, with special emphasis on precipitation and temperature variables. Although there are studies related to climate change in Colombia, few have focused specifically on tropical wetlands and even fewer have employed advanced methodologies, such as Monte Carlo Simulation and ARIMA Family models, to project future scenarios in this region. In this context, this study aims to fill this gap by providing a detailed analysis and projections to serve as a basis for the design of mitigation and adaptation strategies.

This work focuses on three fundamental aspects: first, the collection and analysis of historical climate data (1990-2022) from weather stations in the region, complemented with temperature information obtained from Google Earth Engine (GEE); second, the projection of future climate variability scenarios (2022-2040) using stochastic models of the ARIMA family, together with Monte Carlo simulations, the evaluation of the potential impacts of these changes in key areas such as food security, water resources, biodiversity and ecosystem services, in accordance with the guidelines of the Third National Communication on Climate Change (TCNCC) and the NDC Colombia Indicators.

The objective of this article is to provide a comprehensive assessment of possible climate change scenarios in the CCZ, identifying the most significant risks and proposing strategies to mitigate the expected impacts. The aim is not only to contribute to scientific knowledge on climate variability in wetlands, but also to provide a replicable framework to facilitate the planning of adaptation policies in other tropical ecosystems subject to similar challenges.

MATERIALS AND METHOD

RESEARCH APPROACH AND DESIGN

The research was developed under a quantitative approach (Hernández, 2018) and adopted an analytical-explanatory design. The main objective was to understand the relationships between precipitation and temperature variables in the La Zapatosa Cenotage Complex (CCZ), evaluating both historical patterns and future projections using stochastic models. Possible confounding factors were controlled and statistical associations between variables were quantified.

POPULATION, SAMPLE AND DATA COLLECTION

The study population included meteorological stations located in the municipalities of Chimichagua, Tamalameque, Curumaní, Chiriguaná and El Banco. The meteorological stations were selected by means of a non-probabilistic directed sampling, based on technical criteria of reliability, historical continuity and representative spatial coverage of the CCZ area of influence. Priority was given to those stations that had at least twenty years of continuous and validated data, following the qualification and approval level established by the IDEAM through its DHIME platform, being a decision that allowed guaranteeing the quality of the time series used in the modeling, minimizing the uncertainty associated with gaps or inconsistencies in the records, in addition, seeking a heterogeneous spatial distribution that covered different strategic municipalities in the departments of Cesar and Magdalena, in order to capture the local climatic particularities within the hydrological system of the CCZ. On the other hand, in the case of temperature data, records from the ERA5-LAND dataset adjusted to the coordinates of the selected stations were used, which allowed a consistent comparison between meteorological variables.

Monthly data (1990-2022) were downloaded in CSV format from the DHIME platform of IDEAM (Instituto de Hidrología, Meteorología y Estudios Ambientales) and complemented with ERA5-LAND records. The data were processed and analyzed using PYTHON (version 3.x) and its libraries: PANDAS, NUMPY and MATPLOTLIB. ARC GIS PRO (ESRI, Inc., Redlands, California, USA) was used for geospatial analysis.

STATISTICAL ANALYSIS AND PREPROCESSING

An exploratory analysis of the data was performed for:

- **Identify gaps and outliers:** Summary statistical techniques were applied and time series were plotted.
- **Impute missing data:** The IDW (Inverse Distance Weighted) method was used, based on spatial proximity between stations.
- **Verify data consistency:** Levene's test was applied to evaluate the homogeneity of variances between the original and imputed series.

In addition, normality tests were performed and serial dependence was evaluated by means of correlograms to ensure the necessary assumptions for subsequent modeling.

IMPLEMENTATION OF ARIMA MODELS

- SARIMA Model Adjustment

For time series modeling, the SARIMA (Seasonal ARIMA) model was implemented in PYTHON using the STATSMODELS library. The steps followed were:

- Import of the library:

```
from statsmodels.tsa.statespace.
sarimax import SARIMAX
```

Model fit: The model was set up for the series of interest using the following expression.

Parameter optimization: A grid search was performed by varying the parameters (p, d, q) and (P, D, Q) to select the model that minimized the Akaike Information Criterion (AIC), defined as:

$$AIC = 2k - 2ln(L) \qquad (1)$$

where k is the number of parameters and L is the maximum likelihood function.

Model validation: The series was divided into two subsets: 80% for training and 20% for testing. After fitting the model with the training set, a prediction was made for the test set. Accuracy was assessed by visual inspection (comparative plots) and calculation of the Error.

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|y_i - \hat{y}_i| \qquad (2)$$

Monte Carlo Simulation: With the adjusted SARIMA model, a Monte Carlo simulation was performed to project multiple future trajectories of the time series:

- **Fitting of the SARIMA Model:** The model was applied to the historical data and its fit was verified using the Ljung-Box test (Ljung & Box, 1978), expecting a p-value > 0.05 to indicate white noise.
- **Simulation configuration:** 1000 simulations and a prediction horizon of 216 months (18 years) were established, generating the corresponding dates.

Stations	Latitude	Length
CHIMICHAGUA [25021240]	9.260083333	-73.80986111
THE CHANNEL [25020240]	9.410472222	-73.89041667
SALOA [25020270]	9.193166667	-73.73130556
HACIENDA EL TERROR [25020650]	8.938777778	-73.56022222
CURUMANI [25020250]	9.197194444	-73.54194444
SPRING THE [25020920]	9.216666667	-73.41666667
ZAPATOZA [25020660]	9.00975	-73.75402778
POPONTE [25020690]	9.423277778	-73.41094444
CHIRIGUANA [25025250]	9.361027778	-73.59338889
RINCONHONDO [25020260]	9.397027778	-73.48802778
LAS FLORES AIRPORT [25025090]	9.046333333	-73.97083333
LOS NEGRITOS [25021200]	9.026666667	-74.07944444
TAMALAMEQUE [25020090]	8.860388889	-73.81544444

Table 1. Meteorological stations of study in the La Zapatosa Complex.

- **Obtaining the forecast:** The model generated multiple trajectories, the results of which were stored in a DataFrame with a date column and 1000 additional columns, each representing a future scenario.
- **Scenario Generation:** The SARIMAX forecast method was used to generate forecasts, adding random perturbations based on the residuals.

CLUSTERING AND PROBABILITY CALCULATION

Once the simulation trajectories were obtained, the most common scenarios were identified by means of a clustering analysis using the K-means algorithm implemented in the SCIKIT-LEARN library.

K-MEANS ALGORITHM

The process was developed as follows:

Initial selection of k centroids at random.

- Assignment of each scenario to the nearest centroid.
- Update of the centroids by calculating the average of the positions of the assigned data.
- Repetition of the process until convergence (without changes in centroids or assignments).

The objective function of the algorithm was defined by the following equation:

$$J = \sum_{j=1}^{K} \sum_{x_i \epsilon C_j} \left\| x_i - \mu_j \right\|^2 \quad (3)$$

Where:

- xi is a data point in cluster CK
- μj is the centroid of the cluster CJ
- $||xi - \mu J||^2$is the squared Euclidean distance between the point xi and the centroid μJ
- K is the number of clusters.

To determine the optimal number of clusters, the elbow method was used, which consists of plotting the number of clusters versus the average distance of the data to the center of their cluster.

CLUSTER PROBABILITY CALCULATION

The Counter() function of SCIKIT-LEARN was used to obtain the frequency of simulations in each cluster and the relative probability was calculated as follows

$$P(C_K) = \frac{N_k}{N} X100\% \quad (4)$$

Where:

- $P(C_k)$ is the cluster probability k
- $N_K$is the number of simulations in the cluster.
- N is the total number of simulations.

PRECIPITATION AND TEMPERATURE VARIATIONS CALCULATION

The following formulas were applied to quantify the change between the projected and historical periods:

- Precipitation Variation Calculation

$$V = \frac{P_S - P_H}{P_H} X\, 100 \quad (5)$$

- Calculation of Temperature Variation

$$V = P_S - P_H \quad (6)$$

Where:

- V Change of the meteorological variable in the projected period.
- P_S Average simulations.
- P_H Average of historical data.

GEOSPATIAL REPRESENTATION

The results were visualized geospatially with ArcGIS Pro (version 3.0, Esri Inc., Redlands, CA, USA), generating precipitation and temperature maps for the historical and projected periods (2022-2040) with the Geo-processing tools integrated in the software. These maps allowed the identification of areas with major changes in the CCZ.

RESULTS

Climate variability was analyzed in the La Zapatosa Complex (CCZ) through the collection and analysis of historical precipitation and temperature data. Records from 13 meteorological stations corresponding to the period 1990-2022 were used for precipitation, and temperature data obtained from Google Earth Engine (GEE).

In the initial phase, an exploratory analysis was carried out in which interpolation and imputation methods were applied to complete missing data and correct outliers. For example, the CHIMICHAGUA station (code 25021240) presented a monthly mean of 167.76 mm, while a maximum of 659.4 mm was recorded. Likewise, an extreme value was identified at station HACIENDA EL TERROR (1585 mm in August 2021), which was treated using the Interpolation of Weighted Distances (IDW) technique. The consistency of the imputed data was verified using Levene's test (p-value = 0.995). Additionally, the GEE temperature data were validated by comparing them with the IDEAM records, finding a significant correlation at the AEROPUERTO LAS FLORES station (r = 0.76).

Subsequently, SARIMA models were implemented for the projection of climate variables. The models were selected based on the Akaike Information Criterion (AIC) and Monte Carlo simulations were run to obtain multiple future trajectories for each season. The projected scenarios were grouped using clustering techniques, identifying those with the highest probability (see Figures 1 and 2).

The impacts of the projected changes were evaluated based on the indicators of the Third National Climate Change Communication (TCNCC) and Colombia's NDC. In terms of food security, the decrease in precipitation and increase in temperature will affect the availability of water for irrigation, reducing agricultural production in municipalities in the CCZ. The TCNCC threat indicators showed a reduction in areas with sufficient rainfall for crops such as plantain and cassava, and an increase in crop heat stress.

With respect to water resources, the projected decrease in precipitation and increase in temperature will increase water demand and reduce the availability of surface water. Aquatic and terrestrial ecosystems will also be affected, with a reduction in natural vegetation cover that will impact biodiversity and ecosystem services, such as climate regulation and protection against erosion.

Variable	Metrics	Station	Value
Precipitation	Maximum	RINCONHONDO [25020260]	210.31 mm
	Minimal	SPRING THE [25020920]	113.91 mm
	Average (between seasons)	-	147.90 mm
Temperature	Maximum	THE CHANNEL [25020240]	28,80 °C
	Minimal	HACIENDA EL TERROR [25020650]	23,66 °C
	Average (between seasons)	-	27,53 °C

Table 2. Multi-annual comparison of precipitation and temperatures by station (1990-2022) Meteorological stations of study in the La Zapatosa Complex.

From the comparison between the historical maps (1990-2022) Figure 3, and the projections (2022-2040) Figure 4, two main trends can be observed:

DECREASE IN PRECIPITATION:

- In the historical period (1990-2022), the maximum precipitation values were mainly concentrated in the southwestern zone of the La Zapatosa Cenotage Complex (CCZ), with ranges reaching up to approximately 163-167 mm per month.
- In the projection (2022-2040), there is a decrease in these maximum values (around 158-162 mm), and the area with lower precipitation expands, showing a pattern of lower precipitation throughout the CCZ.
- Areas that previously recorded intermediate precipitation values now show slightly lower ranges, indicating a generalized downward trend in most stations and subregions.

TEMPERATURE INCREASE:

- In the historical period, temperatures ranged from approximately 26.0 °C to 27.3 °C, with the highest values also located towards the southwestern region.
- In the projection, the range shifts toward higher values (approximately 27.1 °C to 28.5 °C), suggesting sustained warming throughout the CCZ.
- The same zone with higher temperatures (southwest) is maintained, although with a more pronounced increase, exceeding 28 °C in the areas of highest projected heat.

Taken together, these maps confirm the trend of a drier and warmer climate in the CCZ for the coming decades. Reductions in precipitation, coupled with increases in temperature, could have significant effects on water availability, agriculture, and the integrity of wetland ecosystems.

The spatial analysis was carried out through the elaboration of precipitation and temperature maps using ArcGIS Pro, which made it possible to identify the spatial distribution of both variables in the CCZ (see Figures 3 and 4).

Long-term projections indicated that, for the period 2022-2040, precipitation decreased by an average of 1.40% per year and temperature increased by a total of 0.96 °C, with an average annual increase of 0.052 °C. In addition, TCNCC and NDC Colombia indicators were used to assess the impact of these changes on water availability and agricultural production in the CCZ.

The municipalities of Chimichagua, Tamalameque, Curumaní, Chiriguaná and El Banco based on the *synthesis* document *for the declaration of the Cenagoso de la Zapatosa Complex as a protected area* (Interadministrative Agreement No. 205 2017) of the University of Magdalena, CORPAMAG and CORPOCESAR. They are key actors involved in the framework of the DRMI declaration, a

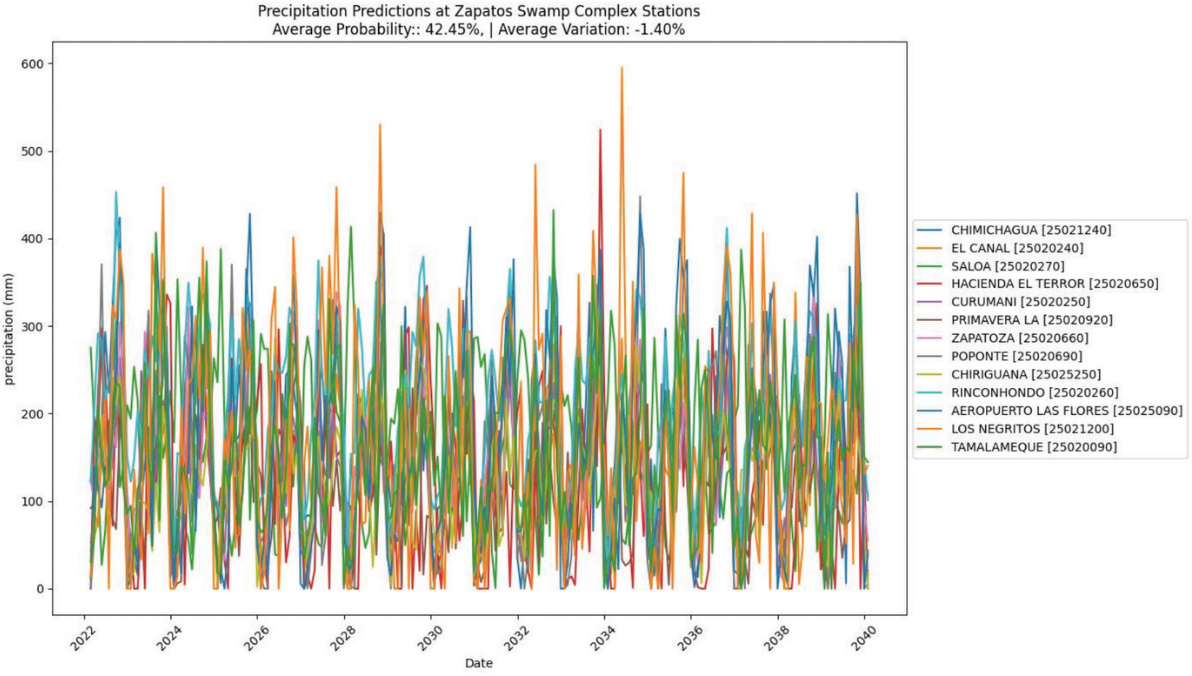

Figure 1. Precipitation projections for the La Zapatosa Complex 2022-2040.

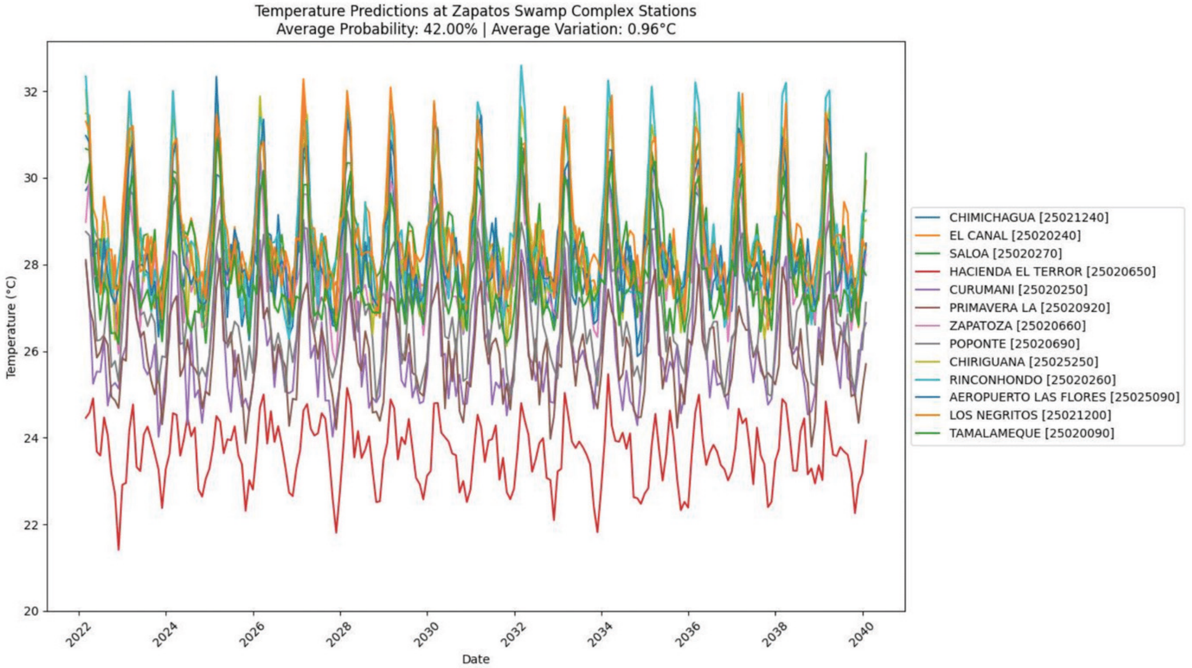

Figure 2. Temperature Projections for the La Zapatosa Complex 2022-2040

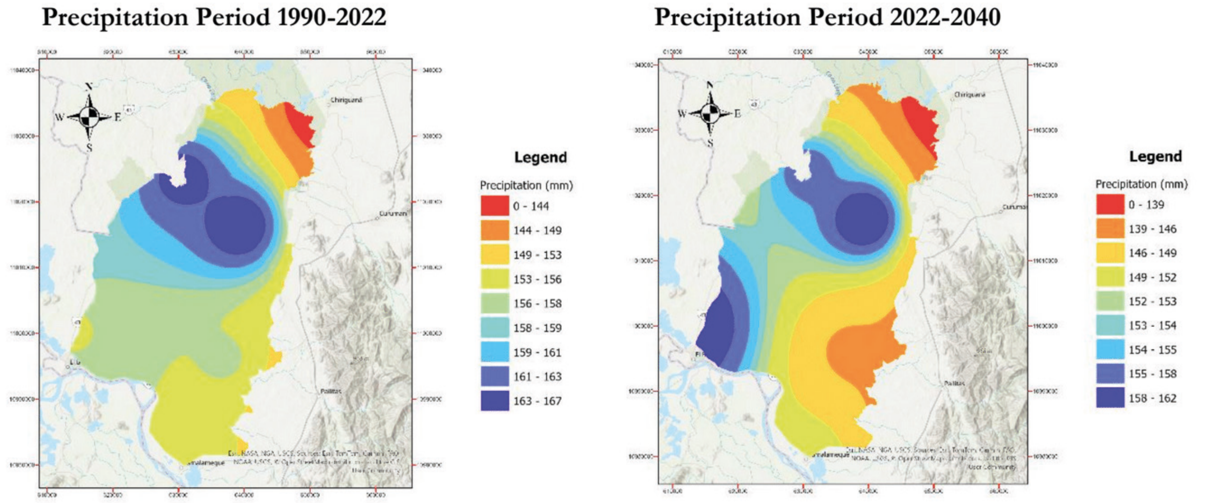

Figure 3. Precipitation map for the period 1990-2022 and 2022-2040.

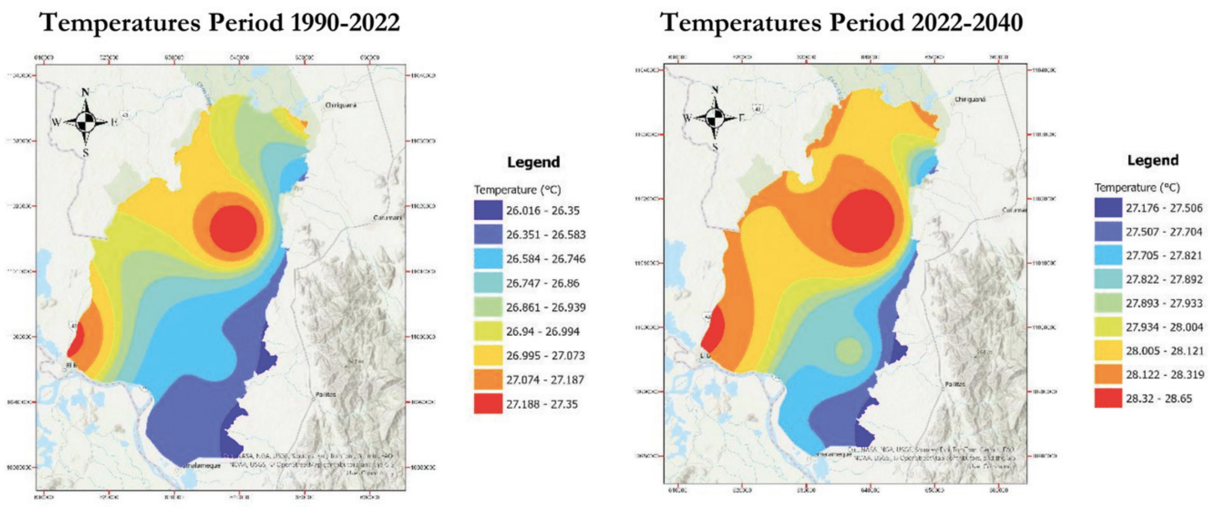

Figure 4. Temperature maps for the period 1990-2022 and 2022-2040.

regional strategy coordinated by CORPOCESAR, CORPAMAG and the Ministry of Environment. This collective approach integrates actions that address the aforementioned challenges:

Water deficit and climate change: The municipalities support the DRMI's priority actions, such as the recovery of the CCZ's water capacity (elimination of clogged canals and illegal dams) to guarantee water storage in rainy seasons and its availability during droughts. Good agricultural and livestock practices are promoted to reduce excessive water demand and pollution, but no specific municipal programs are detailed. The DRMI includes ecological restoration strategies for wetlands and forests, critical ecosystems for thermal and water regulation.

Disaster risk management: Within the framework of the DRMI, the municipalities prioritize flood mitigation (78.27% of the area has a medium-high threat) by conserving the natural function of the CCZ as a hydrological regulator. The management of forest fires in beach areas is proposed, linked to the prohibition of uncontrolled burning, although no specific municipal protocols are mentioned.

Climate change: The municipalities are aligned with the POMCA of the Lower Cesar River and the Ciénaga Environmental Management Plan (2012-2015), which include measures to mitigate climate change, such as the protection of conservation areas. The DRMI proposes climate adaptation actions, such as ecosystem restoration to buffer the impacts of the projected temperature increase (up to +2.7°C by 2100) and rainfall variability.

DISCUSSION

The results obtained confirm, in quantitative terms, the initial hypothesis that the CCZ is experiencing increasing climatic variability with implications for the availability of water resources and agricultural productivity. The projection of a 1.40% annual decrease in precipitation and the 0.053 °C average annual increase in temperature suggest an increase in water and thermal stress, which could impact the stability of ecosystems and productive activities in the region.

The results obtained in this study on climatic variability in the La Zapatosa Complex (CCZ), using Monte Carlo simulations and SARIMA models, reveal significant changes in the climatic conditions of the region that need to be considered when analyzing the effects of climate change. In particular, projections show a 1.40% reduction in annual precipitation and a 0.96°C increase in average temperature between 2022 and 2040, which could have serious consequences on water resources and biodiversity in the area.

Regarding precipitation, the results suggest a decrease of 1.40% per year. This trend coincides with other previous studies, such as that of Buitrago (2023), who reported a reduction in mean annual flow in the upper sub-basin of the Iquira River of between 37% and 54%, depending on the climate scenarios considered. Similarly, this study shows how the decrease in precipitation could affect the capacity of the CCZ to regulate water flows, as Rodriguez & Salazar (2023) found in their analysis of Chile, where the decrease in precipitation generated adverse effects on water resources and agriculture during the La Niña phenomenon.

In terms of temperature increase, the results show a projected increase of 0.96°C. This finding is consistent with the records of Leal & Portes (2020), who also documented a considerable increase in temperature in several areas of Colombia. In their research, they observed a 3.37°C increase in average temperature over a 20-year period, reflecting the cumulative effect of climate change on ecosystems and human activities. In the context of the CCZ, the increase in temperature could put local agriculture at risk and increase the heat stress of crops that depend on a more stable climate, such as plantain and cassava.

The use of Monte Carlo simulation in this study allowed us to capture the uncertainty inherent in climate projections, providing a variety of possible future scenarios. This is particularly relevant because, as Ramos (2014) demonstrates in his Peru study, stochastic simulations provide a more realistic representation of future climate scenarios by allowing us to explore different possible trajectories under different conditions. This approach allows more informed decisions to be made in contexts where climate projections are uncertain.

The cluster analysis also identified the areas of the CCZ most likely to experience decreases in precipitation and increases in temperature. This pattern is similar to that found by Alvarino & Ocampo (2015) in their study of climate behavior in Girardot, where warmer areas experienced a more pronounced increase in temperature, highlighting the importance of considering local characteristics when making climate projections.

In terms of impacts on water resources and biodiversity, the results of this study reinforce concerns about water availability in the region. Reduced precipitation and increased temperature will directly affect the amount of water available for agriculture, which could jeopardize food security in the CCZ. The Third National Climate Change Communication (TCNCC, 2020) had already warned about the growing threat to water resources in Colombia, especially in areas such as the CCZ, which rely on wetlands to regulate water flows.

In addition, impacts on local biodiversity are imminent. Decreased precipitation and increased temperature could alter aquatic and terrestrial ecosystems, reducing vegetation cover and affecting local fauna. This phenomenon has been documented in several studies, such as that of Rodríguez & Salazar (2023), who also observed how extreme climatic events, such as La Niña, can modify vegetation and aquatic ecosystems, and how this affects the species that depend on these habitats.

Regarding the historical maps (1990-2022) and projections (2022-2040), it was observed that the areas with the highest precipitation, located in the southwest of the CCZ, will be the most affected, with a generalized decrease in maximum precipitation values. This pattern aligns with observations made by Ramos (2014) on the northern coast of Peru and Leal & Portes (2020) in Colombia, who also reported a decrease in maximum precipitation in their respective studies. This behavior could increase the vulnerability of local communities, which depend on these ecosystems for their subsistence.

It can be summarized that the results obtained in this study highlight the urgent need for climate change adaptation measures in the region. Strategic planning for water resource management and ecosystem protection should be a priority, as suggested by previous studies by Rodriguez & Salazar (2023) and the Ministry of Environment and Sustainable Development (2020), which advocate the implementation of adaptation policies that help mitigate the effects of climate change. This study confirms that the region is at risk and that rapid action must be taken to mitigate the effects of climate variability and ensure the resilience of the communities that depend on the CCZ.

CONCLUSIONS

This research on climatic variability in the La Zapatosa Complex (CCZ) has shown that climate change will have significant effects on precipitation and temperature patterns in the region. Through the application of techniques such as Monte Carlo Simulation and SARIMA models, an average annual decrease of 1.40% in precipitation and an increase of 0.96°C in temperature up to 2040 were projected. These results indicate a cumulative impact that will compromise the availability of water resources, the stability of ecosystems and the food security of local communities dependent on activities such as agriculture and fishing.

The findings highlight the urgency of implementing adaptation strategies in natural resource management in the CCZ. The projected reduction in precipitation and increase in temperatures could alter hydrological cycles, increasing the region's vulnerability to more frequent and prolonged droughts. This situation calls for concrete measures, such as the optimization of water infrastructure, the promotion of efficient irrigation technologies, and the diversification of crops resistant to drought and heat stress conditions. Furthermore, the limited adaptive capacity of local communities, evidenced by indicators of insufficient preparedness, underscores the need to invest in training and sustainable technologies to strengthen their resilience to climate change.

In addition to the climatic characterization, it is known that the Cienagoso de la Zapatosa Complex (CCZ) is made up of approximately 1,900 marshes, home to 202 bird species, of which 34 are migratory. Among these, species of conservation importance were recorded,

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such as the Caribbean guacharaca (Ortalis garrula) and the chavarri (Chauna chavaria), which is classified as vulnerable at the national level. Similarly, threatened species such as the mabuya (Mabuya mabouya) and the bichichi (Saguinus oedipus), both classified as critically endangered, as well as the tapeti (Sylvilagus brasiliensis), which is endangered, were also detected.

This study has relevant implications both at the local level and in the field of scientific knowledge. In the context of the CCZ, the results highlight the absence of a robust environmental management framework as a critical factor that could lead to the degradation of ecosystem services, affecting biodiversity and economic activities such as ecotourism and fisheries. At a broader level, the research contributes to the understanding of climate change impacts in tropical wetlands, providing a replicable model for assessing and planning adaptation in similar ecosystems. This reinforces the importance of integrating climate projections into environmental planning in vulnerable regions.

Regarding adaptation and mitigation measures, there is a need to evaluate costs and possible barriers to implementation, taking into account the current strategies of the environmental authority and national plans. A more detailed estimate of financial resources and the feasibility of the proposed measures would contribute to the adoption of more effective and realistic public policies. In this way, the information presented in the article could be better articulated with land-use plans and environmental management initiatives at different scales.

However, the results should not be interpreted beyond what the data allow. Although the projections are robust, their accuracy could be improved with higher resolution regional climate models and additional data on the impact on specific species. For future work, we recommend further analysis of the effects of climate variability on biodiversity in the CCZ, as well as evaluating the effectiveness of proposed adaptation strategies, such as agricultural diversification and restoration of degraded areas.

In short, this study highlights the need to act proactively in the face of climate challenges in the CCZ. Collaboration between local authorities, communities and non-governmental organizations will be key to ensuring the sustainability of the complex by protecting its ecosystems and strengthening adaptive capacity. These actions will not only preserve the region's natural resources, but also ensure the well-being of the populations that depend on them.

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