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LONG-TERM TRENDS IN TEMPERATURE AND PRECIPITATION VARIABILITY AND THEIR IMPLICATIONS FOR REGIONAL CLIMATE CHANGE

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Abstract

Regional temperature variability and precipitation variability have been strongly affected by climate change, highlighting the need for long-term assessments. This work examined historical temperature and precipitation data from several meteorological stations in the Sinaloa state, Mexico, to look for trends. Descriptive statistics, Mann–Kendall trend test, Sen's slope estimation and climatic anomaly assessment were used to analyze data from 1961 to 2020. Increasing trends in maximum temperature were found at 33 of 37 stations with a median warming rate of 0.266°C per decade. Minimums were more variable regionally. The mean annual precipitation was 733.08 mm, with a median trend of −7.832 mm decade−1, but only at six stations was there a statistically significant trend. The seasonal analysis showed that significant amount of rainfall had occurred during wet season, and climatic anomalies indicated that there were significant variations between seasons. Regional analysis showed higher precipitation in the south of Sinaloa and slightly higher maximum temperatures in the north regions. These results show significant climate spatial and temporal variability which is crucial for continuing monitoring of meteorological variables, better water-resource management and regional climate adaptation measures.

Keywords: Climate Change, Temperature Trends, Precipitation Variability, Meteorological Observations, Regional Climate Analysis

1. Introduction

Climate change has become one of the most important environmental issues that faces the 21st century and is affecting the hydrological cycles, agricultural production, regional ecology and atmosphere. Temperature and precipitation are key climatic parameters which affect water resource distribution, seasonal weather, and environmental sustainability. Changes in such parameters over time offer valuable clues to climatic shifts in the region, and to new environmental hazards. Increase in temperatures may increase the moisture demand of the atmosphere, increase the rate of evaporation and alter the hydrological cycle; changes in precipitation patterns may affect the likelihood of droughts, flooding, and water availability. Climate response is not uniform, however, across the region due to the effects of regional topography, atmospheric circulation, land-use characteristics and ocean proximity. Therefore, it is crucial to examine historical temperature and precipitation data to identify long-term climate trends and short-term meteorological variability, and to formulate scientifically and adaptively driven strategies at regional level (Todaro et al., 2022).

There is a strong basis for assessing climatic variability on various temporal and spatial scales on the basis of long-term meteorological observations. Scientists can detect warming trends, seasonal variations in precipitation, and increased or decreased likelihood for extreme precipitation patterns in the past by analyzing historical temperature and precipitation data. The use of statistical methods, such as trend estimation and analysis of temporal variability, has grown in significance for detection of significant climatic change in observational data. Studies in Ethiopia helped to show that there is spatial and temporal variability in climate patterns, thus the need to look at specific regions instead of using a blanket average of climate (Ware et al., 2023). In a similar manner, the long-term climatic evaluations conducted in Bangladesh showed significant differences in temperature and rainfall features, which have impacts on the overall climate situation and agricultural production of the region (Alam et al. 2023). The results show the need for in-depth meteorological studies, combining temperature and precipitation data, to better understand the dynamics of regional climates.

The variability in temperature is one of the most important aspects of regional climate change as rising temperatures in the atmosphere will impact rates of evaporation, soil moisture, ecosystem functions and water needs for agriculture, among others. The long-term trend of the maximum and minimum temperatures may also differ due to differences in daytime heating or nighttime cooling, cloud cover, and interactions with the land surface. These indicators, considered individually give a more detailed picture of the changes of temperature than relying solely on the mean temperature (Gogien et al., 2023). Extensive studies of extremes of temperature and precipitation have shown the need to consider climatic indicators over a number of decades to determine potential environmental risk and changes to agricultural suitability (Mainuddin et al., 2022). Moreover, recent studies have shown that human-induced climate change can have an impact on precipitation characteristics, highlighting the need to consider climatic observations in the context of atmospheric variability and anthropogenic forcing (Ham et al., 2023). However, without further attribution analyses observational trend detection cannot rule out any specific cause of the regional climatic changes.

Precipitation variability is also a significant factor of regional climatic assessment since it directly affects freshwater resources, agricultural production, recharge of groundwater, and extremes in

rainfall (Moazzam et al., 2022 B). Precipitation often shows significant interannual variability, and strong seasonal variation, making its long-term behavior difficult to interpret. Increased variability in precipitation amounts can lead to more frequent dry spells or heavy rainfalls, even if total amounts of precipitation per year are not significantly different. A study of precipitation variations over the last 100 years has indicated that anthropogenic climate change can exacerbate the variations of precipitation patterns, which means the study of temporal investigations is necessary (Zhang et al., 2024). Studies in West Africa also indicated the effects of rainfall variability and drought on rainfed agricultural systems, especially in the areas where rain-fed agricultural productivity is highly dependent on the reliability of seasonal rainfall (Tefera et al., 2025). Therefore, assessing annual and seasonal precipitation characteristics becomes essential to understand the hydrological vulnerability at a regional scale.

Geographical differences in the temperature and precipitation behavior are more and more included in regional climate investigations by making comparisons between each other. Different levels of elevation, distance from coastlines, vegetation types and atmospheric circulation, can create different climatic conditions in a relatively small geographical area (Zhou et al., 2023). In South Korea, researchers have shown that using rainfall variability assessment alongside drought indicators can be helpful for distinguishing spatial and temporal variations in hydroclimatic conditions (Moazzam et al., 2022 A). Likewise, investigations in the Himalayan catchments revealed significant differences in the seasonal distribution and extreme rainfall features, highlighting the need to consider the geographical context in interpreting meteorological observations (Swain et al., 2022). The results indicate that station-level observations should be used in regional climate assessments where possible, so that regional trends can be separated from station-level trends. This is especially useful in areas with diverse geographical locations and weather conditions from coastal to mountains.

The situation in Sinaloa, Mexico, in the northwest of Mexico, is similar as it has a geographical setting relevant for studying long-term temperature and precipitation variability, with coastal processes, seasonal rainfall regimes, and considerable topographical variations affecting the climate of Sinaloa. A better understanding of how the climate behaves in this region is crucial for the assessment of possible consequences for agriculture, water resource management and environmental planning (Feldman et al., 2024). In other geographical settings, previous investigations have proven the utility of long time series precipitation assessments to detect the long-term climatic trends and fluctuations over the period of observations (Sharma & Priya, 2023). Nevertheless, the adaptation of maximum and minimum historical temperature, variability in annual and seasonal precipitation, climatic anomalies and based on the geographical characteristics of a station, the comparison of climatic conditions at station level are needed in order to obtain a complete assessment of regional climate. In addition, differences in station coverage, observation completeness and temporal variability must be taken into account, to avoid misleading interpretations (Mehta & Yadav, 2022). The present study analyzes long-term meteorological data from all over Sinaloa in order to describe the trends in temperature and precipitation in the region, evaluate climatic anomalies, and explore the differences among the data observed in the region. The study was guided by the following three research objectives:

1. To quantify long-term trends in maximum and minimum temperatures using historical meteorological observations across Sinaloa, Mexico.

2.To evaluate annual and seasonal precipitation variability, including rainfall anomalies and statistically significant temporal trends.

3.To examine regional differences in temperature and precipitation patterns and assess their implications for climate change.

2. Materials and Methods

2.1 Study Area and Meteorological Dataset

Retrospective quantitative design to explore the long-term temperature and precipitation variability over Sinaloa, Mexico (Mora et al., 2025). Historical meteorological data were collected from the 92-Y-Meteorological dataset, which includes data from several monitoring stations. Data comprised daily, monthly and annual precipitation, max and minimum temperatures and evaporation data together with geographical station information. Spatial comparisons could be made with latitude, longitude and altitude. The analysis was aimed at determining the temporal trends of temperature and precipitation along with differences in the spatial coverage of observations at different meteorological stations.

2.2 Data Preparation and Quality Assessment

The data in meteorological observations has been arranged by station ID, date of measurement and the climatic variable measured. Data from the daily observations were checked for missing dates, duplicate dates, inconsistent measurements, and unrealistic temperature or precipitation readings. Precipitation totals and temperature averages were computed from adequate daily records for the year. Observations were added to trends after checking for station-year completeness. Temperature was in Celsius and precipitation was in millimeters. There was no automatic replacement of missing measurements and data gaps in the annual record were avoided wherever possible when conducting analyses where they might bias long-term climatic patterns.

2.3 Long-Term Temperature Trend Analysis

Annual average of daily high and low temperatures were used for long term temperature variability. When both indicators were available, mean annual temperature was calculated as the average of these two indicators. Linear regression, Mann–Kendall trend test and Sen's slope estimation were used to determine temporal changes. The methods chosen to estimate trend direction, magnitude and statistical significance. Positive slopes meant an increase in temperature and negative slopes meant a decrease in temperature. Data for trend estimation were presented in degrees Celsius per decade to allow for comparisons between stations and time periods.

2.4. Assessment of Precipitation Variability and Anomaly

The variability of precipitation was analysed with the help of annual and seasonal rainfall totals obtained from daily meteorological data. Interannual variations were evaluated using descriptive statistics, coefficient of variation and deviations from the average of reference periods. The precipitation anomalies were obtained by subtracting the reference mean of the corresponding year from the observed total for that year. Positive anomalies were associated with wetter than reference conditions, and negative anomalies with drier than reference conditions. The Mann–Kendall tests and Sen's slope estimates were used to analyze precipitation trends. Rainfall distribution was

determined by seasonal comparisons in which the same calendar months were used throughout the period to define a season.

2.5 Statistical Analysis and Regional Climate Interpretation

To summarize climatic variability and check differences between meteorological stations, statistical analyses were designed. Descriptive indicators were used: Mean, Standard deviation, Minimum, Maximum and Coefficient of variance. The significance of trends was determined based on a 5% threshold, accounting for unequal observational coverage and temporal autocorrelation. The geographical differences in temperature and precipitation trends were explored using the station coordinates. Data processing, estimation of trends and graphical representation were assisted by Python-based statistical procedures. Observed trends were not assumed to imply climatic causation, but were interpreted with caution.

3. Results

3.1 Characteristics of Historical Meteorological Observations

The analysis period was from 1961 to 2020 and the meteorological stations used were 50 distributed throughout the state of Sinaloa. Following annual completeness criteria 1,978 station-year records were retained for precipitation and 1,939 for temperature. The mean annual precipitation was 733.08 mm, varying significantly from one year to another and from one place to another. The mean of annual maximum temperature was 32.68°C and the mean of annual minimum temperature was 16.76°C. The differences highlighted a high degree of climatic variability throughout the monitoring network and provided the descriptive foundation for the subsequent trend and regional variability analysis (Table 1) (Figure 1).

Table 1. Descriptive Statistics of Historical Meteorological Observations

Parameter	N	Mean	SD	Minimum	Maximum
Precipitation (mm)	1978	733.08	340.86	27.40	3931.00
Maximum temperature (°C)	1939	32.68	2.39	21.64	37.94
Minimum temperature (°C)	1939	16.76	2.11	5.28	21.62

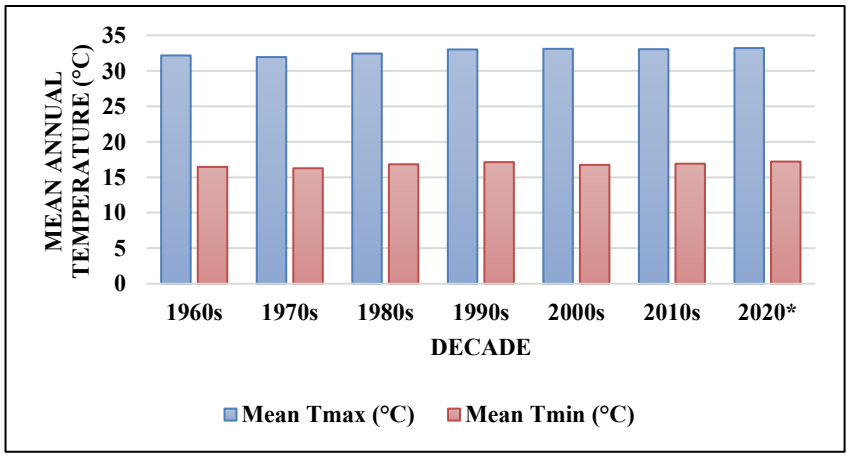

Figure 1. Decadal Variations in Maximum and Minimum Temperature Across Sinaloa

3.2 Long-Term Trends in Maximum and Minimum Temperature

Over the longer-term, the maximum temperatures across the monitoring network were predominantly increasing. Of the 37 stations with adequate observations, 33 had positive trends in maximum temperature, and four negative trends. The median slope was 0.266°C per decade and 29 stations had statistically significant slopes. Changes in minimum temperature were less consistent; there were 19 positive and 18 negative. The median slope of their records is 0.015°C per decade. These results suggested that daytime maximum temperatures might be warming more strongly than night minimum temperatures and that this warming trend might be more geographically consistent (Table 2) (Figure 2).

Table 2. Long-Term Temperature Trend Statistics

Temperature indicator	Stations	Positive	Negative	Significant	Median slope (°C/decade)
Maximum	37	33	4	29	0.266
Minimum	37	19	18	22	0.015

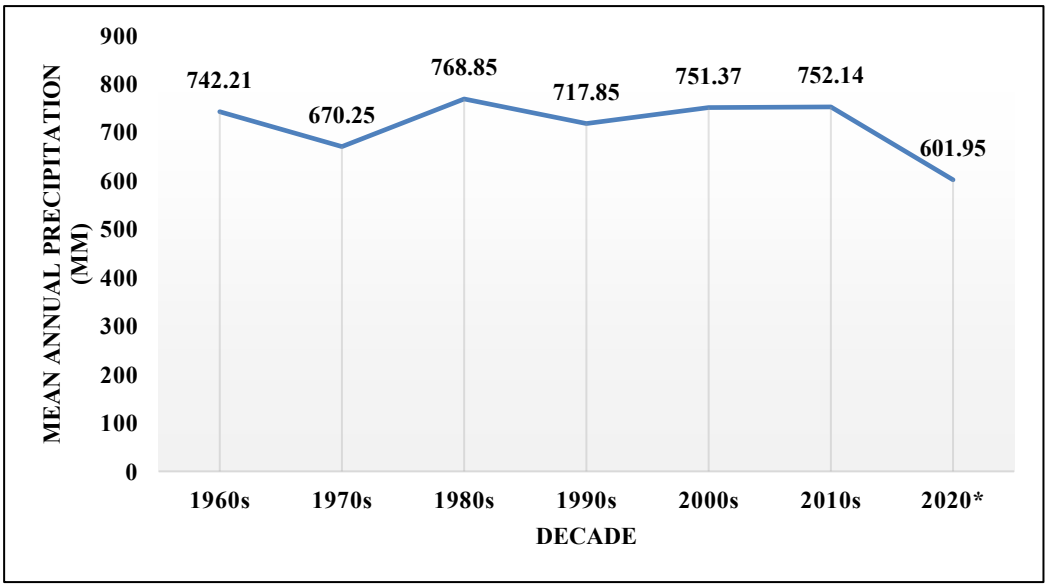

Figure 2. Decadal Changes in Mean Annual Precipitation Across Sinaloa

3.3 Annual and Seasonal Precipitation Variability

Interannual and seasonal variations were observed in precipitation across the study area. The mean annual total was 733.08 mm with a standard deviation of 340.86 mm over the number of station-years available. The mean precipitation in wet season was 636.39 mm while that in the dry season was 96.98 mm. Of 38 stations that were suited for trend analysis, 15 had positive trends and 23 had negative trends. There were only six trends at the station level that were statistically significant. Across stations, there was a slight negative trend in the median station slope (−7.832 mm per decade) (Table 3) (Figure 3).

Table 3. Precipitation Variability and Trend Statistics

Indicator	N	Mean (mm)	SD (mm)	Median (mm)
Annual	1978	733.08	340.86	—
Wet season	2016	636.39	306.93	610.53
Dry season	2033	96.98	93.05	69.10

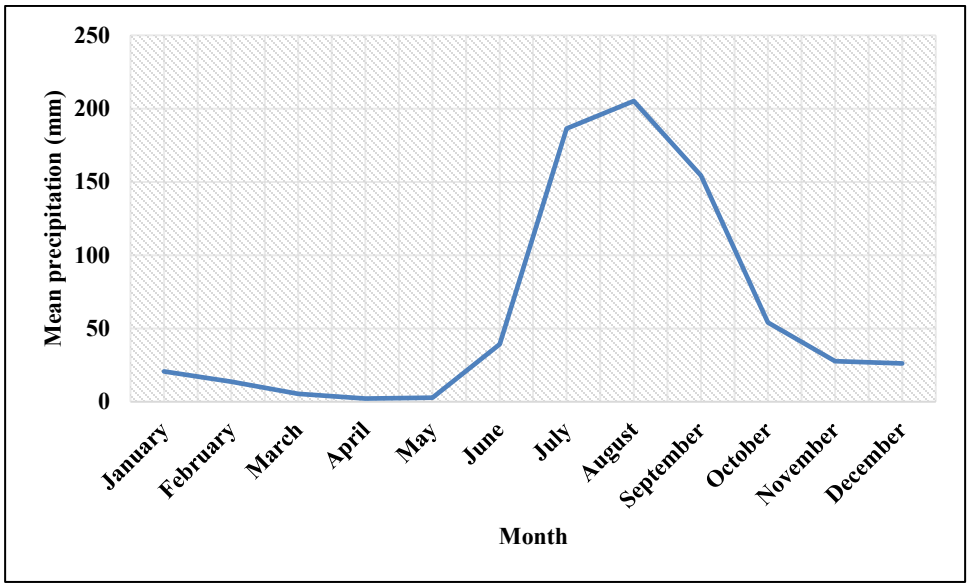

Figure 3. Monthly Precipitation Distribution Across Sinaloa

3.4 Temperature and Precipitation Anomalies

Annual station-averaged observations were used to assess the climate anomalies against the reference period of 1981–2010. The mean of the precipitation was 739.69 mm, with the highest positive anomaly being 305.69 mm in 2004 and the highest negative anomaly being −234.38 mm in 1987. Anomalies in maximum temperatures varied from −1.34°C to 1.16°C and in minimum temperature varied from −1.33°C to 1.34°C. The breaks showed a significant change in regional climate from year to year. Annual regional averages may have been affected by changes in the number of stations (Table 4) (Figure 4).

Table 4. Historical Temperature and Precipitation Anomalies

Indicator	Reference mean	Minimum anomaly	Maximum anomaly	Minimum year	Maximum year
Precipitation (mm)	739.69	-234.38	305.69	1987	2004
Maximum temperature	32.84	-1.34	1.16	1971	2002

(°C)					
Minimum temperature (°C)	16.90	-1.33	1.34	1975	2015

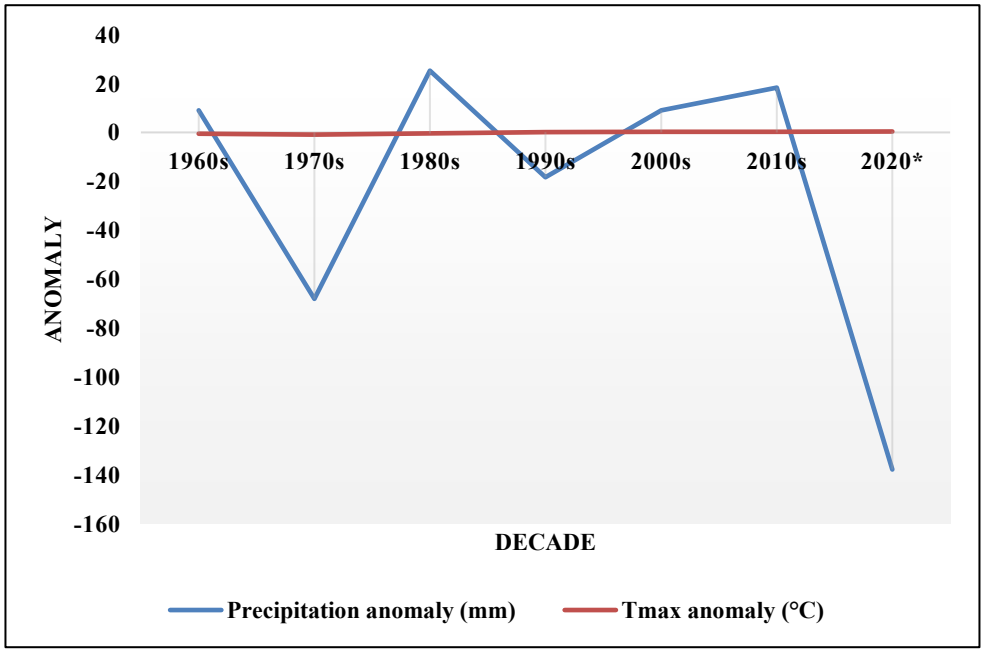

Figure 4. Decadal Temperature and Precipitation Anomalies Relative to 1981–2010

3.5 Regional Differences in Climatic Trends

Results of regional comparisons showed significant differences in climatic conditions throughout Sinaloa. The mean annual precipitation at southern stations was higher than at the northern ones with a difference of 805.4 mm and 659.8 mm respectively. The mean maximum temperatures were somewhat higher in the northern group while minimum temperatures were higher in the southern group. These findings indicated geographical heterogeneity in climatic conditions, but did not confirm a difference in the level of long-term trends (Table 5) (Figure 5).

Table 5. Regional Comparison of Meteorological Conditions

Region	Stations	Precipitation (mm)	Tmax (°C)	Tmin (°C)
Northern	25	659.8	33.00	16.13
Southern	25	805.4	32.37	17.36

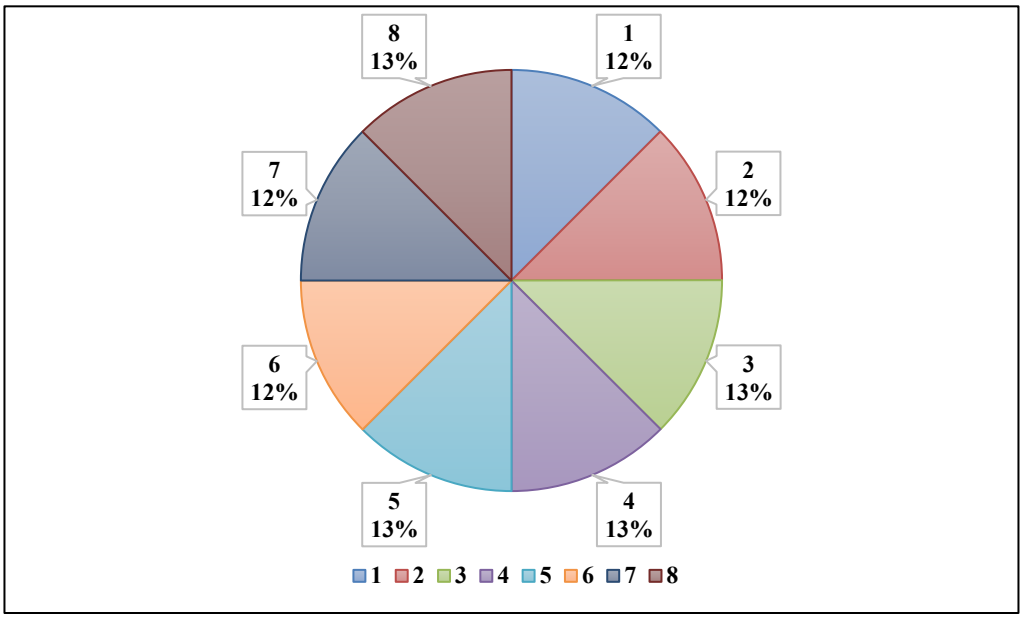

Figure 5. Station-Level Differences in Long-Term Maximum Temperature Trends

4. Discussion

Variability in temperature and precipitation over the region of Sinaloa, Mexico, with clear signatures of long-term temperature and precipitation changes and geographical variability. The results showed that the maximum temperature had a general increasing trend with 33 of the 37 stations analyzed having positive trends and a median Sen's slope of 0.266°C per decade. The minimum-temperature trends were much more varied, with almost as many stations showing positive trends as negative trends. It is possible to conclude from these results that warming over the study area has occurred more uniformly during the day time of the year than warming during the night time of the year. Similar studies in the southern part of Ethiopia have shown that warming trends vary significantly from station to station, suggesting the role of regional climatic characteristics on the observed warming trends (Dalle et al., 2023). The differences accentuate the value of considering maximum and minimum temperatures separately and not only annual mean temperatures.

The rise in maximum temperature is significant for regional atmospheric and hydrological processes as observed. Increased evaporative demand due to higher daytime temperatures may impact soil water availability, affect soil thermal regime, and enhance heat stress on agricultural systems. The warming tendency observed in the present analysis did not directly assess crop productivity; however, its implications for temperature-sensitive crop operations are discussed. Changing temperature conditions were shown to be relevant for Nebraska agriculture, due to the important relationships found between air temperature extremes and corn and soybean yield (dos Santos et al., 2022). Likewise, studies on the relationship between vegetation resilience and water availability and variability indicate that changes in temperature might also affect ecosystem stability in conjunction with hydrological conditions, over time (Smith & Boers, 2023). But, more observations of soil moisture, vegetation response, and productivity would be needed to establish such consequences in Sinaloa.

The result of the precipitation analysis showed that there was a significant variation in the

precipitation between years, with the mean annual precipitation of 733.08 mm and the standard deviation of 340.86 mm. The station-level trend assessment showed precipitation tendencies were negative at 23 of 38 stations, but only six of these had statistically significant precipitation tendencies. However, the overall tendency for precipitation to decrease was relatively weak (median = −7.832 mm per decade); few station-level trends were significant, so it is not a definitive downward trend. It was found that comparable studies in southwestern Ethiopia revealed high seasonality of rainfall and associated risk for rain-fed agricultural production, highlighting that the reliability of rainfall is important, not only the amount of precipitation recorded over a year (Habte et al., 2023). The observed fluctuations in precipitation experienced in Sinaloa could therefore have implications for water planning decisions for agriculture—especially for those relying on seasonal precipitation.

The differences were also significant between the wet and dry season with average wet season rainfall of 636.39 mm, and 96.98 mm during the dry season. The large seasonal difference suggests a high dependence of the water availability in the region on the concentration of rainfall over specific months. Changes in seasonal rainfall timing can have impacts on the timing of agricultural activities, surface water storage, and groundwater recharge despite fairly small changes in annual rainfall. Past studies in the Mahi River basin showed the potential of precipitation indices and meteorological drought characteristics in indicating spatially differentiated hydrological risks (Sharma et al., 2022). Further, the study on rainfall variability and farmers' production in the Ethiopian highlands highlighted the significance of the distribution of rainfall for the production. (Bedane et al., 2022). Standardized drought indices and seasonal rainfall attributes should be included in future studies as indicated by these comparisons.

It showed that large deviations from normal climatic conditions were observed, with values of precipitation ranging from −234.38 mm to 305.69 mm. The maximum temperature anomalies ranged from −1.34°C to 1.16°C, indicating that there were significant deviations from the reference years in individual years. This is how climate varies from year-to-year and why it's crucial to distinguish between short-term fluctuations and long-term changes. Past precipitation reconstructions over the arid region of Central Asia have shown that precipitation may change on longer timescales and be linked to the large-scale environmental and societal dynamics (Ding et al., 2023). However, the present study's results must be taken with caution as the anomalies found may be affected by the variability in the number of meteorological stations. The reliability of these comparisons could be improved with additional sensitivity analyses employing uniform station coverage.

The average precipitation for the region was significantly higher in southern Sinaloa stations compared to the north with 805.4 mm and 659.8 mm, respectively. Maximum temperatures were slightly higher in the northern stations while the minimum temperatures were higher in the southern stations. Climatic differences between these geographical areas suggest the climate is not spatially homogeneous over the study area. This heterogenuity can have implications on the availability of water and the responses of the ecosystems to water availability at the regional scale. As in other studies, correlations have been found between climatic variability and groundwater quality, implying that hydrological changes can affect groundwater environmental processes (Barbieri et al., 2023). In addition, studies reporting reductions in the resilience of terrestrial ecosystems emphasize the need to assess climatic pressures, in tandem with ecosystem responses

(Yao et al., 2024). This study did not however directly measure groundwater quality or ecosystem resilience so conclusions could not be drawn on these outcomes.

The results also have general implications for the understanding of environmental vulnerability under changing precipitation conditions. While this analysis was based on meteorological metrics, shifts in rainfall can affect human and ecological systems in several ways. Beyond the impacts of hydroclimatic fluctuations on agriculture and environmental systems, associations between precipitation variability and risks of infectious diseases have been identified in international research for young children.In addition to impacts on agriculture and environmental systems, recent international research has shown associations between precipitation variability and risks of infectious disease for young children. However, these findings should not be considered direct health impacts in Sinaloa. The main restrictions are: the station coverage is not even; there are not full historical observations; the stations may not be evenly distributed, and there is no formal climatic attribution analysis. The homogenized meteorological data, the use of autocorrelation corrected trend testing, hydrological indicators and environmental observations should be added to future research to reach a more complete picture of regional climate change and its potential impacts.

5. Conclusion

Historical meteorological observations for Sinaloa, Mexico, are used to detect regional climatic trends and patterns over a long time. The results showed that the maximum temperature increased in most stations, 33 of 37 stations had positive trends; the median rate of maximum temperature change was 0.266°C per decade. Minimum-temperature trends were fairly variable, suggesting some variation in the diurnal/night-time thermal response. The analysis of precipitation proved that a large interannual variability, exceeding 733.08 mm annually on average, was observed, as well as a slight negative trend of −7.832 mm per decade for the period under consideration. But, the lack of statistically significant precipitation trends indicated that an overall regional drying could not be determined. The seasonal analysis revealed high concentration in rainfall during wet season, and climatic anomalies showed significant variations in temperature and rainfall. Regional comparisons also showed that there are differences between the north and the south of Sinaloa, highlighting the geographical differences in climatic conditions. The results highlight the need of long-term monitoring of meteorological data to gain insight into the climatic variability in the region, and to help plan agricultural activities, manage water resources and adapt to climate variability. Future studies should include homogenized station data, more advanced drought indicators and hydrological data to enhance trend reliability and better understand the environmental impact of the region's climatic changes.

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