Assessing Climate Variability and Change in Pretoria (1964–2024)

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1. Introduction

Climate change can be defined as the long-term shifts in temperature and weather patterns, primarily caused by human activities such as burning fossil fuels (UNFCCC, 1992). The article by Rahman (2013) goes on to specify that the same UNFCCC defines Climate Change as "a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere, and which is in addition to the climate variability observed over comparable time periods". Climate variability is heavily influenced by climate features such as the El Nino-Southern Oscillation and North Atlantic Oscillation, but external factors of such as increase in greenhouse gases and volcanism add onto and worsen the regional climate variability (Salinger, 2005).

Climate change, in the South African context, is said illustrated through a 3 to 6°C increase in temperature by 2081 – 2100 (Ziervogel et al., 2014). The article goes to further stipulate that this change in the country's climate will have a disastrous impact on the national food security, health, water resources, infrastructure and the ecosystem's biodiversity. South Africa's social problems involving high poverty rates, unemployment and inequality lay a foundational issue of having to mitigate through the ever-changing regional climate, that will have the most impact on the poor population.

Pretoria, situated in the Gauteng Province, has undergone significant urban development over the past several decades. Studying climate variability here provides insights into both regional climate trends and the influence of microenvironmental changes such as urbanization. Mamelodi, a township situated on the outskirts of Pretoria, is a provisional area of study due to its encompassing of South Africa's societal issues and how its population has grown over the past years. Conradie (2017) focused on examining how the country's cities increase the global phenomenon of greenhouse gas emissions and how climate change allows for the adverse complexities of urban heat island effect (UHE). But there is a need to define what urban heat island effect is and in essence, Yang et al. (2016) define it to be a phenomenon that relates to the accumulated heat with an urban area due to the surrounding construction buildings and human activities. This heat accumulation is defined to be much higher in the modern and urban areas than the rural areas. The authors also recognize that surface temperature is the underlying factor for urban climate effects, that also helps regulate and control ecological processes. Pretoria serves as a strategically important study site, having featured prominently in several prior climate analyses including studies by Conradie (2017) and Partridge et al. (1997). The study by Partridge et al. (1997), in essence, explains that the long-term rainfall variability in subtropical Southern Africa is strongly influenced by changes in summer insolation caused by orbital precession. In simple terms, it shows how the region's climate and atmosphere naturally functioned before human activities began to alter it. So, Pretoria has established relevance in case studies and that makes it a valuable reference point for continued investigation.

2. Methodology

Mamelodi is a township located in the eastern part of Pretoria, Gauteng (van den Brink, 2006). van den Brink (2006) further goes on to stipulate that Mamelodi that the geographical boundaries of the Magaliesberg borders and the railway line in the south prevented the urban sprawl within the township, but I highly suggest that the evidence for this given notion remains to be unsubstantiated. Research points out that urban sprawl had been a huge issue in Mamelodi, thus the township has grown at an exponential rate because of forced removals during apartheid and post-apartheid relocations driven by housing demand that led to spatial inequality (Eber, 2005; Mkhize, 2015; Mudau, 2024). Conradie (2017) did a similar focus of study that can be well supplemented into this research about how climate change has affected Pretoria's urban climate. The article identifies passive design strategies for buildings that can reduce heat stress and energy use. Some key findings include that urban heat island (UHI) effects will intensify warming in cities, in this case, Pretoria. The author specifies using climate modelling, which are long-term projections to simulate future conditions, and this well complements my seasonal and decadal analysis to be discussed below. The author also used a software named Climate Consultant 6.0 to compare current and future climate conditions and to identify optimal passive design strategies as alternatives to deal with the urban climate issue. This comparison and suggestion of alternative solutions to deal with the issue guide me into aligning my results and ensure that what I have derived from the data is correct and can be explained using external peer-reviewed research.

The climate data used in this data analysis comprises mean monthly minimum and maximum temperatures, as well as the precipitation values for Pretoria, Gauteng. This dataset extracted from the Climatic Research Unit (CRU) TS gridded time series, available at Find the data for your assignment attached. This is the mean monthly temperature (min and max) and precipitation for your selected site: Pretoria, Gauteng. I extracted this dataset from the gridded dataset called CRU https://crudata.uea.ac.uk/cru/data/hrg/. This dataset is widely trusted and used in academic papers. The CRU TS dataset is widely recognized and frequently cited in peer-reviewed literature for its reliability and spatial coverage, making it suitable for long-term climate variability assessments. The dataset file, named Pretoria2_TerraClimate_1964_2024.csv was processed using Python programming language using Google Colab notebook. Several libraries were imported to ensure for the correct data processing and visualization of given contexts of the data. These libraries included pandas, seaborn, matplotlib.

The dataset was converted from monthly data to annual aggregates. To ensure that no missing values appear in the dataset, there was a handling of those missing values and smoothing via rolling averages. Then seasonal groupings were created using calendar-based definitions. Trend analysis was applied using several statistical inferential methods. These included using linear regression for temperature and precipitation trends, the calculation of trend per year and per decade, significance testing using p-values, R2 computation to relay how well the data fits the context given, as well as visualization of trend lines over time series charts and graphs.

To further enhance our understanding of the dataset, a seasonal analysis was done based on sub-setting the data by season and calculating the trend analysis for each season and variable. Then this analysis was displayed into a summary table of seasonal trends with significance flags. For further comprehended analysis, a follow-up analysis of detecting extreme weather events using threshold-based classification and a 10-year moving average analysis to highlight long-term temperature shifts. The microenvironmental analysis was done to fill the gap in the case study, the analysis uses a trend comparison across urbanization periods (Pre-Urban, Growth, Modern). This allowed for the interpretation of minimum and maximum temperature range trends that can be used to identify the urban heat island signatures. And finally, all the figures obtained in the Results section were automatically exported to a Word document with captions and layout control for each graph as well as embedding summary tables for trends and findings.

3. Results

The following visualizations illustrate key trends in temperature, precipitation, seasonal variation, and extreme events:

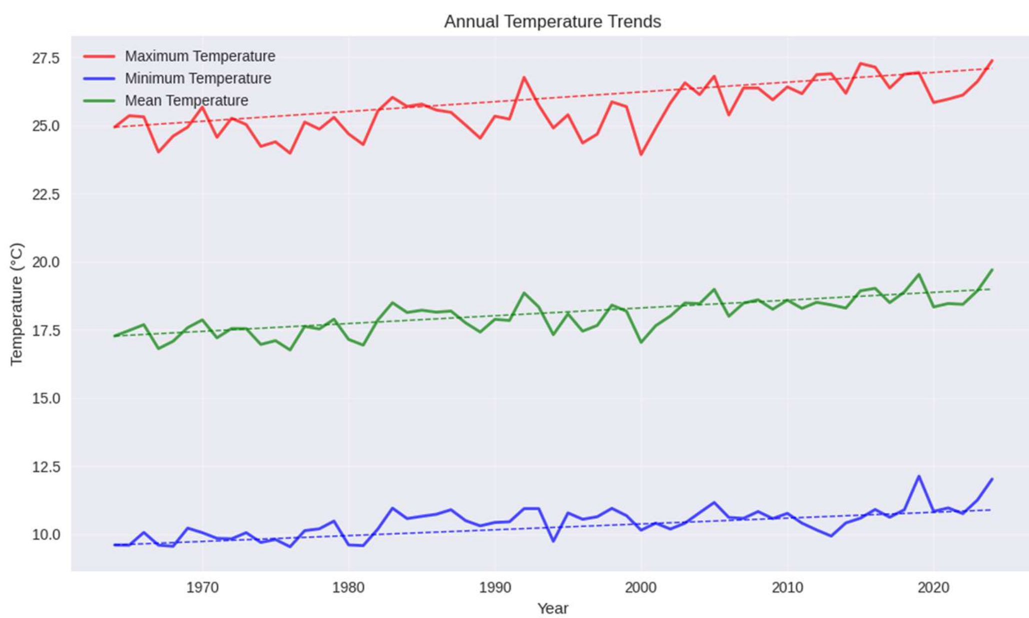

Figure 1: Annual Temperature Trends

The graph (Figure 1) illustrates annual temperature trends for Pretoria over a 60-year period (1964–2024). It reveals a clear upward trajectory in minimum, maximum, and mean temperatures, indicating a consistent warming trend. This pattern suggests long-term increases in surface temperature, potentially linked to broader climatic shifts and urban environmental changes. The lines for each measure show an immediate uptick in the temperature ranges after the year 2000.

Figure 2 below shows the annual precipitation over the six-decade period. It can be noticed that the precipitation values had normal fluctuations between 1964 to 1990. Between approximately 1992 and 2000, there's a noticeable widening of the gap between peak and low rainfall years. This suggests a period of high variability and this kind of spread reflects unstable climatic conditions with a consistent decline in the overall rainfall.

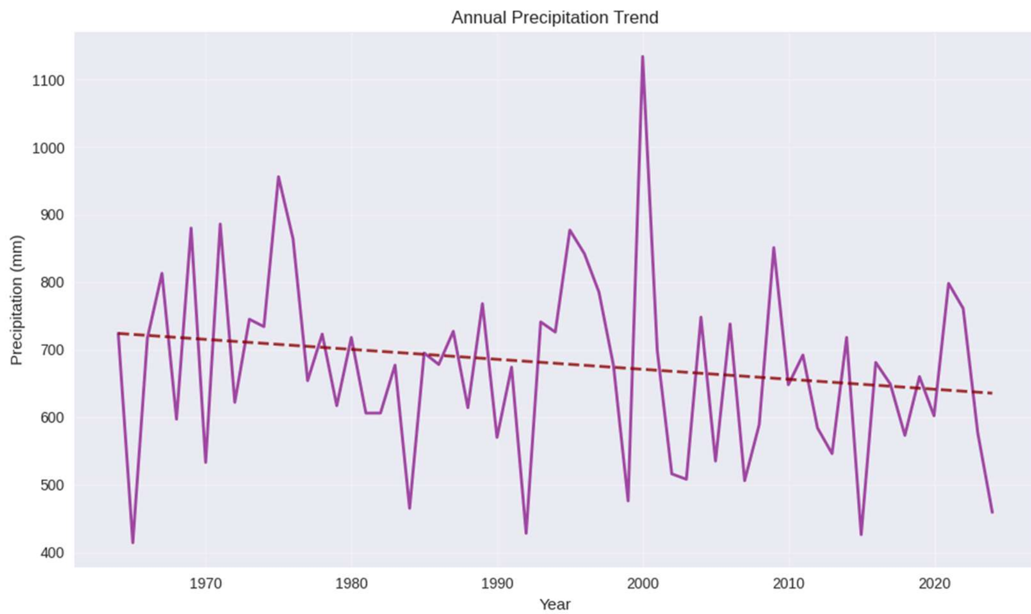

Figure 2: Annual Precipitation Trend

Figure 3 below shows a lower trend of temperature values that ranged between 13.5 °C and just below 16 °C before the year 2000. However, following this period, a noticeable increase in temperature was observed, rising to a new range of 14.8 °C to a peak of nearly 17 °C.

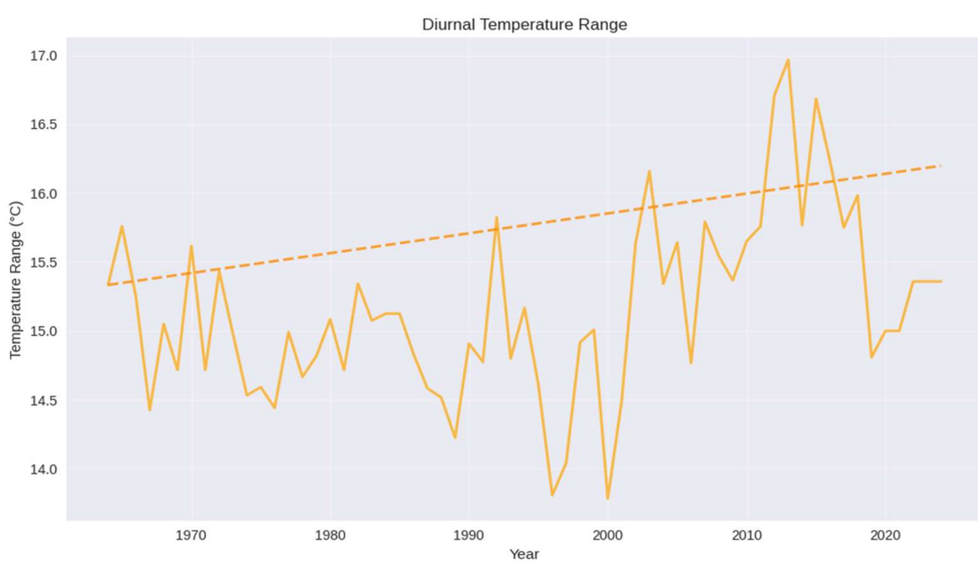

Figure 3: Diurnal Temperature Range

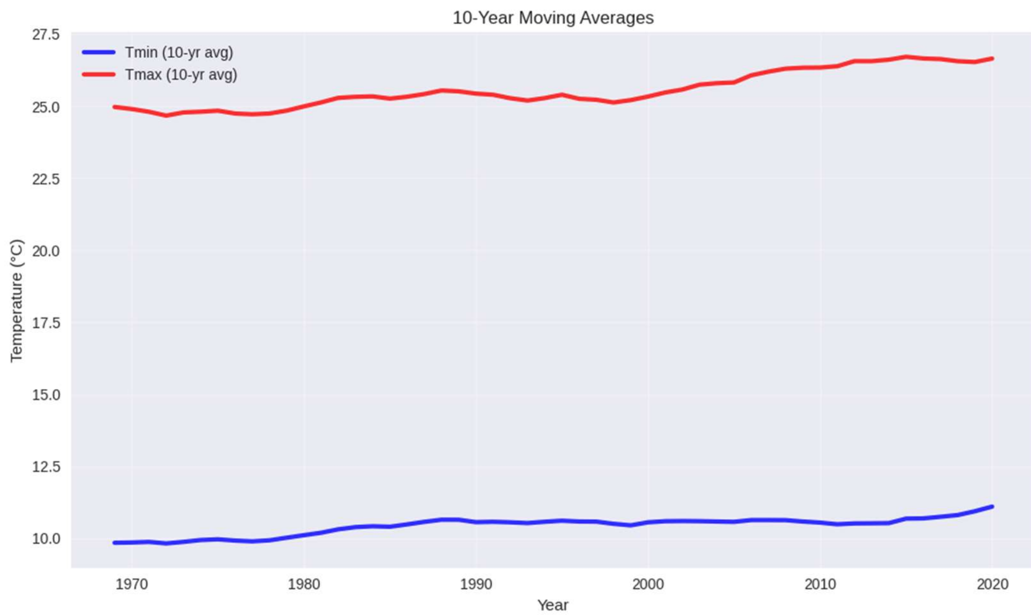

Figure 4: 10 Year Moving Averages

The above figure (Figure 4) illustrates the 10-year moving averages for both the minimum and maximum temperatures over the years. The Tmin 10-year average line stays relatively the same, but a minute increase can be seen towards the last 10 years (2010 to 2020). During the double 10-year average between 1980 and 2000, the temperature can be seen to uplift above the 10 °C mark and stay consistent throughout to eventually increase in the last decade's moving average. Both trends show long-term warming, with Tmin rising more steadily and sharply, especially in recent decades - while Tmax also increases but with more variability. The smoothing process filters out short-term fluctuations, making the overall warming pattern clear. This suggests a consistent rise in nighttime temperatures, possibly linked to urban heat island effects, and reinforces evidence of sustained climate warming in the region.

The next figure (Figure 5) shows the seasonal temperature trends. From all the graphs given, an overall trend of a positive trendline is visible for each season. The Summer and Spring seasons seem to have hit a new peak of 30 °C for the Tmax. The minimum temperature trend for Autumn, Summer and Spring seems to have had a steady rise that wasn't as much abrupt as the Winter season. Winter's trendline appears to show a greater steep increase compared to the other three seasons. The lowest temperature for Winter on the graph seems to be around 1 °C, which was around 1964. And now currently the minimum temperature sits at approximately 5 °C for 2024. The lowest Tmin value for Summer remains to be at around 14 °C between the years of 1970 and 1980. At the 2024 mark, it stands to have a new Tmin value of around 16 °C.

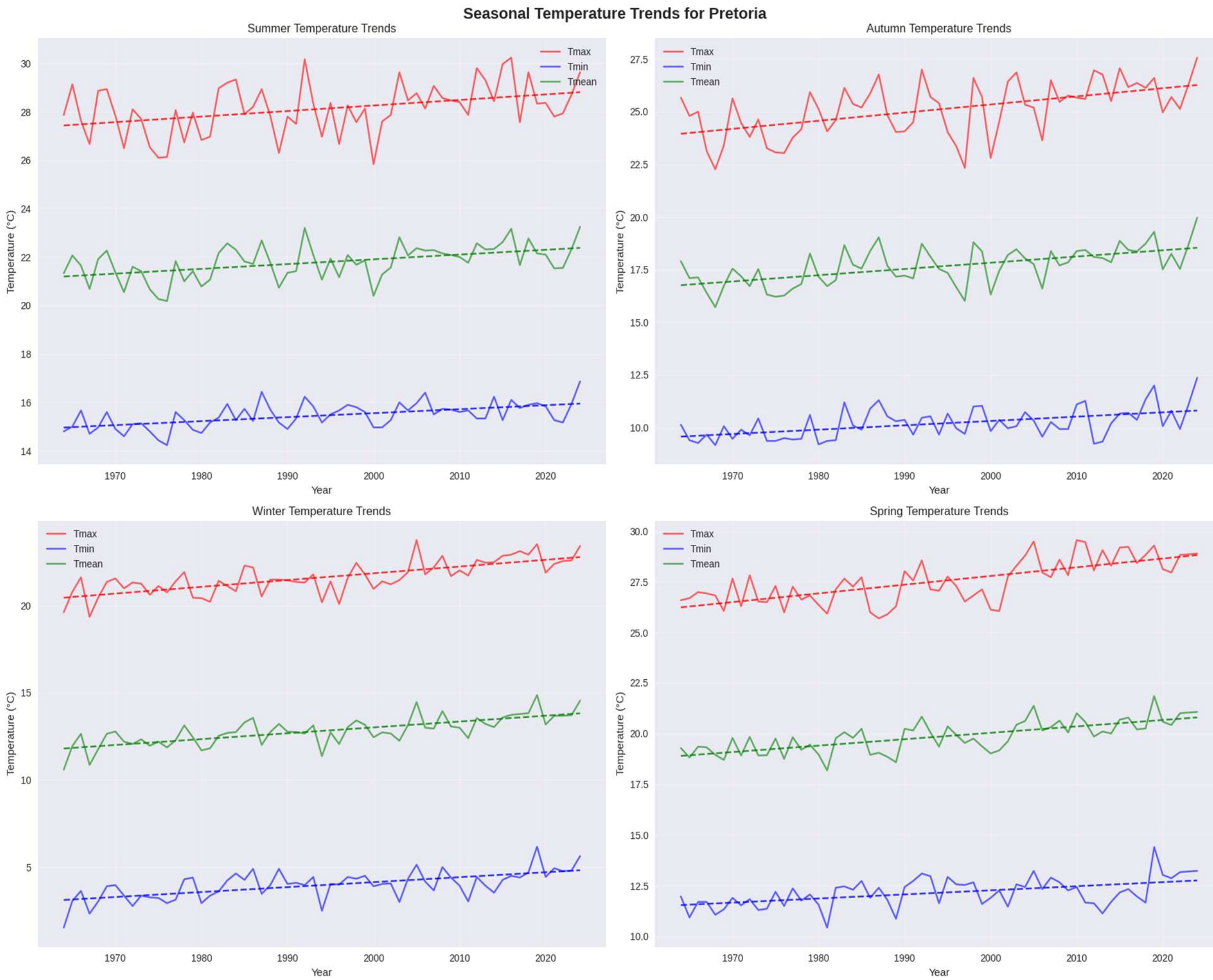

Figure 5:Seasonal Trends

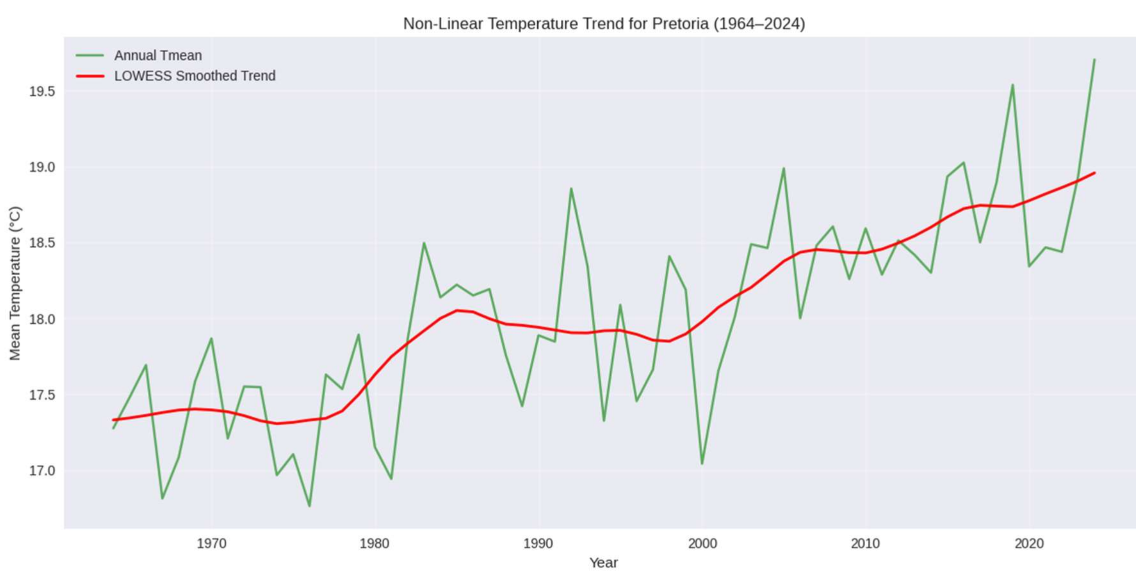

Figure 6:Non-Linear Temperature Trend for Pretoria (1964-2024)

Figure 6 uses a non-linear method to show the trend in temperature. Rather than using a linear trendline, this graph allows us to see the long-term trend for the average temperature. From the period of around 1978 to 1985, we can see a steep increase in average temperature for the LOWESS smoothed line in red from 17.4 °C to a high of 18.1 °C. From then on, it became a continuous increase and had now reached the height of around 18.8 °C. The annual tmean line in green represents the actual fluctuations of the temperatures. There are some noticeable dips within the observed values, especially the individual years of 1980 and 2000. The 21st century saw Pretoria on a steep rise that continued after 2000.

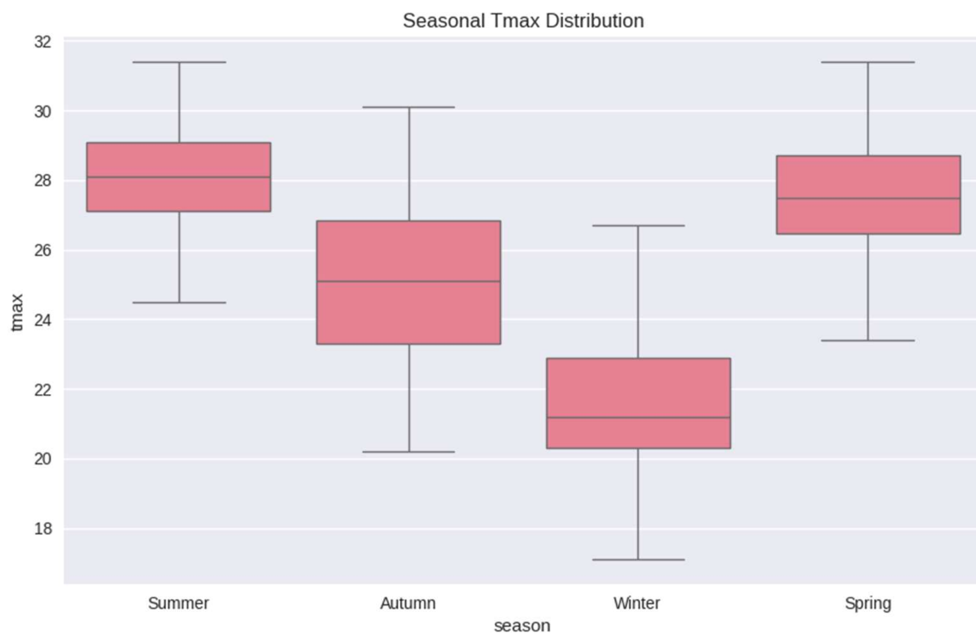

Figure 7: Seasonal Tmax Distribution

Figure 7 can be interpreted to show the distribution of the maximum temperature per season using a boxplot visualization. The Winter season as expected has a lower Tmax temperature than the rest, and the same for summer season having the highest Tmax temperature. The winter boxplot seems to be the only one that has a skewed distribution. The summer boxplot seems to have the smallest interquartile range compared to the other, suggesting that 50% of the temperatures for that season are more tightly clustered around the median temperature. This leads to the insinuation that most of the data for the summer boxplot has the most consistent maximum temperature values between all four seasons, whereas the winter boxplot shows a bigger interquartile range to suggest a high variability for the maximum temperature. Urbanization leads to a variation in the maximum temperature due to the urban heat island effect. In simplification, the surrounding buildings of Pretoria could have possibly trapped the heat and held on to the greenhouse gases, leading to the high variability of the maximum temperature, especially for the winter.

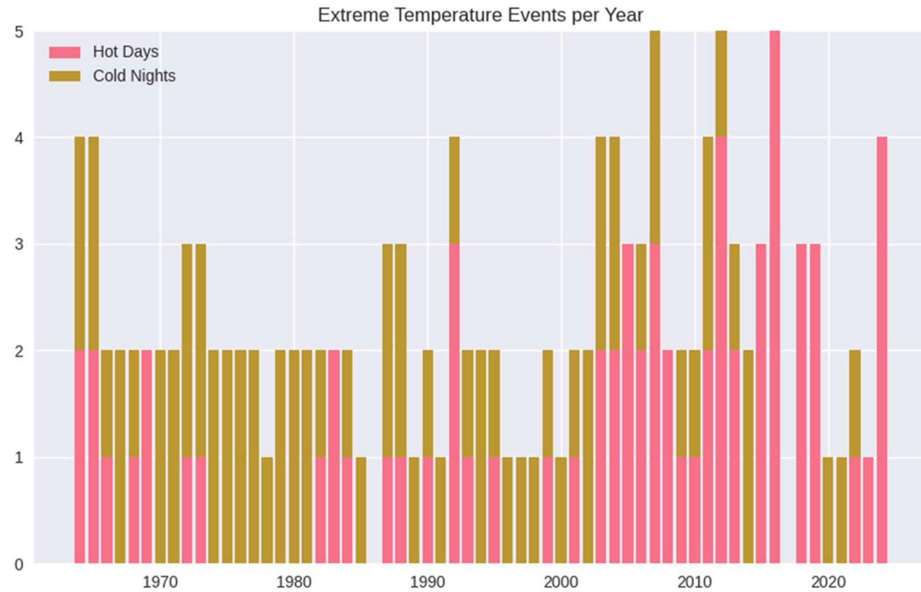

Figure 8: Extreme Temperature Events per Year

Figure 8 shows the extreme temperature events that may have occurred per year. And by interpretation, the graph shows annual counts of hot days and cold nights, with noticeable year-to-year variability. Over time, cold nights appear to decline in frequency, especially in recent decades, while hot days show a less consistent but upward tendency, with more frequent spikes in later years. Together, these patterns suggest a shift toward warmer conditions and increased temperature extremes.

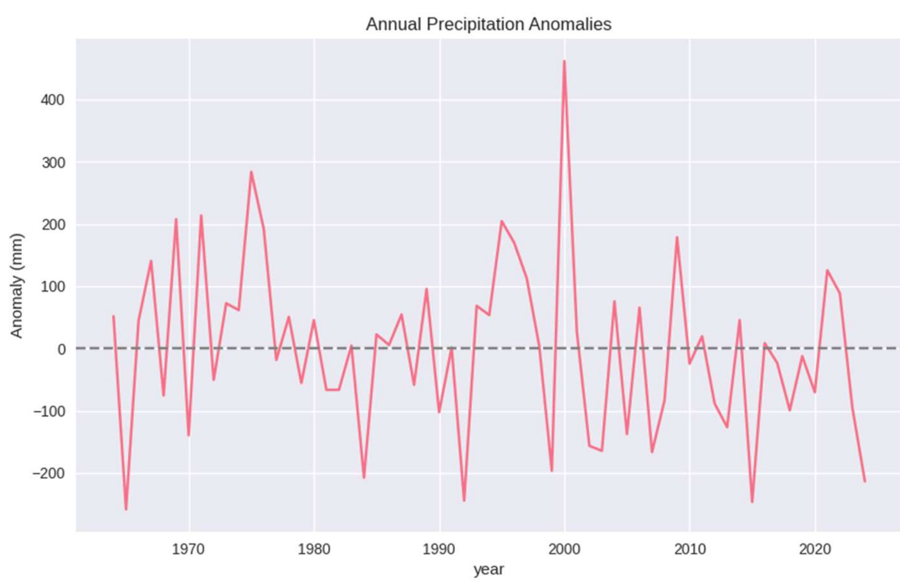

Figure 9: Annual Precipitation Anomalies

Figure 9 is an anomaly line graph that depicts the annual precipitation in mm. The graph illustrates yearly rainfall totals differing from the long-term average calculated over the 1964-2024 period. The dashed horizontal line at zero marks this baseline. Years with values above the line reflect wetter-than-average conditions, while those below indicate drier-than-average years. The plot reveals notable fluctuations in rainfall from year to year, with pronounced wet periods around 1975 and 2000, and significantly dry spells in the mid-1960s, mid-1980s, and near 2015. Overall, the graph highlights Pretoria's inter-annual precipitation variability across six decades. Figure 10 below shows the trend by the minimum temperature into three defined periods based on urban development phases. The early period can be grouped under the years 1964 to 1985, the growth period of 1986 to 2005 can be seen as the growth period and finally the modern period, which persists today can be grouped under the years of 2006 to 2024 on the graph. The lines within each colored segment point to the linear trend for minimum temperature during that specific period. An upward sloping line signifies warming nights, a downward slope indicates cooling nights, and a flat line suggests minimal change. The shaded areas surrounding the lines denote the confidence intervals, providing an estimate of the range within the true trend likely falls. One can observe how the rate of minimum temperature increase, a key indicator of the urban heat island effect, may have varied in correlation with different stages of Pretoria's urban growth.

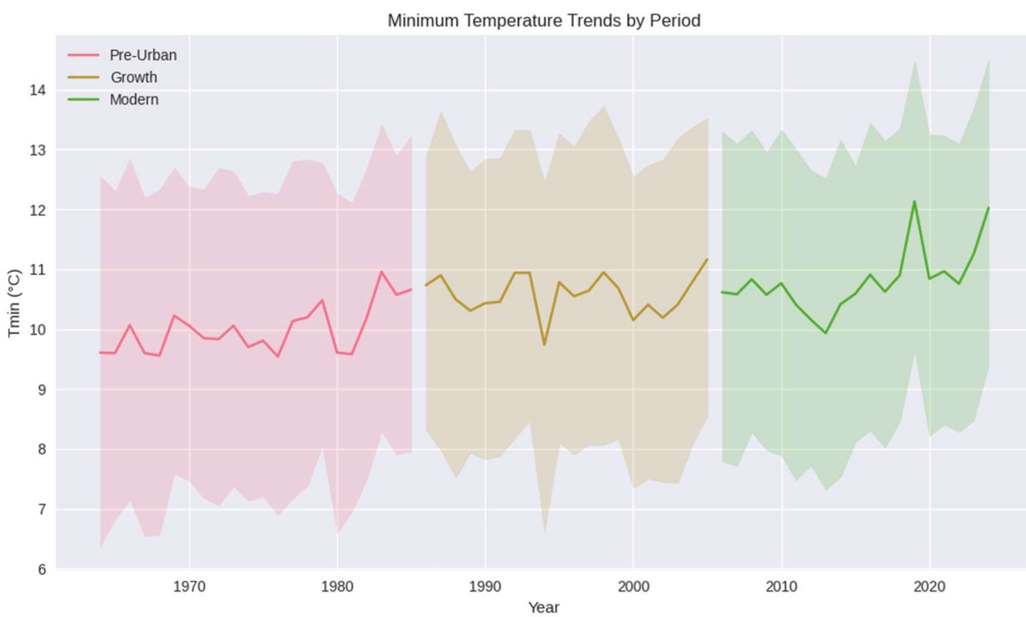

Figure 10: Minimum Temperature Trends by Period

The results below on Table 1 allows for an observation of seeing if all the variables measured in this data analysis are viable to determine the effects of urban heat islands in Pretoria and how significant they are. The table below states that all the variables for each given season (Tmax, Tmin, Tmean) have seen an increase in degrees Celsius per decade, and they are significantly important to the analysis of the data. Most trends on average are shown to be around the values of 0.165 to 0.430, with Spring and Winter having the highest jump in average temperature trend per decade.

Seasonal Temperature Trends Summary

Season	Variable	Trend (°C/decade)	Significant
Summer	tmax	0.229	Yes
Summer	tmin	0.165	Yes
Summer	tmean	0.197	Yes
Autumn	tmax	0.386	Yes
Autumn	tmin	0.206	Yes
Autumn	tmean	0.296	Yes
Winter	tmax	0.388	Yes
Winter	tmin	0.284	Yes
Winter	tmean	0.336	Yes
Spring	tmax	0.43	Yes
Spring	tmin	0.202	Yes
Spring	tmean	0.316	Yes

Table 1: Summary of the Seasonal Temperature Trends

Table 2 below summarizes the temperature trends above, showcasing the relation strength using the R^2 column. From observation, Tmax has a significantly higher temperature trend per decade with the second strongest relation. The average temperature (Tmean) has the second highest temperature trend per decade and the most positive or strongest relation amongst the three variables.

Summary of Temperature Trends

Variable	Trend (°C/decade)	P-value	Significant	R^2	Period
TMAX	0.358	0.0000	Yes	0.511	1964-2024
TMIN	0.214	0.0000	Yes	0.478	1964-2024
TMEAN	0.286	0.0000	Yes	0.586	1964-2024

Table 2: Summary of Temperature Trends

Microenvironmental Analysis Summary

Indicator	Value	Interpretation
Minimum Temperature Trend	0.214°C/decade	Consistent with urban heat island effects
Temperature Range Trend	0.144°C/decade	Stable or increasing range
Tmin Trend (Early Period (1964-1985))	0.364°C/decade	Period-specific warming
Tmin Trend (Growth Period (1986-2005))	0.009°C/decade	Period-specific warming
Tmin Trend (Modern Period (2006-2024))	0.549°C/decade	Period-specific warming

Table 3: Summary of the Microenvironmental Analysis

Table 3 is a microenvironmental analysis summary table to showcase the suspected indicators of a changing urban environment for Pretoria. These indicators include the different stages of urban development and their trends as well as how they could be interpreted.

4. Discussion

An insight from Turpie et al. (2002) that supports Figure 1 is that climate change (characterized by consistent rise in temperature) will have a disastrous effect on the country's GDP, decreasing it by at least 1.5 to 3 percent. Precipitation is an important factor to allow for agricultural growth, having a stunning correlation of 98.2% with a country's overall economic growth Kara & Diken (2020) and that the rainfall trends influence economic performance in agriculture-heavy regions (Damania et al., 2020). But given the context for this report, Gauteng is not necessarily an agriculture-heavy region but can be viewed as a strategic region to introduce urban agriculture through the lens of urban sustainability, green infrastructure and socio-economic resilience, positioning rainfall as a key input for local food systems, informal economies and climate resilience (Van Huyssteen et al. 2020). The observed decline in the annual precipitation in Figure 2 undermines the local urban agriculture around Gauteng (Pretoria), and as Van Huyssteen et al. (2020) explains that most Johannesburg's urban agriculture occurs in places with most unemployment rates (usually townships and informal settlements), and this can possibly apply to the township of Mamelodi to an extent. But the authors also clarify using spatial analysis that although these underserved communities are expected to be the most likely population to do urban agriculture, they are still underrepresented in that space due to limited access to land (dense infrastructure and housing) and water resources (fragmented municipal support).

The spike during the year 2000 in the same figure can be attributed to the Tropical Cyclone Eline, this is in accordance with the article by Reason & Keibel (2004). The cyclone made landfall in late February 2000 in Mozambique and though Pretoria wasn't the main epicenter of the flooding, the city did receive an elevated rainfall due to the broader synoptic system the cyclone helped create. So, in simple terms, a tropical-extratropical cloud band was extended across the interior plateau, which included Gauteng. Figure 3 depicts the annual temperature range, and shows a positive trendline (uptrend), which illustrates that temperature has been consistently rising during the past six decades of 1964 to 1994. This is the key illustration of how humans can perceive and experience climate change: an increase in temperature leads to more humid conditions that humans cannot physiologically tolerate in climatic events such as heatwaves and droughts. This pronounced warming trend post-2000 is in correlation with rapid urban expansion that occurred during the same period (Conradie, 2017).

In the case of Figure 10, the early period indicates a limited urban development, which can be attributed to apartheid's government tight control of spatial planning that enforced racial segregation and limited infrastructure in black townships, including Mamelodi (Hendler, 2015). Historical analyses accurately anticipated Pretoria's spatial expansion, including the growth of Atteridgeville, Mamelodi, Centurion, and the densification of areas like Arcadia and Sunnyside (Horn, 2021). This urban growth trajectory aligns with observed increases in minimum temperatures, particularly during the "Growth" and "Modern" periods. The rise in nighttime temperatures - often more sensitive to land use changes - suggests a strong urban heat island effect, where built environments retain heat and alter local microclimates. Horn (2021) further goes to quote the publication by The Centre for Development and Enterprise (1998a) with a note that Pretoria faces the challenge of redefining its identity and adapting to new urban realities, which now include climate resilience as a critical dimension. The warming trend in the graph is most pronounced post-2000, coinciding with rapid urban expansion. Seasonal shifts in Figure 5 suggest increased summer Tmax variability. The rise in hot days and reduction in cold nights of Figure 8 reflect broader warming patterns, potentially amplified by local land cover changes.

Chakwizira et al. (2014) focused on urbanization being the main driver in Pretoria and how it can be mitigated or at least minimize the effects of an uncontained urban growth. The authors simply amplify that there has to be an integration of urban policies that balance growth with sustainability, this notion reinforces the need for localized climate adaptation strategies. The article mentions that uncontained urban growth creates unforeseen and foreseen challenges in the spatial and socio-economic spectrums of the Gauteng region, including Pretoria. This well supports the notion that there can be uneven climate impacts across Pretoria, especially in historically marginalized areas like Mamelodi.

Adeyemi et al. (2022) present research demonstrating a clear connection between the growth of Pretoria's urban areas and the increase in land surface temperatures. Over thirty years, as impervious surfaces like roads and buildings expanded, thermal measurements rose notably—particularly in highly developed regions such as Centurion and Mamelodi. By employing satellite imagery and GIS methods, the study verifies that built-up areas experience markedly higher temperatures, highlighting the urban heat island phenomenon. These results align with your report's findings on minimum temperature trends and emphasize the impact of land use changes on localized warming. Additionally, the authors recommend climate-aware urban planning to mitigate heat stress and foster environmental sustainability.

5. Conclusion

Climate change has led to indefinite long-term shifts in the global temperature and weather patterns. This phenomenon is the leading factor for earth's global warming state. Greenhouse gas emissions have severely increased and impacted the planet such that urban heat islands have become a by-factor. The frequency of extreme events has changed, reflecting broader climate instability. Minimum temperatures show a consistent upward trend, especially in recent years, pointing to intensified nighttime warming. These patterns suggest a growing influence from urbanization and land use changes on local climate dynamics. Effective adaptation will require targeted strategies that account for Pretoria's environmental context. Further research into microclimatic drivers is essential to guide sustainable planning and long-term resilience.

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