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National Climate Status of Madagascar: Rainfall and Temperature Trends (1950 - 2025)

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Abstract: This study presents an analysis of climate trends observed in Madagascar over the period from 1950 to 2025, focusing on nine standardized climate indices for precipitation and temperature (TX90p, TN90p, SU25, TR20, RD, R10mm, R20mm). The methodological approach is based on the recommendations of McKee et al. (1993) for calculating standardized anomalies and classifying excesses/deficits into seven classes (±0.5; ±1; ±2). The daily data are sourced from the fixed-site network of Madagascar's Directorate General of Meteorology (DGM).
The results indicate a significant warming trend across the entire territory, with an increase in positive mean temperature anomalies frequently exceeding +0.255°C per decade compared to the 1991 - 2020 normal. From a national perspective, the TX90p (hot days) heat index does not show a significant detected trend, while the TN90p (hot nights) index shows a decreasing trend of -0.062 per decade. With regard to precipitation, the results are more mixed: although the national average shows a slight but significant downward trend (-0.067 per decade), there has been an increase in interannual variability, characterized by alternating years of moderate surpluses and moderate deficits. This study thus provides an updated basis for the development of climate change adaptation policies in Madagascar.
Keywords: Climate indices, standardized anomalies, trends, Madagascar.

I. INTRODUCTION

Madagascar is recognized as one of the country's most vulnerable to climate change, despite its negligible contribution to global greenhouse gas emissions [1]. The Big Island regularly faces extreme weather events: severe droughts in the far south, devastating tropical cyclones on the east coast, and flooding in low-lying areas [2]. Understanding long-term climate trends is therefore a major challenge for food security, water resource management, and development planning [3].

Systematic analyses of Madagascar's climate date back to the work of Mark Tadross, Luc Randriamarolaza, Zo Rabefitia, and Zheng Ki Yip (2008) on climate change [4]. Since then, several studies have documented the observed trends: significant warming of minimum and maximum temperatures [5], an increase in the frequency of warm nights, and changes in rainfall patterns [6]. However, most of these studies are based on time series that cover different reference periods (Klein Tank & Können, 2003) [7]. Furthermore, the adoption of a standardized classification of anomalies, in accordance with the recommendations of the World Meteorological Organization (WMO), remains inconsistent across national reports [8].

This study aims to address these gaps by providing a unified analysis of climate trends in Madagascar for the period 1950 - 2025, using:

- A quality-controlled database derived from the national network of weather stations operated by the Directorate General of Meteorology of Madagascar (DGM);
- The standardized anomaly methodology based on the thresholds recommended by McKee et al. (1993) [9];
- A visual classification normalized using ColorBrewer palettes [8].

The originality of this study lies in the integration of nine climate indices (precipitation, temperatures, and extremes) into a single analytical framework, enabling a direct comparison with regional and international benchmarks (Spinoni et al., 2019; IOM, 2024) [10].

II. METHODS AND MATERIALS

A. Study area and data used

The study covers the entire territory of Madagascar, with an aggregated analysis at the national level. The data were obtained from the network of weather stations operated by the General Directorate of Meteorology of Madagascar, following quality control in accordance with WMO standards (Klein Tank & Können, 2003) [7] (Table 1 and Figure 1).

Table 1: Weather stations in Madagascar relevant to the analysis

STATIONS	ID WMO	LATITUDE	LONGITUDE	ELEVATION (m)
Antsiranana	67009	-12.4	49.3	105
Sambava	67023	-14.28333	50.2	5
Antalaha	67025	-15.0	50.3	6
Ambohitsilaozana	67067	-17.7	48.5	786
Toamasina	67095	-18.1	49.4	6
Farafangana	67157	-22.8	47.8	6
Taolagnaro	67197	-25.0	47.0	8
Nosy-Be	67012	-13.3	48.3	11
Antsohihy	67020	-14.9	48.0	28
Mahajanga	67027	-15.7	46.4	22
Antananarivo	67085	-18.9	47.5	1310
Ivato	67083	-18.8	47.5	1264
Besalampy	67037	-16.8	44.5	36
Antsirabe	67107	-19.9	47.1	1540
Morondava	67117	-20.3	44.3	8
Fianarantsoa	67137	-21.5	47.1	1106
Toliara	67161	-23.4	43.7	8

Source: DGM

Figure 1: Spatial distribution of weather stations

Data source: Madagascar Meteorological Directorate
Study period: 1950 to 2025
Reference period: 1991 to 2020
Number of stations: 17 synoptic stations distributed throughout the country

B. Daily variables used

Only years with at least 300 days of valid data per station were included in the annual aggregation, in accordance with the recommendations of the World Meteorological Organization [10] (Table 2).

Table 2: Daily variables used

Variable	Description	Unit
RR	Total daily precipitation	mm
TX	Daily maximum temperature	°C
TN	Daily minimum temperature	°C
TM	Daily average temperature = (TX+TN)/2	°C

1) Calculated climate indices

Nine indices were calculated from the daily time series, following the standardized definitions of the Expert Team on Climate Change (ETCCDI) [7] (Table 3):

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Table 3: Climate indices

Index	Definition	Threshold
RR_tot	Annual total precipitation	Sum of RR ≥ 1 mm
TM_avg	Annual average temperature	Average of TM
RD	Rainy days	RR ≥ 1 mm
TX90p	Hot days	TX > 90th moving percentile (5 days)
TN90p	Hot nights	TN > 90th moving percentile (5 days)
SU25	Summer days	TX > 25°C
TR20	Tropical nights	TN > 20°C
R10mm	Heavy rain days	RR ≥ 10 mm
R20mm	Very heavy rain days	RR ≥ 20 mm

Source: [7]

The calculation of moving percentiles for TX90p and TN90p uses a centered 5-day window, in accordance with the method recommended by the World Meteorological Organization. A hot day (hot night) is defined as a daily maximum (minimum) temperature exceeding the 90th percentile of the distribution of maximum (minimum) temperatures over a 5-day window (Reference Period: 1991 - 2020) [11].

2) Calculation of standardized deviations (Z-scores)

The reference period chosen for calculating the normals is 1991 to 2020, in accordance with WMO recommendations for recent climate assessments [7].

Formula for the standardized anomaly (Z-score):

The formula for the standardized anomaly is as follows [9]:

$$Z = \frac{X_i - \mu_{ref}}{\sigma_{ref}} \#(1)$$

Where:

- X_i : the annual value of the index for year i.
- μ_{ref} : the mean of the index over the reference period from 1991 to 2020.
- σ_{ref} : the standard deviation of the index over the reference period from 1991 to 2020.

For the average temperature (TM_avg), a simple (unstandardized) anomaly was calculated because interpreting it in degrees Celsius is more intuitive for decision-makers [3]:

$$Anomalie_{TM} = TM_i - TM_{ref} \#(2)$$

Where:

- TM_i : the annual average temperature for year i.
- TM_{ref} : the average of the average temperatures over the reference period from 1991 to 2020.

3) WMO 7 class classification

In accordance with the recommendations of McKee et al. (1993) and the World Meteorological Organization, the standardized anomalies were classified into seven categories [9] (Table 4):

Table 4 : WMO 7 class classification

Z-score	Classification (Rain)	Classification (Temperature)
> 2	High surplus	Very hot
]1 ; 2]	Moderate surplus	Moderately hot
]0,5 ; 1]	Low surplus	Slightly hot
[-0,5 ; 0,5]	Normal	Normal
[-1 ; -0,5[	Slight deficit	Slightly cold
[-2 ; -1[	Moderate deficit	Moderately cold
< -2	Significant deficit	Very cold

Source: [9]

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This 7-class classification has been adopted by the General Directorate of Meteorology of Madagascar (2023) and by the European Union Joint Research Centre for drought warning bulletins (UNICEF/JRC, 2024) [7], [12].

4) Standardized color palettes

To ensure immediate and universal visual interpretation, two contrasting ColorBrewer palettes were used [8]:

BrBG (Brown to Blue-Green) palette for precipitation:

- Brown for deficit/aridity
- Blue-Green for surplus/humidity

RdBu (Red to Blue) palette for temperatures:

- Red for warm/positive anomaly
- Blue for cold/negative anomaly

These palettes are implemented in the R package RColorBrewer.

5) Statistical analysis of trends

Three complementary methods were used to characterize temporal trends (Table 5):

Table 5: Statistical analysis of trends

Method	Objective
Linear regression	Estimation of the slope and the coefficient of determination R^2
Mann-Kendall test	Nonparametric trend detection
Sen's slope estimator	Robust estimation of the median slope

Significance level: $p < 0.05$

6) Software and packages used

All analyses were performed using R version 4.4.3 (R Core Team, 2022). The following packages were used:

- dplyr, tidyr, purrr: data manipulation
- lubridate: date handling
- zoo: calculation of moving percentiles
- Kendall, trend: statistical tests (Mann-Kendall, Sen's slope)
- ggplot2: visualization
- openxlsx: export of results

III. RESULTS

A. Annual Precipitation (RR_tot)

Analysis of standardized anomalies in annual precipitation over the period 1950 - 2025 reveals high interannual variability with a significant linear trend ($p = 0.0118$). The Mann-Kendall test confirms the decreasing trend (-0.067 per decade) (Figure 2).

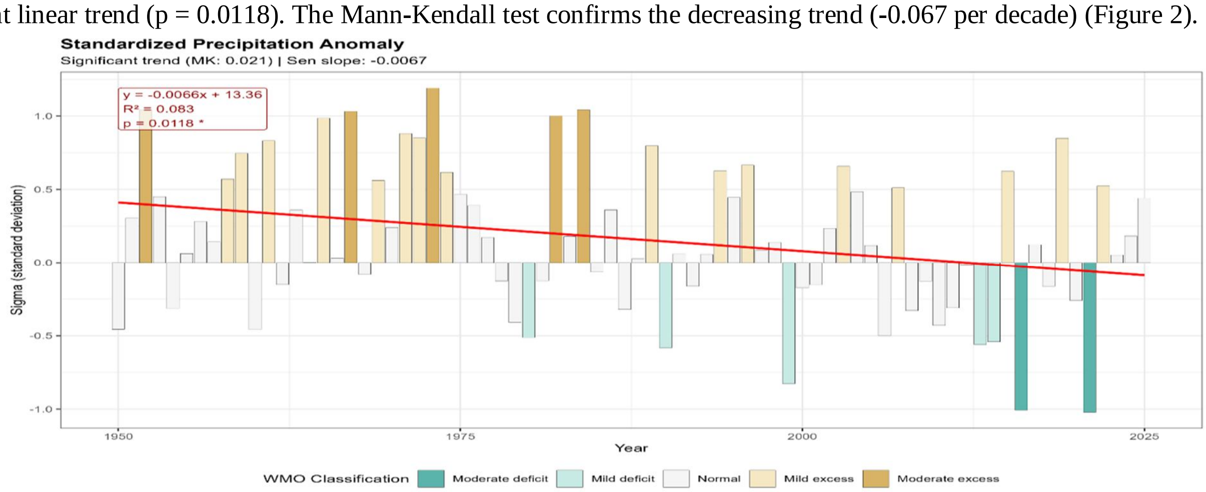

Figure 2: Standardized precipitation anomaly

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
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Volume 14 Issue V May 2026- Available at www.ijraset.com

Extreme years identified:

- Moderate surplus ($1 < Z \leq 2$): 1952, 1967, 1973, 1982, 1984
- Moderate deficits ($-2 \leq Z < -1$): 2016, 2021

The WMO 7-class classification shows that 63.2% of the years fall into the "Normal" category ($-0.5 < Z < 0.5$), consistent with the expected theoretical distribution.

B. Annual Average Temperature (TM_avg)

The annual average temperature shows a highly significant warming trend (p = 0). The Sen slope is estimated at +0.0255°C per year (+0.255°C per decade) (Figure 3).

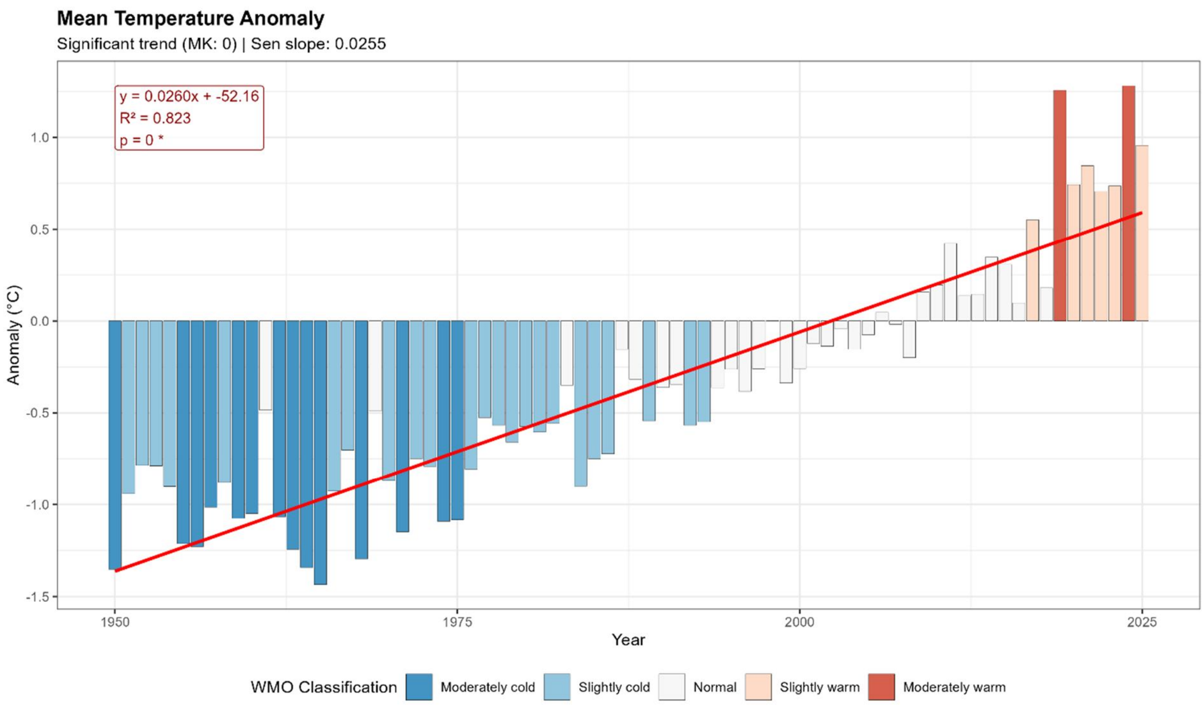

Figure 3: Mean temperature anomaly

Trends over time (Figure 3):

- 1950 - 2005: generally negative or near-zero anomalies
- 2006 - 2016: shift toward positive anomalies close to normal
- 2017 - 2025: marked acceleration, with anomalies frequently exceeding +0.5°C

The warmest years of the study period are 2019 (+1.27°C) and 2024 (+1.28°C). The year 2024 is thus the warmest year ever recorded in Madagascar since systematic measurements began.

C. Heat Indexes (TX90p and TN90p)

The index for hot days shows a downward trend that is not statistically significant, while the index for hot nights shows a statistically significant downward trend (Table 6).

Table 6: Heat Indexes (TX90p and TN90p)

Index	p-value	Sen slope per decade
TX90p (hot days)	< 0.0896	-0.024
TN90p (hot nights)	< 0.0001	-0.062

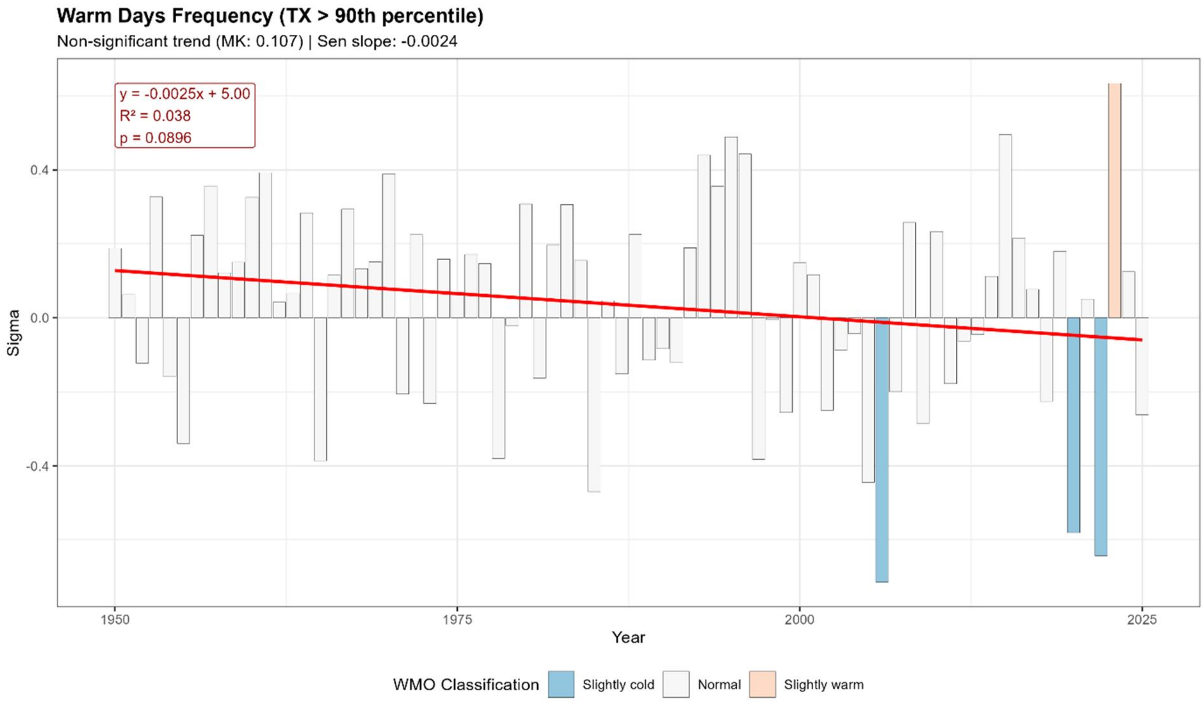

Figure 4: Warm days frequency (TX > 90th percentile)

Over the study period, only 2023 shows a slight surplus of TX90p ($0.5 < Z \leq 1$), while 2006, 2020, and 2022 show slight deficits of TX90p ($-1 \leq Z < -0.5$) (Figure 4).

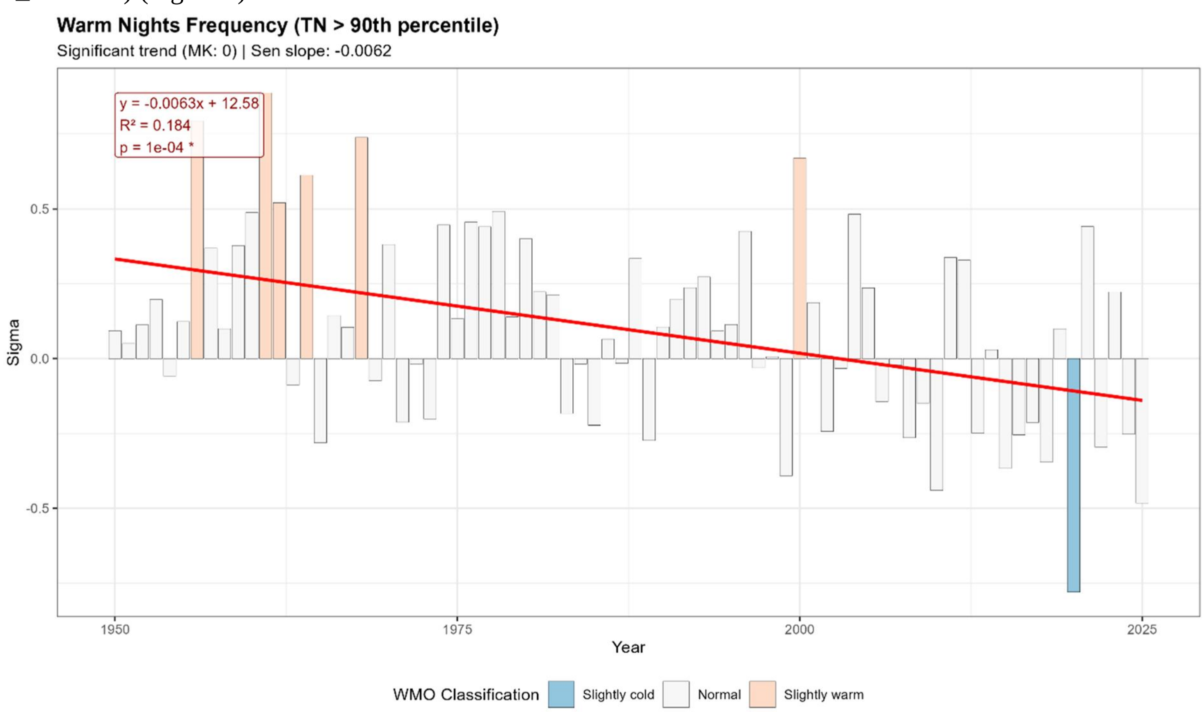

Figure 5: Warm nights frequency (TN > 90th percentile)

Over the study period, only 2020 showed a slight deficit in TX90p ($-1 \leq Z < -0.5$), while 1956, 1961, 1962, 1964, 1968, and 2000 showed slight surpluses in TX90p ($0.5 < Z \leq 1$) (Figure 5).

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D. Temperature Thresholds (SU25 and TR20)

The SU25 (summer days, TX > 25°C) and TR20 (tropical nights, TN > 20°C) indices confirm the overall warming trend (Table 7):

Table 7 : Temperature Thresholds (SU25 and TR20)

Index	Sen slope per decade	p-value		Record year
SU25	+0.355	0		2024 (Z = +1.286)
TR20	+0.369	0		2019 (Z = +1.697)

A faster increase in tropical nights (TR20) compared to summer days (SU25) is characteristic of asymmetric warming, in which minimum temperatures rise faster than maximum temperatures.

The year 2019 saw the highest number of tropical nights ever recorded in Madagascar (TR20) (Figure 6).

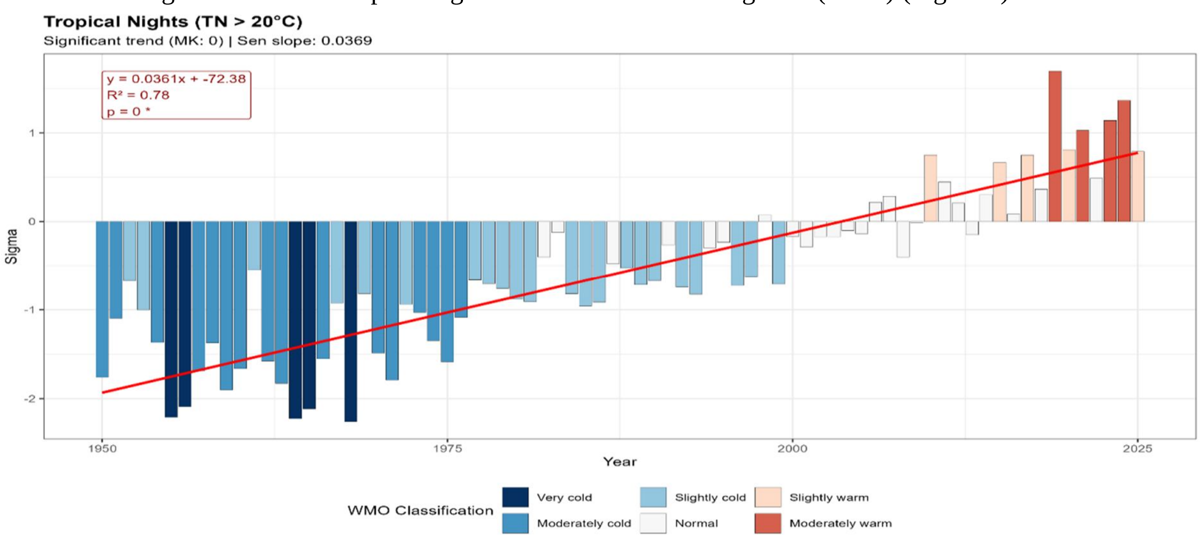

Figure 6: Tropical nights (TN > 20 °C)

The year 2024 saw the highest number of summer days ever recorded in Madagascar (SU25) (Figure 7).

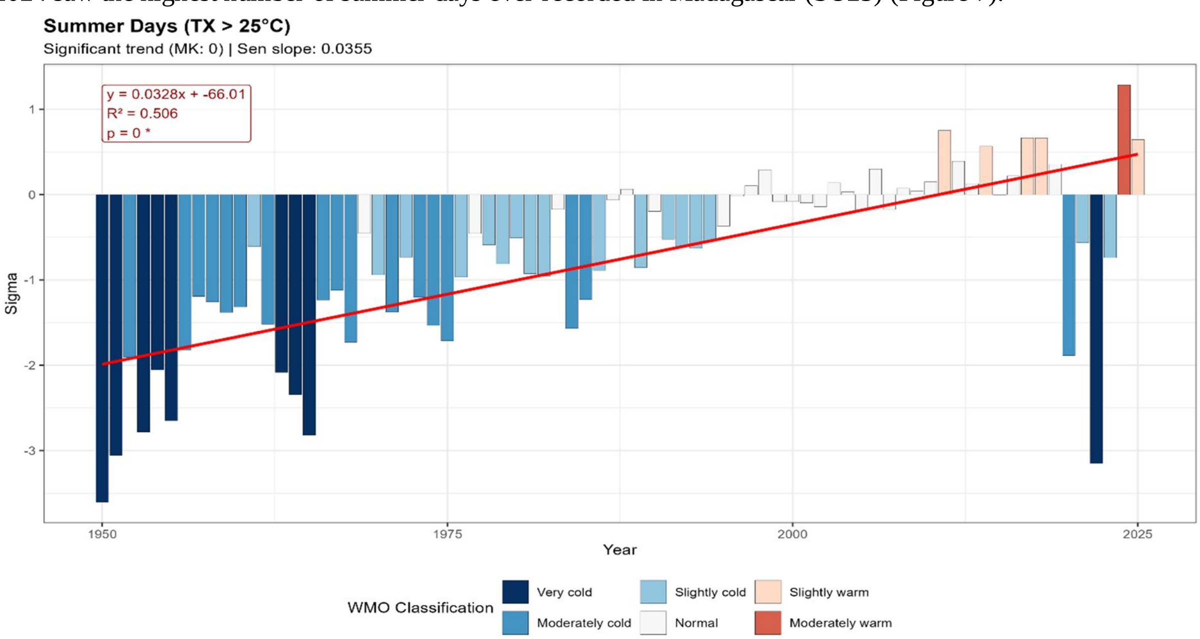

Figure 7: Summer days (TX > 25 °C)

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
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Volume 14 Issue V May 2026- Available at www.ijraset.com

E. Extreme Precipitation Indices (RD, R10mm, R20mm)

Trends in extreme precipitation indices vary depending on the index in question (Table 8).

Table 8 : Extreme precipitation indices (RD, R10mm, R20mm)

Index	Sen's slope per decade	Significance of the Mann-Kendall test
RD (days with rainfall ≥ 1 mm	-0.145	Significant trend
R10mm (days with rainfall ≥ 10 mm)	-0.093	Significant trend
R20mm (days with rainfall ≥ 20 mm)	-0.1061	Significant trend

The number of rainy days, days with heavy rain, and days with very heavy rain varies greatly.

Years with extreme numbers of rainy days (Figure 8):

- 1951, 1952, 1958, 1965, 1967, 1971, 1973, 1974, 1982, 1984, and 1989 were years with a moderate surplus.
- 2020 and 2021 were years with a moderate deficit.

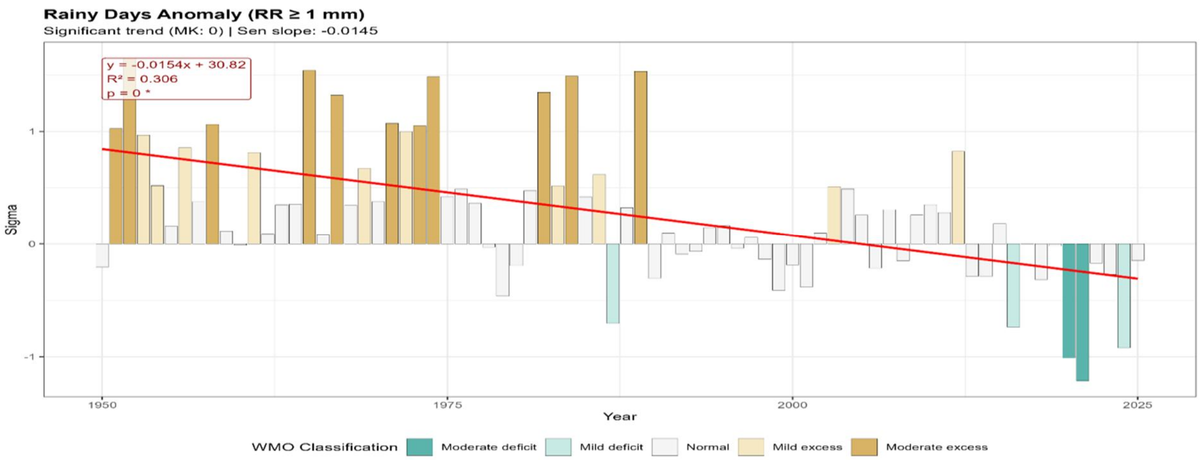

Figure 8: Rainy days anomaly (RR ≥ 1 mm)

Years identified as having extreme amounts of heavy rainfall (Figure 9):

- 1952, 1961, 1965, 1967, 1972, 1982, 1984, and 1989 were years with moderate surpluses.
- 1990, 1999, 2016, and 2021 are years with a slight deficit.

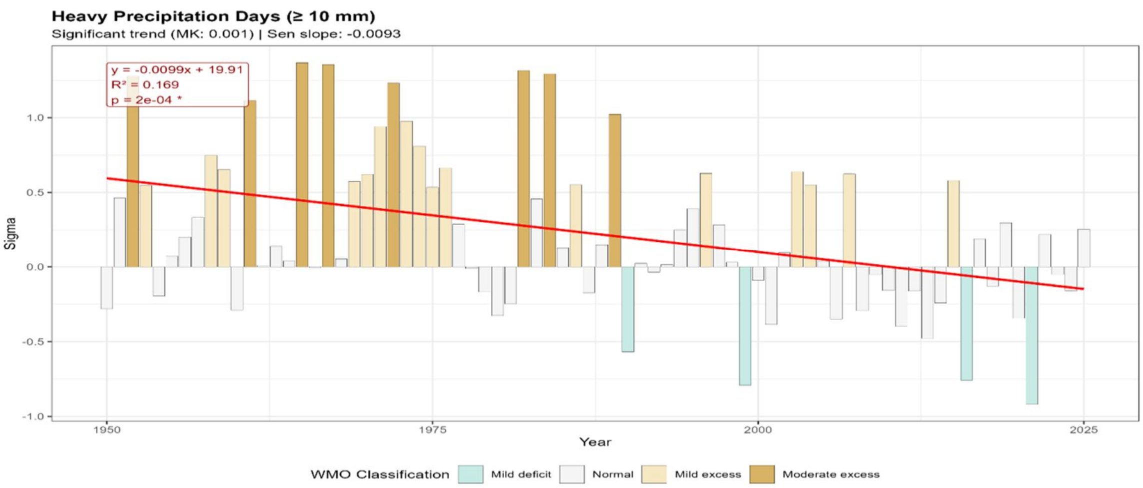

Figure 9: Heavy precipitation days (≥ 10 mm)

The years identified as having extreme levels of very heavy rainfall (Figure 10):

- 1967, 1973, 1974, and 1982 were years with a moderate surplus.
- 2010, 2013, 2016, and 2021 were years with a slight deficit.

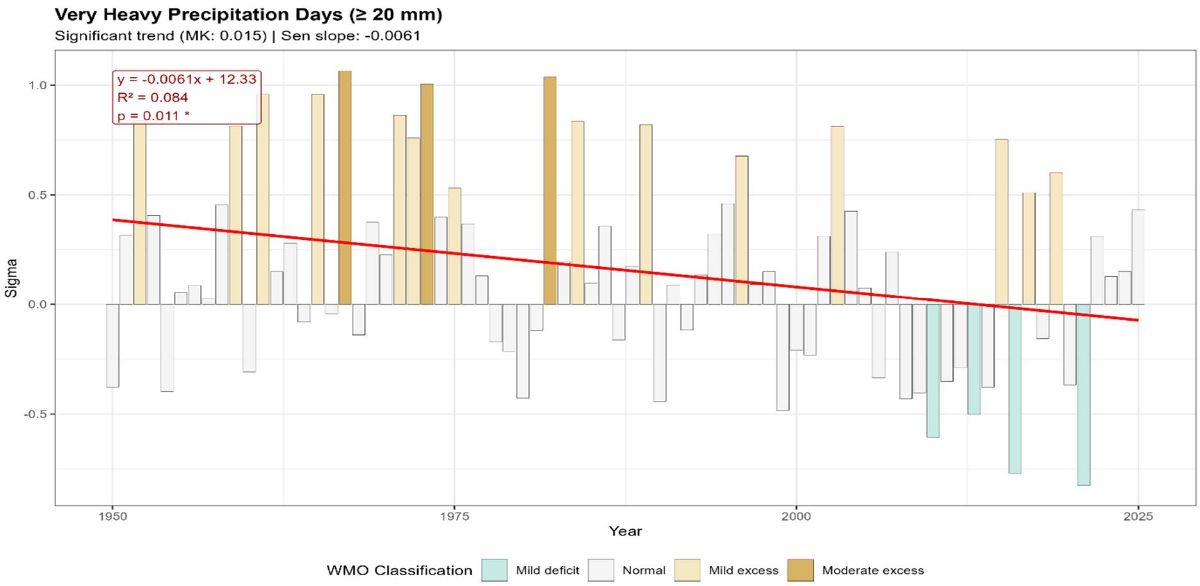

Figure 10: Very heavy precipitation day (≥ 20 mm)

IV. DISCUSSION

A. *Consistency with national standards*

Our findings regarding the significant warming trend (p = 0), which is +0.255°C per decade, are fully consistent with the work of Randriamarolaza (2020), who documented an increase of +0.23°C per decade in the average temperature in Madagascar over the period from 1950 to 2018 [5]. This finding confirms the robustness of our methodology and the quality of the time series. Furthermore, the World Bank (2024) reports that Madagascar is warming faster than the global average (+0.24°C per decade compared to +0.18°C per decade for the globe) [3]. Our estimate (+0.255°C per decade) confirms this assessment and highlights the particular vulnerability of Madagascar.

Regarding the asymmetry of warming (TR20 is increasing faster than SU25), our results confirm the analyses by Randriamarolaza (2023), who attributes this phenomenon to increased cloud cover and atmospheric humidity, which trap more heat at night [6].

An analysis of standardized anomalies in annual precipitation over the period 1950–2025 reveals high interannual variability with a decreasing trend (–0.067 per decade).

The significant trend in R20mm (+0.11 per decade, p = 0.011) suggests an intensification of extreme precipitation, a signal expected as a result of warming (Spinoni et al., 2019) [10].

With regard to extreme precipitation, our results (R20mm showing a very slight but significant decrease) are not really consistent with the projections by Spinoni et al. (2019) for Southern Africa and the southwestern Indian Ocean [10]. These authors predict a 10% to 20% increase in the intensity of extreme precipitation by 2050, with major consequences for flood and erosion risks [10].

The significant decrease in the total number of rainy days (-0.145 per decade), combined with an increase in evapotranspiration due to warming, could reduce groundwater recharge, exacerbating water stress during the dry season.

B. *Methodological discrepancies and limitations*

Although generally consistent, our results show some discrepancies with certain references:

1) Different reference period: Randriamarolaza (2020) uses the period 1981–2010 as the baseline, whereas we have adopted 1991–2020 (WMO recommendation) [5]. This difference slightly affects the values of the standardized anomalies, but not the significance of the trends (McKee et al., 1993) [9].
2) Classification thresholds: Some studies (Spinoni et al., 2019) use a 9-class classification (with thresholds at ±0.5, ±1, ±1.5, and ±2) to achieve greater granularity [10]. Our choice of a 7-class classification (McKee et al., 1993) prioritizes ease of interpretation for decision-makers, at the expense of greater analytical precision [9].

3) Density of the stationary network: The Madagascar Directorate General of Meteorology (2023) notes that certain regions (particularly the southwest) are undersampled, which may introduce biases in the national aggregate [7]. The use of satellite data (UNICEF/JRC, 2024) could complement our analysis in future versions [12].

V. CONCLUSION

This study analyzed precipitation and temperature trends in Madagascar for the period 1950 - 2025, using a standardized methodology in accordance with WMO recommendations (McKee et al., 1993; Klein Tank & Können, 2003) [7], [9].

The main findings are as follows:

- Significant warming: the annual average temperature is rising by +0.255°C per decade ($p = 0$), a rate higher than the global average (World Bank, 2024) [3]. The years 2019 and 2024 were the warmest on record.
- Asymmetry in warming: Tropical nights (TR20) are increasing more rapidly (+0.369 per decade) than summer days (SU25, +0.355 per decade).
- Intensification of extreme precipitation: Annual precipitation shows a slight but significant decrease (0.067 per decade), while the number of days with very heavy rain (R20mm) is decreasing very slightly (-0.061 per decade).

These findings provide a scientific basis for the development of climate change adaptation policies in Madagascar (National Adaptation Plan, Nationally Determined Contribution). Future work should include:

- A spatial analysis at the regional level (South, East, Central, West, North) to identify the most vulnerable areas (IOM, 2024) [13].
- The integration of satellite data to improve spatial coverage in undersampled regions (UNICEF/JRC, 2024) [12].
- Projections for 2050 and 2100 based on CMIP6 models [6].
- An attribution analysis to distinguish anthropogenic forcings from natural variability [6].

VI. ACKNOWLEDGMENTS

We would like to thank the General Directorate of Meteorology of Madagascar for providing access to station data.

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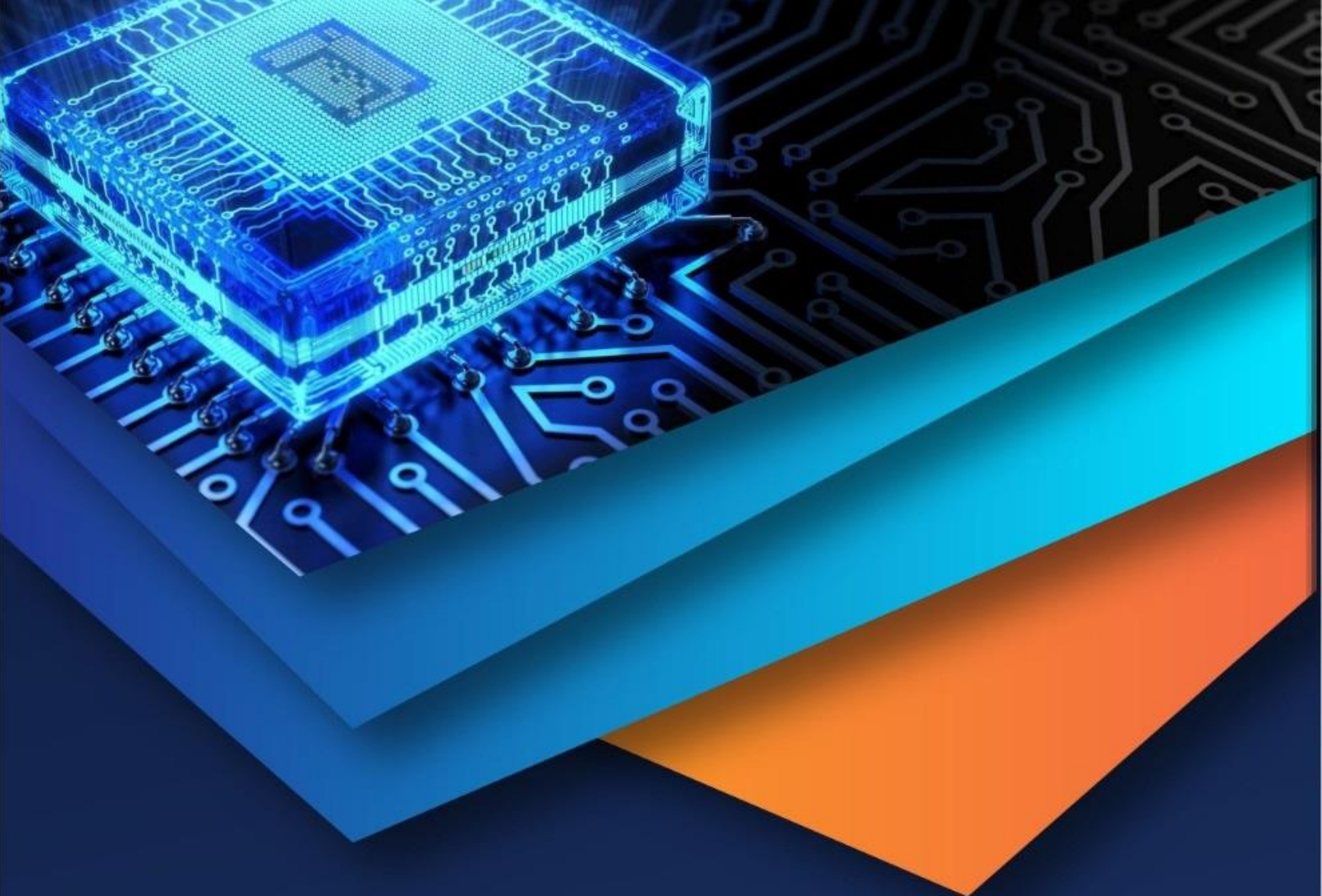

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