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Inżynieria i Analiza Danych

Climat Change in Madagascar (1984–2024): A 40-Year Assessment of Thermodynamic and Hydrological Trends

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1. INTRODUCTION

Madagascar's tropical rainforest is highly sensitive to climate variability, including changes in temperature, rainfall patterns, and extreme weather events. Understanding these changes is essential for assessing ecosystem health, anticipating hydrological risks, and guiding conservation and adaptation strategies. This report investigates long-term climate trends and variability in the region to provide insights into potential environmental impacts.

2. METHODOLOGY, STUDY AREA AND DATA

This analysis is based on climate and land-surface data obtained from the ERA5 hourly data on single levels reanalysis dataset (1940–present) provided by the European Centre for Medium-Range Weather Forecasts (ECMWF).
The analysis covers the period 1984–2024, allowing for the assessment of long-term climatic variability and trends over a 40-year timescale. The study area is located in Madagascar, and the data were initially extracted for a regular latitude–longitude grid spanning approximately -15.0°S to -16.5°S latitude and 49.5°E to 50.5°E longitude. This region captures a portion of the tropical rainforest ecosystem in Madagascar.
The variables used in the analysis include: 10 m u-component of wind, 10 m v-component of wind, 2 m air temperature, total precipitation, skin temperature, surface solar radiation downward, total cloud cover, evaporation, runoff, soil temperature at level 1, volumetric soil water content at layer 1, volumetric soil water content at layer 2, leaf area index of high vegetation, and leaf area index of low vegetation.
For each day, values were extracted at 00:00 and 12:00 UTC, after which spatial aggregation was performed. Specifically, all grid-point values within the selected domain were aggregated to a single central representative point (approximately -15.75°S, 50.0°E) using spatial averaging.

3. RESEARCH QUESTIONS

3.1 Is there a statistically significant upward trend in 2 m air temperature and skin temperature over the period 1984–2024?

3.2 Is the minimum night-time temperature (derived from 00:00 UTC data) increasing at a faster rate than the daytime maximum temperature (derived from 12:00 UTC data), indicating asymmetric warming?

3.3 How have the number of consecutive dry days (CDD) and the rainfall-to-evaporation ratio changed over time? Do these changes, along with the regional water balance indicate a progressive shift toward drier conditions under increasing global temperatures?

3.4 How does skin temperature effects on 10 m peak wind speeds during the January–March Cyclone seasonn?

3.5 How do variations in the intensity of the rain, as well as water and light availability, influence vegetation health and high-canopy forest growth, as measured by the Leaf Area Index (LAI)?

4. STATISTICAL ANALYSIS AND VISUALIZATION

4.1 Analysis of trends, sesonality and asymmetrics in Madagascar temperature

Madagascar's tropical climate is characterized by a hot, wet season from November to April and a cooler, dry season from May to October.

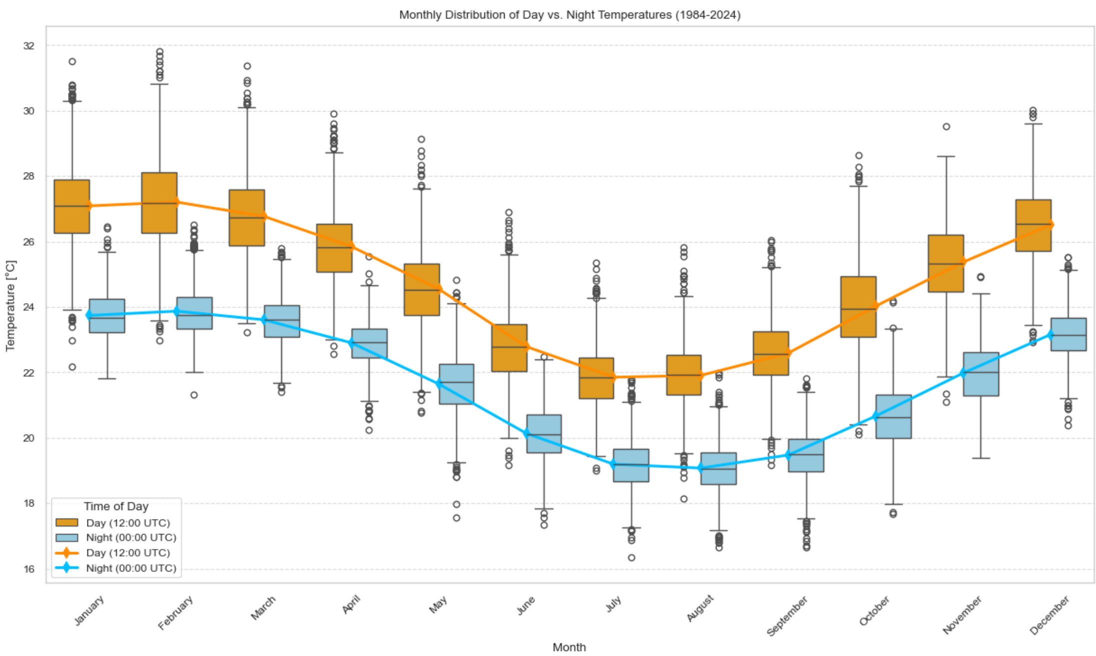

Fig 1. Monthly distribution of daytime (12:00 UTC) and nighttime (00:00 UTC) 2-m air temperatures in Madagascar (1984–2024).

The monthly distribution of 2-m air temperatures reveals high variability in daytime temperatures, with frequent outliers during transitional months such as May and June, indicating increased thermal instability and intensification of maximum temperature extremes. Nighttime temperatures exhibit fewer outliers but still show sporadic deviations, reflecting occasional extreme minimum events (Fig. 1). Analysis of monthly mean temperatures demonstrates a progressive warming trend from 1984 to 2024, particularly during the cooler season (July–August), when average temperatures increased from below 20 °C in the early period to approximately 21.5 °C by 2024 (Fig. 2).

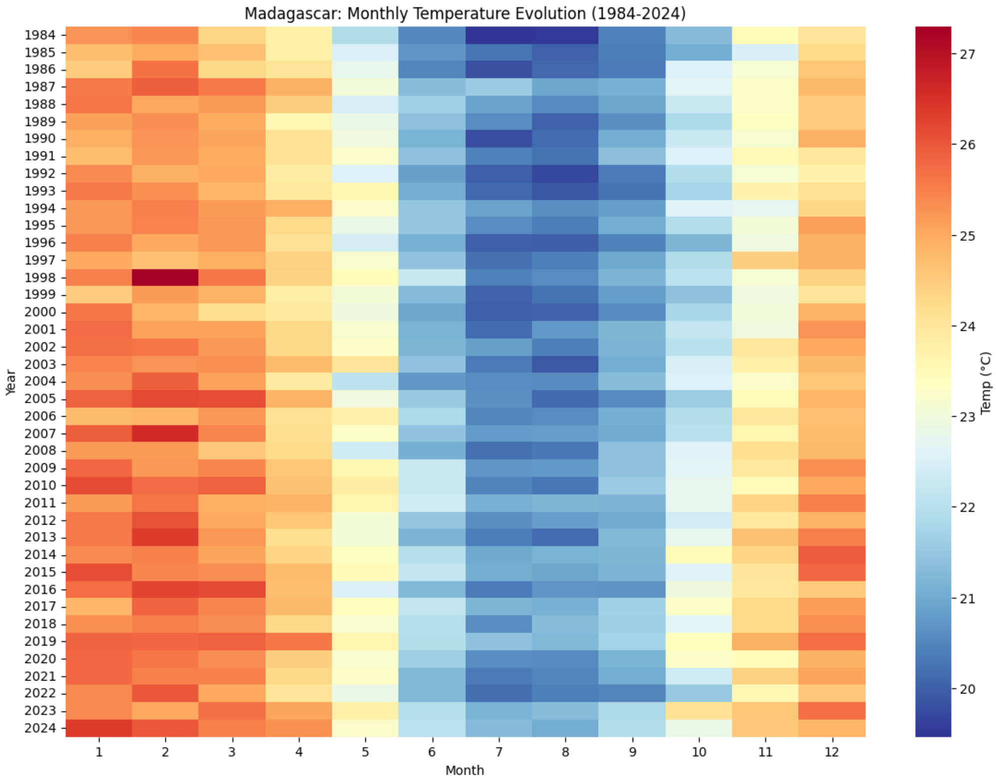

Fig 2. Monthly mean 2-m air temperature evolution in Madagascar (1984–2024).

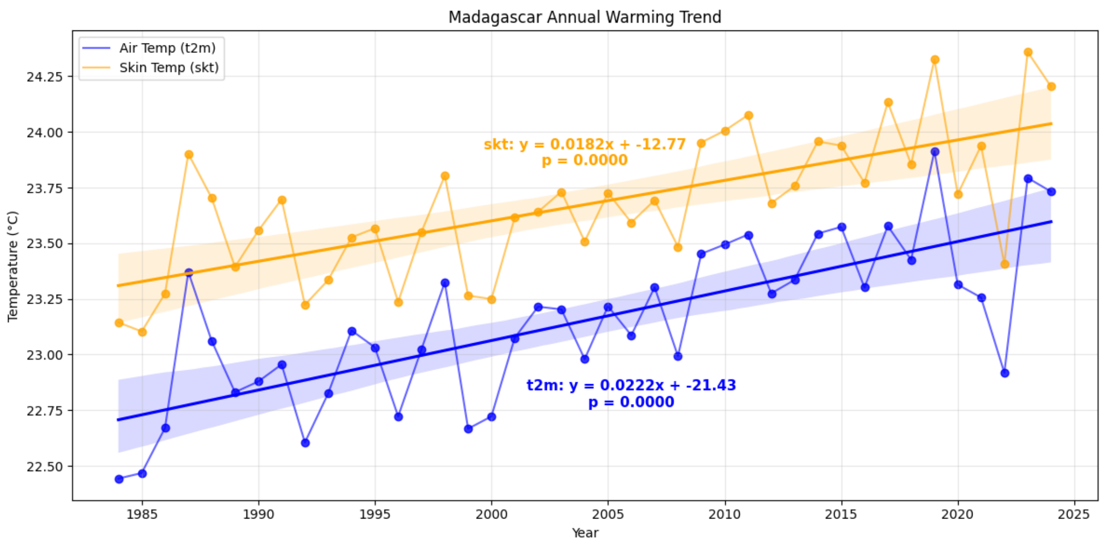

Fig 3. Annual warming trends for 2-m air temperature and skin temperature in Madagascar (1984–2024).

Linear regression confirms statistically significant positive trends for both variables. Skin temperature follows $y = 0.0182x - 12.77$ with a p-value of 0.0000, while the trend of 2-m air temperature follows $y = 0.0222x - 21.43$ with a p-value of 0.000. The 2-m air temperature has increased by approximately 1.29 °C over the 40-year period. Skin temperature remains consistently higher than 2-m air temperature, although the difference diminishes toward the end of the record (Fig. 3). These results demonstrate a highly significant long-term warming trend.

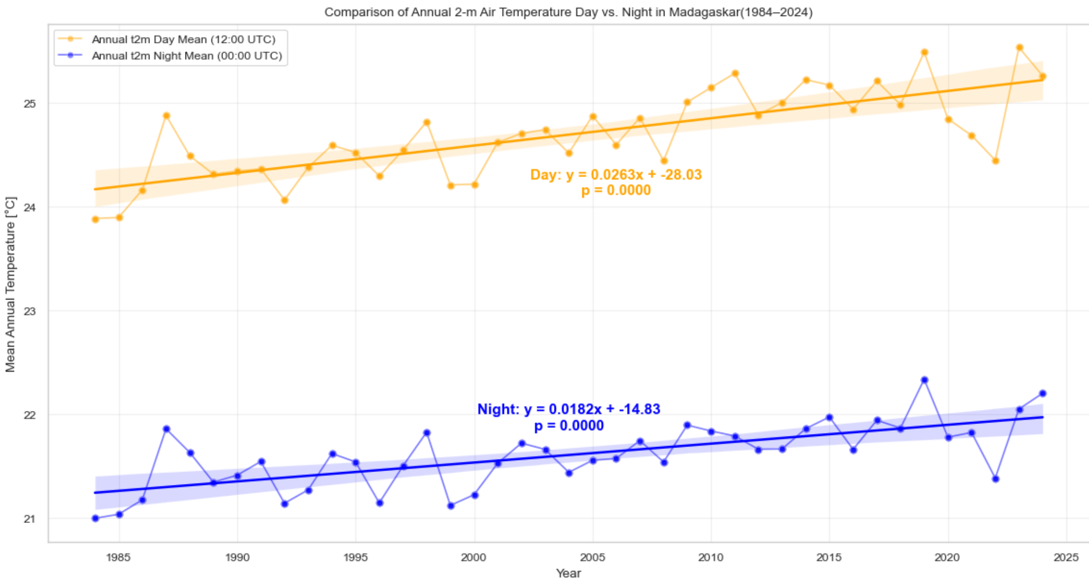

Fig 4. Annual warming trends for day and night 2-m air temperature in Madagascar (1984–2024).

Evaluation of asymmetric warming shows statistically significant increases in both daytime (0.0263 °C/ year) and nighttime (0.0182 °C/ year) temperatures. Contrary to the expectation of faster nighttime warming, daytime temperatures have increased slightly more, indicating largely symmetrical warming across the diel cycle. These results suggest that thermal intensification in the Madagascar rainforest affects both day and night temperatures without reducing diurnal temperature ranges. (Fig 4.)

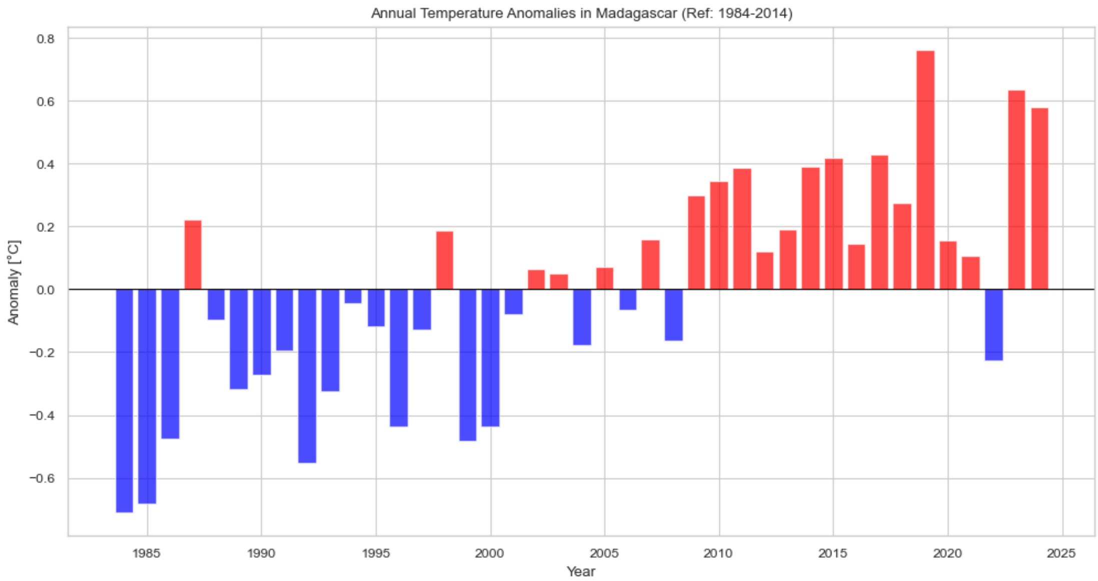

Fig 5. Annual temperature anomalies in Madagascar in years 1984 – 2024.

The bar plot (Fig 5) shows annual temperature anomalies relative to the 1984–2014 reference period. A clear long-term warming trend is evident, documenting a marked climatic shift in the region. The first two decades (1984–2003) are dominated by negative anomalies with the coldest year occurring in 1984 (approximately –0.7 °C). From 2003 onward, negative anomalies become increasingly rare, and since 2009 nearly all years exhibit temperatures above the long-term mean. Key deviations include 2019, which stands out as the warmest year in the record (approximately +0.76 °C), and 2022, a cooler outlier in the last decade (approximately –0.2 °C).

4.2 Hydroclimate trends in the Madagascar rainforest

The Madagascar rainforest is characterized by a predominantly wet climate, reflected in a generally positive annual rainfall-to-evaporation (P/E) ratio ranging from approximately 1.3 to 2.1 (Fig. 6b).

Fig 6. Hydrological variability in the Madagascar rainforest (1984–2024) (a) Consecutive Dry Days, (b) annual rainfall-to-evaporation ratio, (c) total perception

Despite rising temperatures, the analyzed hydrological indicators show no statistically significant long-term trends. Consecutive Dry Days (CDD), which measure the length of continuous dry periods, display strong interannual variability but no consistent pattern (Fig. 6a). The period from 2002 to 2012 is characterized by fewer dry days and a higher annual water balance, with 2013 standing out for exceptionally low total precipitation and the highest CDD in four decades. This interval (2002–2008) also corresponds to a transition in temperature anomalies, during which values approached the four-decade mean before increasing again (Fig. 5). Correlation analysis (Fig. 7) further indicates no significant relationship between total precipitation and 2-m air temperature, suggesting that recent warming has not resulted in systematic changes in rainfall over the study period.

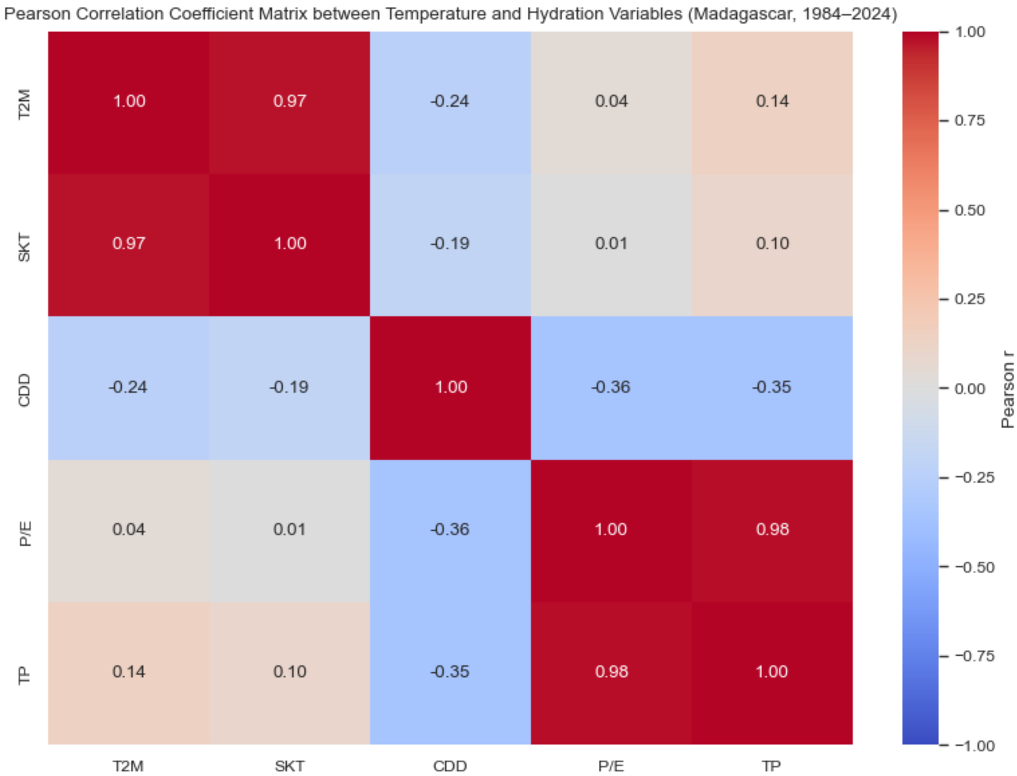

Fig 7. Pearson Correlation Coefficient Matrix between Temperature and Hydration Variables (Madagascar, 1984–2024)

4.3 Wind Analysis During the Cyclone Season

The cyclone season in Madagascar occurs from January through March. Fig 8. shows the maximum wind speeds recorded during this period. Between approximately 2002 and 2008, several seasons exhibited below-average peak winds, followed by years with exceptionally strong events. In 2018, the highest cyclone-season wind speeds were observed, coinciding with the year's largest total precipitation (Fig. 6c), suggesting that intense cyclones may contribute to flooding.

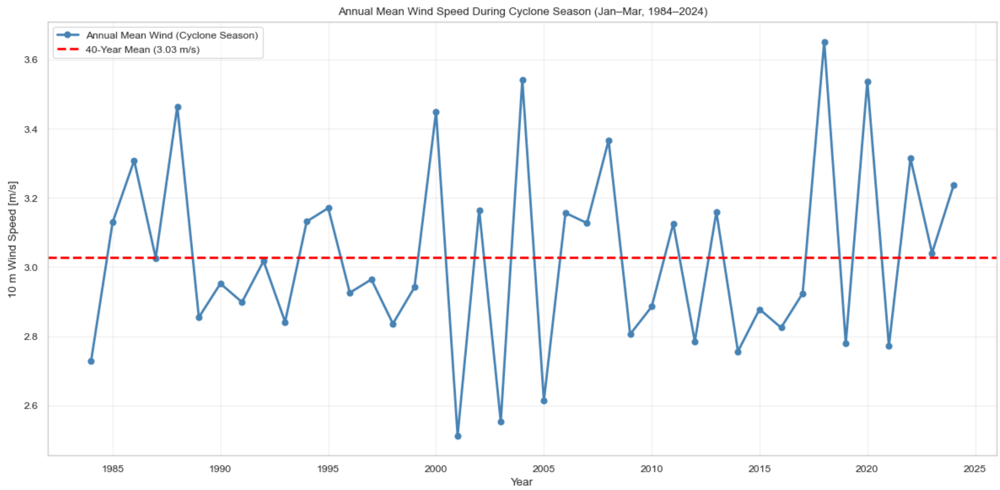

Fig 8. Maximum 10 m wind speeds recorded during the cyclone season (January–March) in Madagascar from 1984 to 2024.

However, Pearson correlation analysis (Fig. 9) does not indicate a statistically significant relationship between wind speed, total precipitation (Fig. 6c), and temperature during the cyclone season.

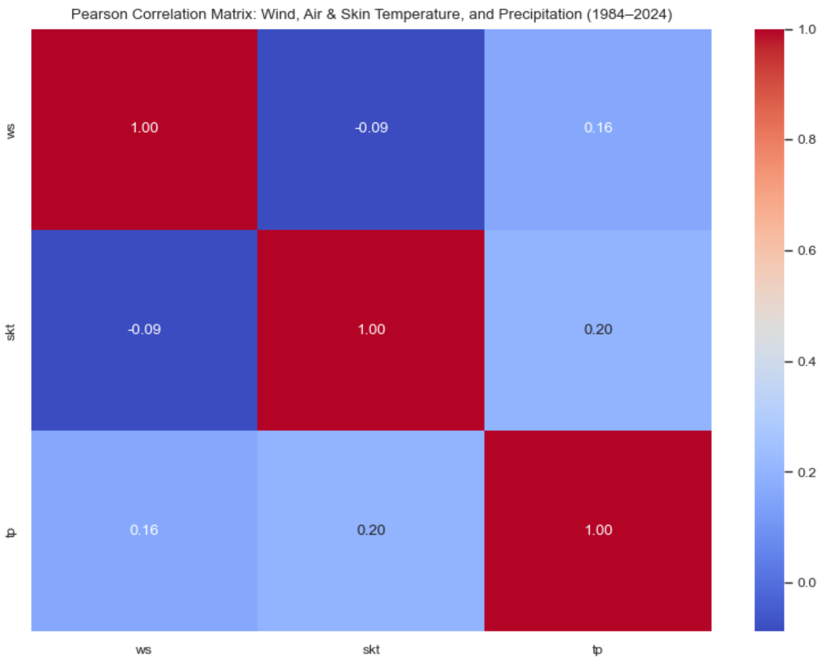

Fig 9. Pearson Correlation Coefficient Matrix between Wind Speed, 2-m air Temperature and Total Perception (Madagascar, 1984–2024)

4.4 Vegetation Response to Rainy Season Dynamics and Resource Availability

Madagascar's rainforest, with a dense and uniform canopy of narrowly ranged tall trees, exhibited minimal variation in high-canopy LAI, which ranged between approximately 3.015 and 3.035, reflecting a resilient canopy or consistently high biomass. No clear linear relationship was observed with total rainfall (110–200 mm) (Fig 10a), and top-layer soil moisture (0.258–0.266 $m^3\,m^{-3}$; Fig. 10b) showed only slight central clustering without a trend toward higher LAI. Surface solar radiation displayed the greatest scatter, with slightly lower LAI under extremely high values (>1.0 $W\,m^{-2}$; Fig. 10c), potentially due to photoinhibitory stress or increased transpiration, though this effect was weak and not statistically significant.

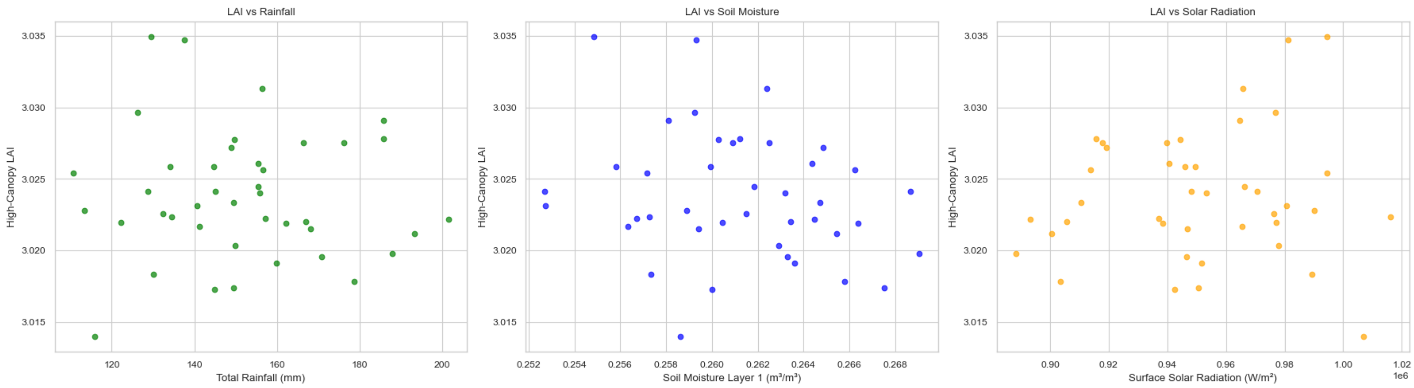

Fig. 10. High-canopy LAI in the Madagascar rainforest (1984–2024)
(a) LAI vs Total Rainfall, (b) LAI vs Soil Moisture (Layer 1), (c) LAI vs Surface Solar Radiation

5. SUMMARY

Madagascar's rainforest has experienced significant warming from 1984 to 2024, with both daytime and nighttime temperatures increasing steadily. Hydroclimatic variables, including precipitation, soil moisture, and consecutive dry days, show strong interannual variability but no clear long-term trends, indicating no shift toward drier conditions. Peak cyclone-season winds fluctuate between years but are not consistently linked to temperature or rainfall extremes. High-canopy LAI remains stable, responding only slightly to water availability and showing limited sensitivity to solar radiation, highlighting the resilience of the rainforest canopy to seasonal climatic variability.

6. POTENTIAL TARGETS FOR ML MODELS

The insights gained from exploratory data analysis indicate that machine learning techniques can be effectively applied to predict future climatic and ecological changes in the Madagascar rainforest. Potential targets for such models include high-canopy Leaf Area Index (LAI) as a proxy for vegetation health, 2 m air temperature and skin temperature to capture warming trends, and hydroclimatic indicators such as seasonal precipitation totals, rainfall-to-evaporation ratios, and consecutive dry days. ML approaches such as time series forecasting models like ARIMA can be used to project temperature or precipitation trends, while regression-based models (Random Forest or Gradient Boosting) can quantify the influence of water and light availability on LAI. Additionally, classification models could be employed to anticipate extreme events, such as high wind speeds during the cyclone season. By leveraging the patterns of interannual and seasonal variability revealed through analysis.

7. LITERATURE

https://www.ircwash.org/sites/default/files/Heath-2010-Madagascar.pdf

https://climateknowledgeportal.worldbank.org/country/madagascar/climate-data-historical

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