



Long-Term Climate Variability and Environmental Health Implications in Palembang, Indonesia (1992–2025)



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Abstract: This study provides a comprehensive assessment of long-term climate variability in Palembang, Indonesia, over the period 1992–2025, with particular emphasis on temperature-driven heat exposure and associated environmental health risks. Monthly observational data obtained from the Meteorology, Climatology, and Geophysics Agency (Badan Meteorologi, Klimatologi, dan Geofisika, BMKG) were analyzed to evaluate trends in air temperature, relative humidity, precipitation, and wind speed. Linear regression and anomaly-based approaches were applied to quantify temporal changes relative to a 1992–2025 climatological baseline. The results reveal a pronounced and sustained warming trend, with mean air temperature increasing by approximately 1.3–1.5 °C and peak anomalies exceeding +2.0 °C in recent years. The frequency of extreme heat months (≥ 90 th percentile) has increased substantially since 2010. In contrast, relative humidity remains persistently high ($\geq 80\%$) with limited long-term variation, while rainfall and wind speed exhibit strong interannual variability associated with El Niño–Southern Oscillation (ENSO) dynamics. These findings indicate intensifying thermal stress and increasing environmental health risks, underscoring the need for integrated climate–health adaptation strategies, including early warning systems and urban resilience planning in rapidly urbanizing tropical regions.

Keywords: Climate variability; Palembang; Indonesia; Temperature; Humidity; Rainfall; Environmental health; Adaptation

1 Introduction

Climate variability in tropical regions is strongly influenced by large-scale climate systems, particularly the El Niño–Southern Oscillation (ENSO), which plays a critical role in modulating temperature, precipitation, and atmospheric conditions across Southeast Asia. El Niño and La Niña events represent key drivers of interannual climate variability, influencing heat exposure, rainfall intensity, and hydrometeorological extremes in Indonesia.

In Palembang, a rapidly urbanizing tropical city, these climatic fluctuations contribute to dynamic environmental conditions that may significantly affect public health. Elevated temperatures, persistent humidity, and variable rainfall patterns can intensify thermal discomfort, exacerbate environmental stress, and influence disease transmission pathways.

Long-term observational datasets are essential for identifying climate trends and understanding their implications. Previous studies have demonstrated that increasing temperatures and the growing frequency of extreme events amplify heat-related health risks, while ENSO-driven rainfall variability affects water availability and vector-borne disease dynamics.

This study aims to evaluate long-term climate variability in Palembang during 1992–2025, with a particular focus on trends associated with El Niño and La Niña events. Using monthly meteorological data from (Badan Meteorologi,

Klimatologi, dan Geofisika, BMKG), this research provides insights to support climate adaptation and evidence-based public health planning in tropical urban environments.

2 Methodology

2.1 Study Area

Palembang (2.99° S, 104.76° E) has a tropical rainforest climate with consistently high temperatures and humidity. Rapid urban expansion, low wind movement, and limited green spaces contribute to elevated urban heat exposure.

2.2 Data Sources

This study uses monthly meteorological data from BMKG Kenten Station in Palembang for 1992–2025, including minimum, mean, and maximum air temperature, relative humidity, rainfall, and wind speed.

2.3 Analytical Methods

Linear regression analysis was employed to quantify long-term trends in temperature, relative humidity, precipitation, and wind speed. Monthly anomalies were calculated relative to a 1992–2025 climatological baseline using the equation:

$$\text{Anomaly} = X_{\text{monthly}} - X_{\text{baseline}}$$

where, X_{monthly} represents observed monthly values and X_{baseline} denotes the corresponding long-term monthly mean. This approach removes seasonal variability and highlights interannual fluctuations.

Extreme climate conditions were defined using threshold-based criteria: extreme heat (≥ 90 th percentile of monthly mean temperature), high humidity ($\geq 80\%$), heavy rainfall (> 300 mm per month), and high wind speed (≥ 4 knots). These thresholds enable consistent identification and comparison of extreme events over time and facilitate the assessment of climate variability associated with ENSO dynamics.

3 Results

3.1 Temporal Variability of Climatic Parameters in Palembang (1992–2025)

Figure 1 illustrates the temporal variability of key climatic variables in Palembang during 1992–2025. Air temperature shows a clear increasing trend, particularly after 2010, with peak values observed in recent years, indicating a consistent warming signal. In contrast, relative humidity remains relatively stable, with only minor interannual fluctuations.

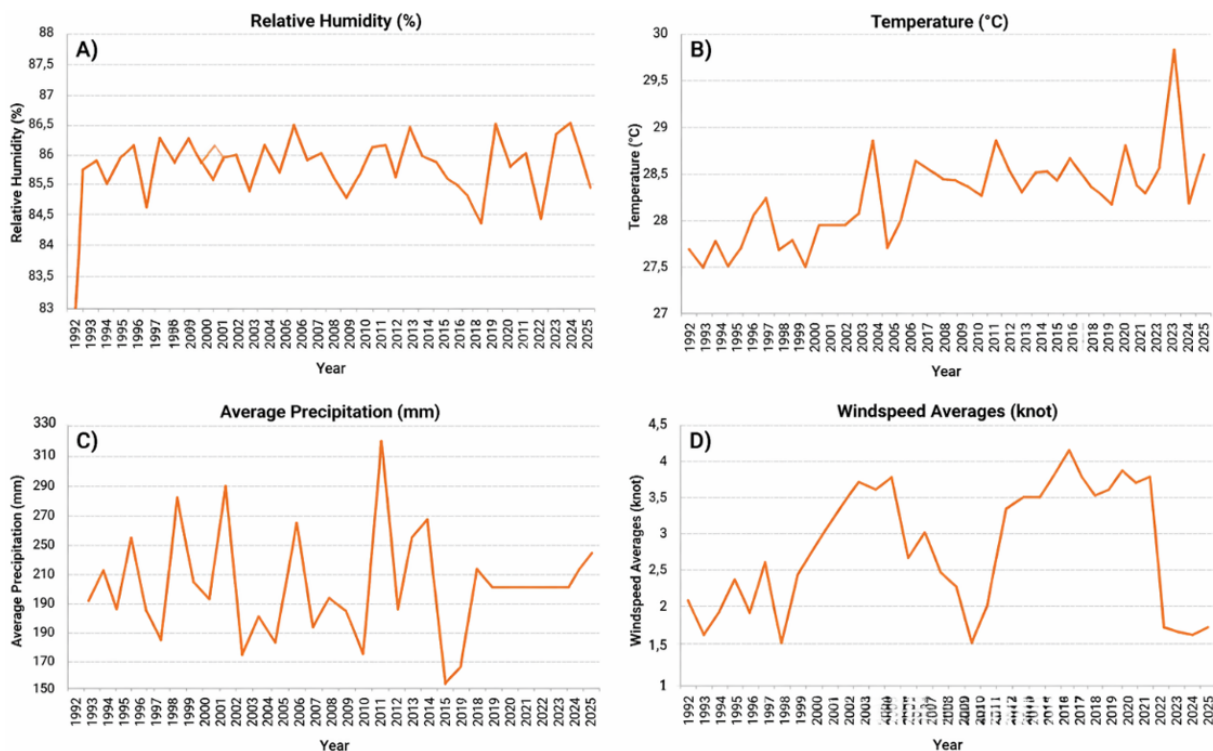


Figure 1. Temporal variability of key climatic variables in Palembang City (1992–2025)

Precipitation exhibits high variability without a clear long-term trend, reflecting the influence of large-scale climate variability such as ENSO. Periods of reduced rainfall are evident in several years, suggesting potential drought-related conditions. Wind speed shows moderate variability, with an increasing tendency during the early 2000s followed by stabilization in recent years. Overall, the results indicate that temperature is the dominant changing variable, while other climatic parameters demonstrate variability primarily driven by interannual climate oscillations.

3.2 Monthly Anomalies of Key Climatic Variables in Palembang (1992–2025)

Figure 2 presents the temporal patterns of monthly anomalies in key climatic variables in Palembang from 1992 to 2025, including temperature, relative humidity, precipitation, and wind speed. A clear transition from predominantly negative to positive anomalies is evident, particularly for temperature, indicating a sustained warming trend. In contrast, precipitation, humidity, and wind speed exhibit considerable interannual variability without a consistent directional trend. The increasing occurrence of positive anomalies in recent years suggests intensified climate variability, potentially associated with ENSO dynamics. These findings indicate that temperature is the most responsive variable, while other climatic factors remain highly variable but less systematically changing.

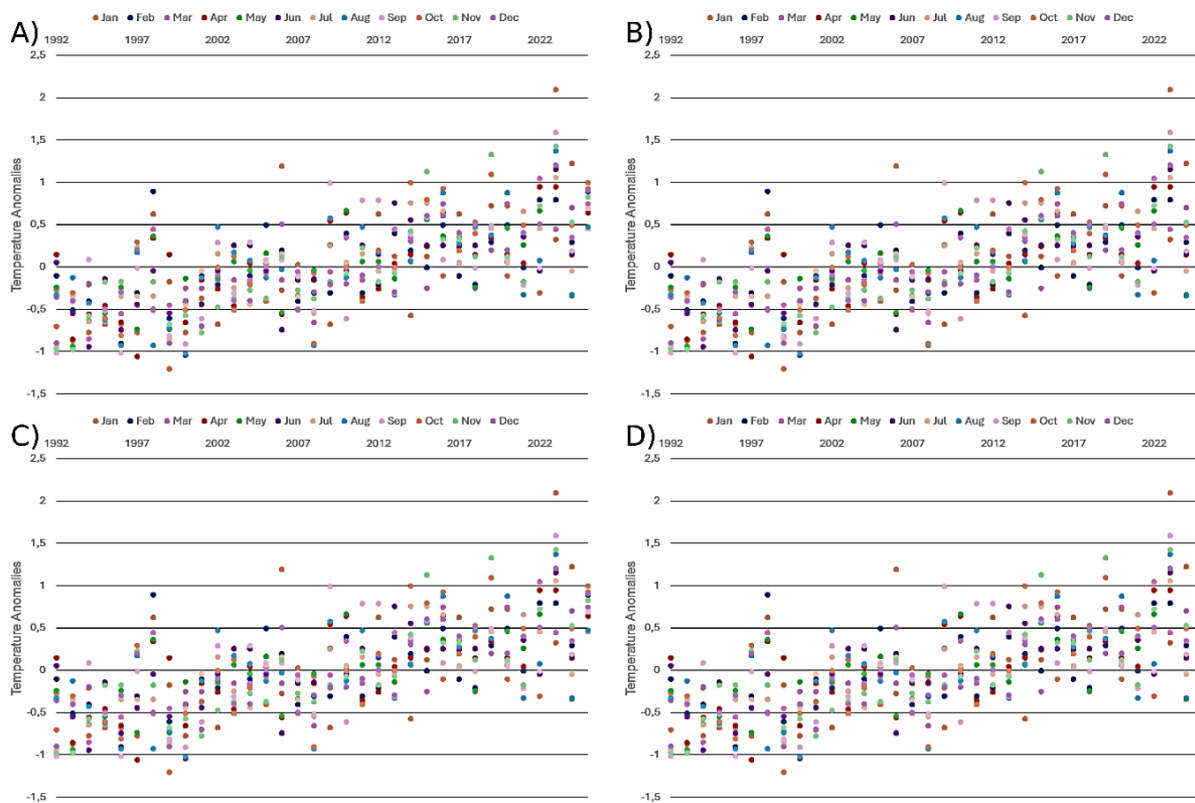


Figure 2. Temporal pattern of climate anomalies (1992–2025)

3.3 Temporal Variability of Extreme Climate Events in Palembang (1992–2025)

Figure 3 presents the annual frequency of extreme climate events in Palembang from 1992 to 2025, including extreme heat, high humidity ($\geq 80\%$), intense rainfall (>300 mm), and high wind speed (≥ 4 knots). A substantial increase in extreme heat frequency is evident after 2010, with occurrences rising from fewer than 1 month per year before 2005 to between 3 and 9 months per year in recent periods, indicating intensifying thermal stress.

High humidity conditions remain persistently elevated, typically exceeding 80% for 4–7 months annually, with limited long-term variability. In contrast, extreme rainfall and high wind-speed events exhibit considerable interannual fluctuations without a clear monotonic trend, reflecting the influence of ENSO-related variability. Overall, these findings suggest that temperature-related extremes are intensifying more rapidly than other climatic hazards, while rainfall and wind extremes remain episodic but increasingly variable under changing climate conditions.

3.3.1 Temperature trends (1992–2025)

The analysis reveals a clear warming trend in Palembang City, accompanied by increasing variability and intensification of extreme heat conditions. The warmest month temperature (Figure 1) increased from approximately

27.4–27.7 °C in the early 1990s to ~28.5–29.8 °C in recent years, with a maximum of 29.8 °C, indicating a rise of nearly ~2.0 °C in peak temperature extremes.

Monthly temperature anomalies (Figure 2) further confirm this trend, shifting from predominantly negative values (-1.0 to -0.3 °C) before 2000 to increasingly positive anomalies (0.5 to >2.0 °C) after 2010. Extreme anomalies exceeding +2.0 °C appear in recent years, reflecting intensified warming. Seasonal clustering of positive anomalies is evident during March–June and September–October, suggesting amplification during transitional periods.

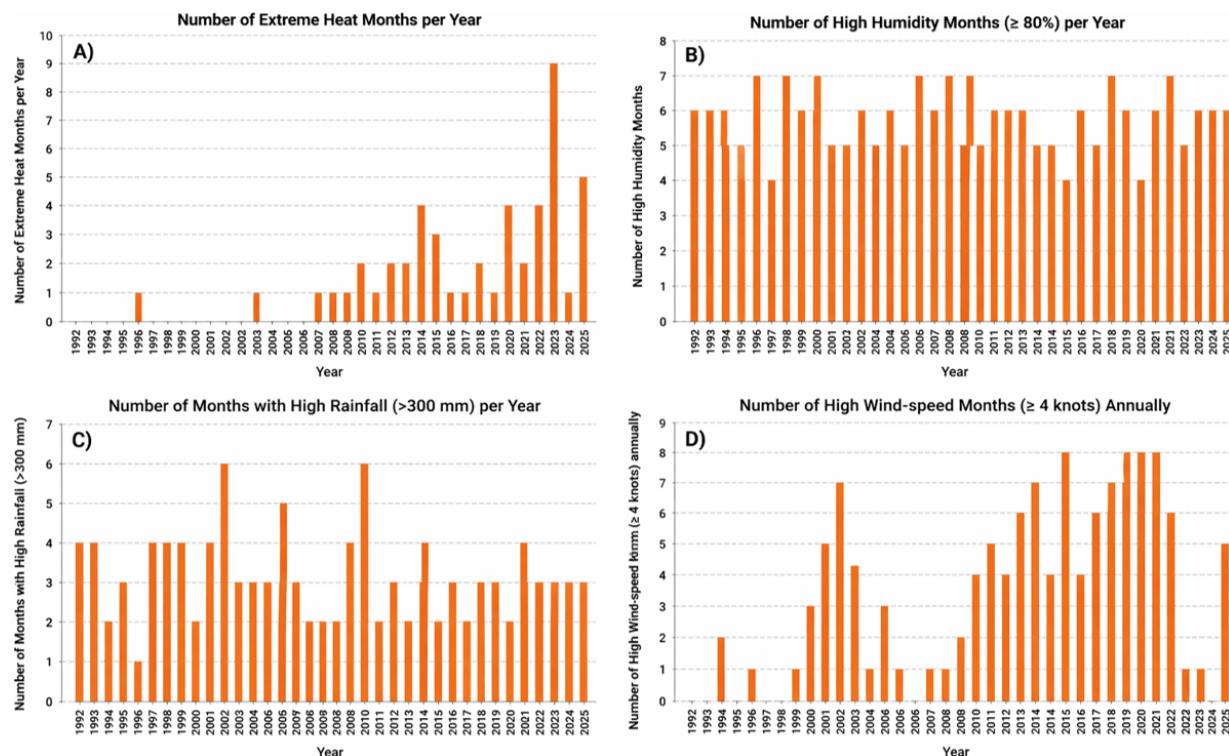


Figure 3. Temporal variability of extreme climate events in Palembang City (1992–2025)

The escalation of extreme heat is most pronounced in Figure 3. Prior to 2005, extreme heat months (≥ 90 th percentile, ~ 28.1 °C) were rare (0–1 months/year), whereas after 2016 they increased sharply to 3–9 months/year, peaking at 9 months.

Overall, these findings indicate a consistent upward temperature trend and a nonlinear intensification of heat extremes, highlighting increasing thermal stress and climate-related risks in Palembang City.

3.3.2 Relative humidity

Relative humidity remained within 78%–86% but exhibited a minor declining trend during peak heat episodes. In 2023, relative humidity dipped to 75%, coinciding with record high temperatures and low precipitation.

3.3.3 Rainfall

Rainfall variability was high, with annual totals ranging from 1,600 mm (El Niño) to 3,000 mm (La Niña). Periods of severe drought alternated with heavy flooding, particularly in 2007, 2010, and 2020. The intensity of short-duration rainfall events increased, suggesting greater convective activity.

3.3.4 Wind speed

Mean wind speed remained relatively stable (1.8 – 5.5 $\text{km}\cdot\text{h}^{-1}$), though isolated gusts exceeding 10 $\text{km}\cdot\text{h}^{-1}$ occurred during thunderstorms. The absence of a strong long-term wind trend contrasts with increasing variability during extreme events.

3.3.5 Regional context (2018–2024)

The 2018–2024 period was characterized by persistent regional warming. World Meteorological Organization (WMO) identified 2023 as among the hottest years on record for Asia, with Indonesia reporting a national anomaly of $+0.5$ °C relative to 1991–2020 [1]. Southeast Asian stations including Singapore (28.4 °C), Hong Kong (24.5 °C), and Bangkok ($+0.9$ °C anomaly) confirmed widespread heat amplification (Table 1).

Table 1. Climate variable trends (2018–2024) across selected Southeast Asian countries

Country/ Region	Average Temperature (Trend)	Official Example Figures	Rainfall (Trend)	Official Example Figures	Relative Humidity (Trend)	Wind Speed (Trend)	Extreme/ENSO Notes
Indonesia	Increasing trend with clear warming; local record observed in 2023	2023 anomaly +0.5 °C (27.2 °C vs 26.7 °C) [2]	Variable trend; rainfall suppressed during El Niño 2023/2024 in many areas	ENSO/IOD 2023 positive phase; wetter conditions in early 2024 [3]	Generally stable to slightly decreasing during strong heat events	Data not consistently available at the national level	ENSO 2023/2024 dominant; high monsoon variability [4]
Thailand	Moderately increasing trend	November 2023 +0.9 °C; September 2023 +0.4 °C	Variable trend	November 2023 +17% above normal; September 2023 +32% [5] 2023 ap-	Generally stable with seasonal variation	Limited national-level data available	Influenced by tropical cyclones and monsoonal vortices in 2023 [6]
Singapore	Strong and rapid warming trend	2023 mean 28.2 °C; 2024 mean 28.4 °C (record)	Increasing trend with wetter conditions in 2023–2024	approximately 2866 mm (7th wettest); 2024 +8.1% above average	Generally stable	Generally stable	Record high temperatures in May and October 2023 [7]
Malaysia	Increasing trend, particularly since the late 2010s and early 2020s	Summary reported in Annual Reports 2018–2023	Variable trend influenced by monsoonal systems	Detailed annual data available in MET Reports [8]	Generally stable	Generally stable	ENSO and IOD influencing monsoon variability [9]
Vietnam	Increasing long-term warming trend	Warming trend observed; aggregated national data limited [10]	Variable trend with increasing flood and flash flood events	Regional Lower Mekong Basin extremes recorded 2018–2023 [11]	Generally stable	Generally stable	Mekong River flow and rainfall variability affecting the Delta [12]
Hong Kong	Strong warming trend	2018 mean 23.9 °C; 2023 mean 24.5 °C (+1.0 °C relative to 1991–2020) [13]	Variable trend	See annual climate summaries	Generally stable	Increasing frequency of extreme wind events (e.g., tropical cyclones in 2023)	Summer 2023 hottest on record; increased Very Hot Days and Hot Nights [14]
Cambodia	Increasing long-term warming trend	Climate profile and Lower Mekong Basin analysis	Variable trend influenced by monsoon patterns	Increasing risks of both flooding and drought [15]	Generally stable	Generally stable	Changes in Tonle Sap flow and flood regime linked to regional rainfall variability

Note: ENSO, El Niño–Southern Oscillation; IOD, Indian Ocean Dipole.

4 Discussion

The analysis shows significant warming in Palembang, consistent with regional patterns across Southeast Asia. Seasonal heat anomalies have intensified, and the frequency of extreme heat suggests a transition toward a warmer thermal regime. These conditions elevate public health risks and underscore the need for urban adaptation strategies.

4.1 Heat–Humidity Interaction and Human Health

The interplay of high temperatures and humidity magnifies thermal discomfort and physiological strain, leading to heat exhaustion, dehydration, and cardiovascular stress. Studies by Li [16], Matthews [17], and Cvijanovic et al. [18] highlighted the critical role of humidity in exacerbating heatwave impacts, particularly in tropical climates. These findings support the need for a heat–humidity index in public health advisories rather than temperature alone.

The observed increase in Palembang’s annual peak monthly temperatures from 1992 to 2024 reflects a broader pattern of regional and global warming. The upward trend and heightened variability in recent years align with documented intensification of heatwaves driven by anthropogenic climate change. Studies show that compound drought heatwave events and persistent extreme heat are becoming more frequent worldwide, particularly in tropical regions [19, 20]. Southeast Asia is projected to experience stronger and longer heatwave episodes as global temperatures rise, consistent with the sharp warming fluctuations observed in the early 2020s [20]. Rising temperatures also have far-reaching implications for human health, ecosystems, and disease dynamics. For instance, extreme heat has been linked to increased transmission risks for vector-borne diseases such as dengue fever, underscoring the public health relevance of these climatic shifts [21]. Additionally, global analyses identify heatwaves as an increasingly critical research focus due to their escalating impacts on agriculture, infrastructure, and societal vulnerability [22]. Overall, the observed temperature pattern in Palembang is consistent with emerging evidence that climate change is amplifying thermal extremes across many low-latitude regions.

4.2 Health System Stress

Rising ambient heat places an indirect burden on healthcare systems. Sapari et al. [23] and Zhu et al. [24] reported increased hospital admissions during heatwaves, particularly among individuals with chronic respiratory and cardiovascular diseases. For Palembang, the projected increase in extreme-heat days underscores the need for adaptive healthcare readiness such as early-warning systems and temporary cooling shelters.

Rising ambient heat imposes indirect yet substantial burdens on healthcare systems by increasing heat-related illnesses, exacerbating chronic diseases, and intensifying demand for medical services, particularly during extreme heat or Urban heat island (UHI)-amplified events. UHI heighten exposure in densely populated areas, compounding physiological stress and increasing vulnerability among older adults, children, and outdoor workers. Studies show that UHI–heatwave interactions elevate morbidity risks and strain emergency care capacities in tropical cities [22]. Broader regional warming further accelerates these impacts, necessitating integrated mitigation strategies. Recent reviews emphasize that urban planning interventions such as greening, reflective surfaces, ventilation corridors, and policy-driven adaptation are essential to reduce UHI severity and prevent avoidable heat-related mortalities [25–27].

4.3 Rainfall Variability and Flood–Vector Risks

The city’s alternation between drought and flooding aligns with regional ENSO/IOD modulation. Extreme rainfall contributes to vector-borne disease outbreaks, as documented by Ith et al. [28] in their multi-country Southeast Asia analysis. Conversely, prolonged dry spells intensify haze episodes and reduce water quality, affecting respiratory health and sanitation.

Rainfall variability in Palembang, influenced by ENSO and IOD modulation, drives oscillations between drought and flooding, amplifying environmental and public health risks. Extreme precipitation increases flood frequency, particularly in rapidly urbanizing regions where land-cover change intensifies runoff and exposure [29, 30]. Flooded environments create favorable breeding conditions for vectors, elevating transmission risks of diseases such as dengue, especially among vulnerable populations [31, 32]. Climate-driven shifts in rainfall patterns further destabilize hydrological cycles, increasing the likelihood of compound flood–vector outbreaks. Understanding these interactions is essential for developing integrated risk reduction strategies that combine hydrometeorological monitoring, urban planning, and strengthened healthcare preparedness.

4.4 Wind and Airborne Pollution

While average wind speeds are low, calm atmospheric conditions limit pollutant dispersion. During peatland fires in South Sumatra, this stagnation elevates particulate concentrations, exacerbating respiratory illnesses. Similar findings have been reported by Huang et al. [33] and Rahman et al. [34] concerning aerosol accumulation during stagnant air periods.

Wind dynamics play a significant role in shaping airborne pollution patterns, particularly through resuspension of particulate matter and the dispersion of industrial emissions. Wind-induced PM₁₀ resuspension can act as a persistent pollution source, prolonging exposure even when primary emissions decline, thereby posing continued risks to urban populations [35]. Airborne pollutants such as lead have been shown to generate severe health impacts, including increased infant mortality, when transported from industrial sources into surrounding communities [36]. Biological indicators like lichens further demonstrate sensitivity to wind-driven pollutant transport, highlighting spatial variability in exposure near industrial sites [37]. Understanding wind–pollution interactions is therefore

essential for designing monitoring systems and implementing mitigation measures that reduce health and ecological risks.

4.5 Climate Drivers and Urbanization

ENSO cycles, land-use change, and urbanization collectively drive Palembang's microclimate shift. Dong et al. [38] and Wei et al. [39] emphasized that compound heat and humidity extremes will likely intensify across Southeast Asia, making urban adaptation essential.

Rising temperatures in Palembang reflect combined influences of regional climate change and UHI amplification. Regional warming elevates baseline temperatures across Southeast Asia, increasing heatwave frequency and intensity. Urbanization further intensifies local warming through reduced vegetation, high impervious surfaces, and anthropogenic heat release. Studies show that UHI effects often strengthen during heatwaves, creating synergistic thermal extremes in tropical cities. Rapid urban growth in Southeast Asia exacerbates nighttime heat retention and human exposure, compounding regional climatic trends. These interactions highlight the need for integrated mitigation strategies combining urban planning, cooling interventions, and broader climate adaptation.

5 Conclusions and Policy Implications

5.1 Conclusions

The 33-year climate record (1992–2025) in Palembang demonstrates a clear and sustained warming trend, accompanied by a significant increase in the frequency and intensity of extreme heat events. Mean temperature has risen by approximately 0.3–0.5 °C, with more pronounced warming observed after 2010. Extreme heat months have increased substantially, indicating a transition toward a more thermally stressed urban environment.

Rainfall patterns exhibit high interannual variability, particularly during ENSO events, while relative humidity remains consistently high, amplifying heat stress conditions. Wind speed shows moderate variability without a significant long-term trend.

These findings highlight the growing influence of climate variability on environmental conditions and public health risks. Strengthening climate–health integration, early warning systems, and adaptive urban planning is essential to enhance resilience in tropical urban settings such as Palembang.

5.2 Policy Implications

Based on these findings, several policy implications can be proposed:

1. Local climate–health integration

Strengthen coordination between meteorological agencies and local health authorities to enable real-time monitoring of temperature, humidity, and air quality, and to support early detection of climate-related health risks.

2. Urban design adaptation

Promote heat-resilient urban infrastructure, including improved ventilation systems, reflective roofing materials, and expansion of urban green spaces, to mitigate the urban heat island effect.

3. Public awareness and early warning systems

Develop community-based heat warning systems and public advisories, including guidance on hydration, work-hour adjustments, and indoor cooling strategies during extreme heat events.

4. Research and data continuity

Expand long-term meteorological observations and integrate them with public health surveillance systems to improve predictive modeling of climate–health interactions.

5. Regional cooperation

Enhance data-sharing and collaboration across Southeast Asian countries to improve climate forecasting accuracy and preparedness for transboundary climate risks such as haze and extreme heat.

5.3 Study Limitations

This study has several limitations that should be acknowledged. First, the analysis is based on data from a single BMKG station in Palembang, which may not fully represent spatial variability across the urban area. Second, the study relies on monthly aggregated data, which limits the ability to capture short-term or daily extreme heat events. Future research should incorporate higher-resolution spatial and temporal data to provide a more detailed assessment of urban climate dynamics.

Author Contributions

Conceptualization, A.D.F. and N.; methodology, A.D.F.; software, A.D.F.; validation, A.D.F., A.R., and T.M.; formal analysis, A.D.F.; investigation, A.D.F.; resources, A.D.F.; data curation, A.D.F.; writing—original draft preparation, A.D.F.; writing—review and editing, A.D.F.; visualization, A.D.F.; supervision, A.D.F.; project

administration, A.D.F.; funding acquisition, M. All authors have read and agreed to the published version of the manuscript.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflict of interest.

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