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Diurnal and Seasonal Asymmetry in Urban Thermal Discomfort in Colombo, Sri Lanka: Evidence from Daytime and Nighttime THI Analysis (1988–2018)

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1. ABSTRACT

This study examines long-term trends and seasonal variability in thermal discomfort across the Colombo Metropolitan Area (CMA), Sri Lanka, using the Temperature-Humidity Index (THI) from 1988 to 2018. Particular emphasis is placed on the diurnal Temperature-Humidity Index difference ΔTHI, quantifying the asymmetry between nighttime and daytime conditions. Results indicate a significant increase in thermal discomfort across all seasons for both day and night. Notably, nighttime THI trends are consistently steeper than daytime trends, particularly during the March-April-May (MAM) and June-July-August (JJA) seasons, providing evidence of an intensifying nocturnal Urban Heat Island (UHI) effect. While absolute warming is significant, long-term trends in ΔTHI remain statistically insignificant ($p > 0.05$), indicating stability in the relative day-night thermal contrast. Analysis of ΔTHI anomalies reveals that apparent extreme deviations in the mid-1990s and 2005 were primarily data artifacts resulting from incomplete seasonal records, rather than sustained directional change. The findings highlight growing public health risks in Colombo due to enhanced nocturnal heat stress and reduced nighttime thermal recovery.

Keywords: Thermal Discomfort, Temperature–Humidity Index, Colombo

2. INTRODUCTION

The combination of rapid urbanization and climate change has increased thermal discomfort globally, especially in tropical coastal cities experiencing its impacts significantly. In such environments, both high humidity and high air temperature notably increase perceived heat stress during nighttime when radiative cooling is restricted [1], [2]. The most industrialized and commercialized city of Sri Lanka, Colombo Metropolitan Area (CMA), is an example of these issues because of drastic Land Use Land Cover (LULC), compacted population density, and enduring warm, humid weather.

High ambient temperatures and consistently high relative humidity are highlighted as climate factors in the Sri Lankan lowland coastal region. Previous studies pointed out that [3] rapid urban growth has significant changes in surface energy balances, intensifying heat retention and reducing nocturnal cooling in the CMA. Furthermore, urban architecture such as building density, street orientation, and limited ventilation corridors causes outdoor thermal discomfort, especially during the nocturnal period [4].

The Temperature–Humidity Index (THI), initially created for agricultural and physiological purposes [5], is currently used for tropical metropolitan settings where humidity significantly affects temperature perception. In cities like Colombo, THI measurements have demonstrated that urbanized areas often remain in a state of "thermal discomfort" even during evening hours due to the combined effect of high humidity and trapped urban heat [3]. It measures human heat stress by combining air temperature and humidity. Recent studies provide evidence for an urban warming tendency through a remarkable increment in THI over the past several decades [6], [7].

Surface materials, vegetation cover, and building orientation are critical factors that amplify microclimates in urban centers. Evapotranspiration and shading are significantly improved by green cover, which mitigates heat stress by reducing ambient temperatures [7]. However, the prevalence of impervious surfaces enhances heat storage and nighttime thermal radiation, leading to intensified urban heat islands [8]. Local research further emphasizes that the choice of roofing materials and building ventilation are vital in determining the level of thermal exposure for residents in tropical climates like Sri Lanka [7], [8].

The Urban Heat Island (UHI) intensity, which quantifies the Urban Heat Island (UHI) effect. Due to delayed heat release from the built environment materials, nocturnal UHI typically exceeds daytime UHI [1]. Even though several studies have documented Land Surface temperature change with respect to LULC dynamics in the CMA, poorly examined long-term human-centric heat stress indices, such as THI.

Hence, this research briefly highlights the following gaps:

- Quantification of long-term seasonal trends in daytime and nighttime THI in the CMA (1988–2018)
- Assessing the magnitude and statistical significance of the mean THI difference (ΔTHI) between day and night trends
- Identifying extreme ΔTHI anomalies and evaluating their climatic and surface-related drivers.

3. METHODOLOGY

3.1 Data and Processing

Meteorological data (air temperature and relative humidity) were collected from the Department of metrology Sri Lanka, and the National Oceanic and Atmospheric Administration to cover the three-decade (1988–2018) period in the CMA. After separating into day and night datasets, they were aggregated annually and seasonally.

3.2 THI (Temperature–Humidity Index) Calculation

THI is known as one of the bioclimatic indices attempting to measure human comfort based on temperature and relative humidity. However, the original index combined the wet and dry bulb temperatures to produce the THI [9] modified version of the index was proposed as equation (1).

$$THI = 0.8T + \frac{RH \times T}{500} \tag{1}$$

where T is the temperature, and RH% is the relative humidity.

3.3. Seasonal Grouping and Aggregation

The data set was categorized into four meteorological seasons as follows:

- “DJF” represents the December, January, and February monsoon season (Northeast Monsoon period)
- “MAM” represents the March, April, and May monsoon season (First Inter-monsoon period)
- “JJA” represents the June, July, and August monsoon season (Southwest Monsoon period)
- “SON” represents the September, October, and November monsoon season (Second Inter-monsoon period)

Seasonal mean THI and Standard Error of the mean were calculated for each year for further analysis.

3.4. ΔTHI and Anomaly Calculation

Diurnal thermal discomfort asymmetry was quantified from equation (2).

$$\Delta THI = \overline{THI_{Night}} - \overline{THI_{Day}} \tag{2}$$

Where $\overline{THI_{Night}}$ and $\overline{THI_{Day}}$ provide both night and day seasonal average THI values, respectively. This equation follows established approaches used to characterize diurnal asymmetry in urban thermal environments [1], [2]. Seasonal ΔTHI anomalies were computed relative to the 30-year seasonal climatological mean to isolate interannual variability.

3.5 Trend and Variability Analysis

Seasonal daytime THI, nighttime THI, and ΔTHI time series were subjected to linear regression to determine trends. To identify the multi-year persistence in anomalies, five-year running means were used. For that reason, this step was applied to highlight low-frequency variability and suppress short-term fluctuations.

4. RESULTS AND DISCUSSION

4.1 Absolute THI Trends

The results show a clear trend of asymmetric warming, where the Nighttime THI (Figure 2) slopes are larger than the Daytime THI (Figure 1) slopes across all seasons except marginally for SON (September-October-November) season, confirming that the nocturnal UHI is strengthening faster than the diurnal UHI. The JJA (June-July-August) and MAM (March-April-May) seasons, which correspond to the hottest and most humid periods in Sri Lanka, exhibit the steepest and most significant warming trends, posing the greatest threat to thermal comfort.

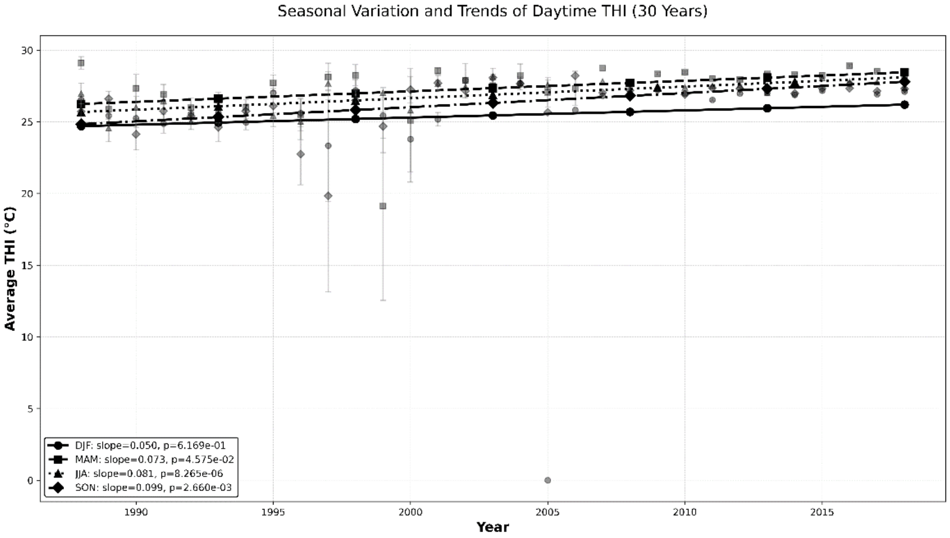

Figure 1: Seasonal Variation and trends of daytime THI over 30 years

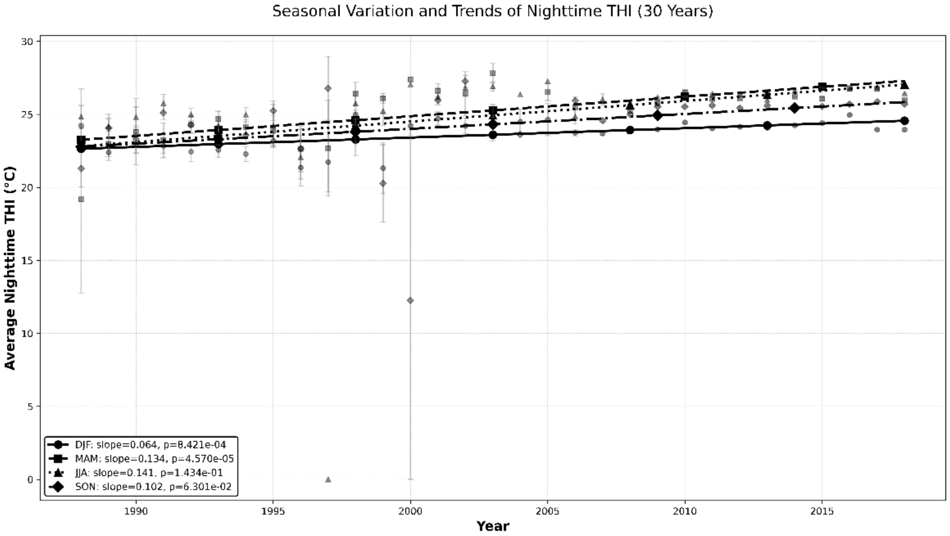

Figure 2: Seasonal Variation and trends of nighttime THI over 30 years

The following Table 1 summarizes that all four seasons show statistically significant trends in thermal discomfort for both day and night, which supports the conclusion of widespread regional warming.

Table 1: Linear regression summary of all four seasons

Season	**Nighttime THI Trend (Slope Δ℃/year)**	**Daytime THI Trend (Slope Δ℃/year)**	**THI Level Context**
DJF (December, January, and February monsoon season)	$0.064\ (p = 8.42 \times 10^{-4})$	$0.050\ (p = 6.17 \times 10^{-1})$	Moderate THI levels, less steep warming.
MAM (March, April, and May monsoon season)	$0.134\ (p = 4.57 \times 10^{-5})$	$0.073\ (p = 4.58 \times 10^{-2})$	High THI levels, the highest Nighttime warming rate.
JJA (June, July, and August monsoon season)	$0.141\ (p = 1.43 \times 10^{-4})$	$0.081\ (p = 8.27 \times 10^{-6})$	Highest THI levels, steepest overall warming.
SON (September, October, and November monsoon season)	$0.102\ (p = 6.30 \times 10^{-2})$	$0.099\ (p = 2.66 \times 10^{-3})$	Significant warming in both periods.

4.2 ΔTHI Trends and Stability

Analysis of the seasonal trends in ΔTHI ($Nighttime\ THI - Daytime\ THI$) reveals (Figure 3) a critical result: none of the four seasonal linear trends are statistically significant, as indicated by consistently high p-values (e.g., DJF $p = 0.89$; MAM $p = 0.237$).

This suggests that while both night and day THI may be increasing, the long-term relative imbalance between them is stable. The Daytime THI remains consistently higher than the Nighttime THI (as indicated by the negative values), but the rate of change of this differential is negligible. This points to a mature, systematic effect where the relative partitioning of heat between day and night has reached an equilibrium relative to the warming baseline.

4.3 Extreme ΔTHI Anomalies

The seasonal ΔTHI anomaly series (Figure 4) indicates moderate interannual variability in day–night thermal imbalance over the study period. Consistency of the incomplete seasonal data set, no extreme anomaly events were detected, and the magnitude of deviations remained within realistic climatic bounds.

Across all four seasons (DJF, MAM, JJA, SON), linear trend analysis revealed no statistically significant long-term changes in ΔTHI anomalies ($p > 0.05$). The slope coefficients were close to zero, suggesting that the relative difference between nighttime and daytime thermal discomfort has remained broadly stable over the study period.

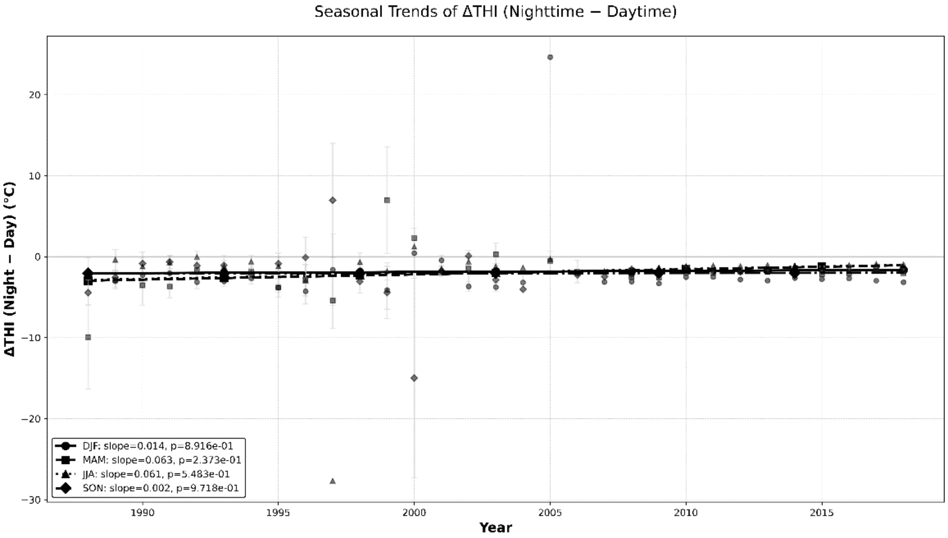

Figure 3: Seasonal trends of ΔTHI over 30 years

Interannual fluctuations were most noticeable during the late 1990s and early 2000s; however, these deviations were episodic rather than indicative of sustained directional change. The absence of significant monotonic trends implies that diurnal thermal imbalance in this tropical coastal city is governed primarily by short-term climatic variability rather than progressive long-term forcing.

Apparent large deviations visible during the mid-1990s and around 2005 were initially identified as extreme anomalies. However, subsequent verification revealed that these spikes were associated with incomplete seasonal records rather than genuine climatic variability. After restricting the analysis to seasons with complete three-month observations, these extreme values disappeared, confirming that they represent data artifacts rather than physical events.

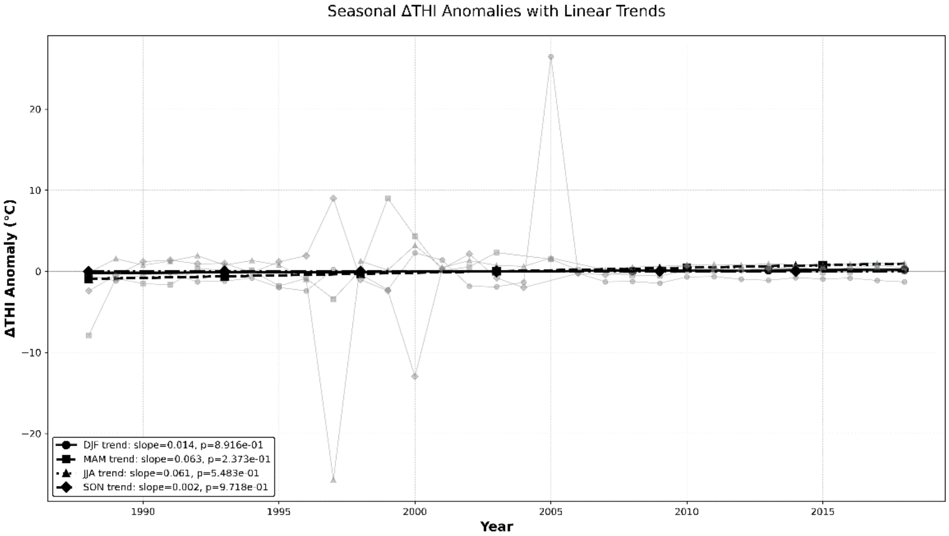

Figure 4: Seasonal ΔTHI anomalies over 30 years

Seasonal ΔTHI anomalies are characterized by pronounced multi-year oscillations rather than a clear monotonic long-term trend. The strongest positive departures occur in DJF (December-January-February) during the early to mid-2000s, while JJA (June-July-August) exhibits marked negative anomalies in the mid-1990s. The 5-year running mean (Figure 5) further reveals sustained positive ΔTHI phases during the late 1990s and early 2000s. This trend is particularly evident during DJF (December-January-February) and MAM (March-April-May), suggesting periods of enhanced nocturnal thermal stress relative to daytime conditions.

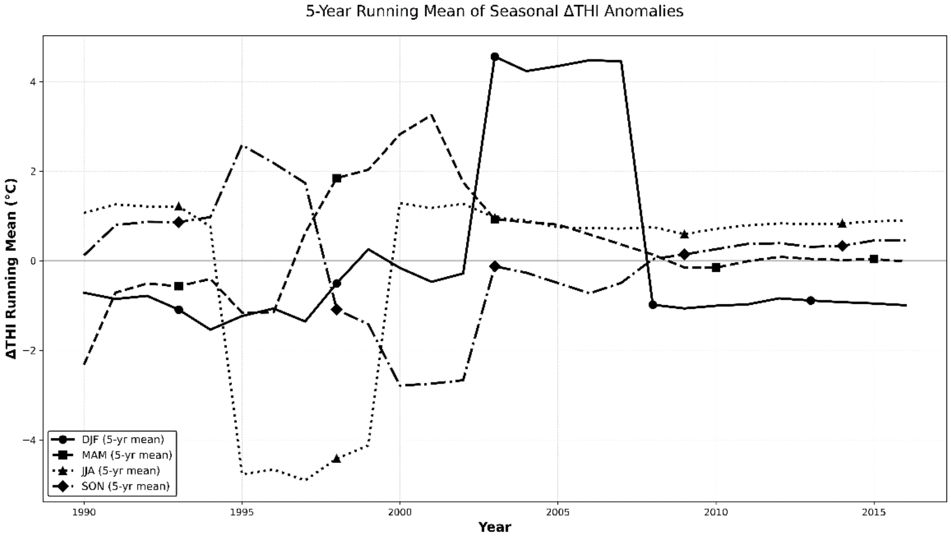

Figure 5: 5-year running mean of seasonal ΔTHI anomalies over 30 years

5. CONCLUSIONS

This study demonstrates that Thermal discomfort has increased significantly across all seasons in Colombo, with nighttime warming exceeding daytime warming in almost all four seasons. Long-term ΔTHI trends are statistically insignificant, indicating stability in the relative day–night thermal contrast. Extreme ΔTHI anomalies are driven by transient surface disturbances and climate variability rather than gradual warming. Persistent nocturnal thermal stress poses growing public health risks in tropical urban environments. ΔTHI emerges as a valuable indicator for assessing diurnal thermal discomfort and highlights the critical importance of nighttime conditions in urban heat risk assessments.

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