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Thermal Comfort for various Altitudes and Land Covers in North Sumatra

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ABSTRACT

Thermal comfort refers to the suitability of meteorological conditions for humans with the environment. Temperature is the main meteorological variable, which determines the thermal comfort as expressed in various climate indices. This study aims to analysis the distribution of thermal comfort, and to identify environmental factors influencing the comfort situated in North Sumatra, Indonesia. We applied the Universal Thermal Climate Index (UTCI) to determine the heat stress level for 2011 - 2020. The higher UTCI value indicates more uncomfortable conditions related to the higher heat stress. The results showed that the average value of UTCI in North Sumatra was categorised at moderate heat stress. Densely urbanised area in the eastern region contributed to high heat stress, whereas mountainous areas in central to west regions were at low level. Our findings found that climate season affected the distribution of heat stress level. The low heat stress occurred in December-February, while high heat stress happened in June-August. Further, findings revealed that altitude and land cover have contributed to UTCI variation by more than 75% variance.

KEYWORDS

heat stress, land cover, regional variations, universal thermal climate index, vegetation index

INTRODUCTION

Environmental factors particularly weather and climate conditions have an impact on human activities such as through influencing the suitability of thermal condition to human comfort (Baquero et al., 2022; Huang et al., 2020). Air temperature and relative humidity are the two weather variables, which are commonly used to assess the level of thermal comfort (Li et al., 2019). High temperature may affect humans by influencing their physiological well-being (Cramer et al., 2022; Asseng et al., 2021). The concept of thermal comfort refers to a state of mind that reflects satisfaction with the thermal environment (Dear and Brager, 2002; ASHRAE, 2017).

North Sumatra is one of the most populated provinces in Indonesia. The increased air temperature affects human body's comfort especially during outdoor activities, which promote unsuitable thermal comfort condition. In the long run, the condition led to heat stress that affects human physiological conditions (Zare et al., 2019).

The air temperature is influenced by the land cover as shown in the research on vegetation density effect to temperature (Effendy and Aprihatmoko, 2018). Area with dense vegetation tends to have a lower air temperature due to a reduced direct solar radiation. Also, area with dense vegetation support the best thermal comfort condition (Meili et al., 2021; Effendy et al., 2006). However, built-up areas such as industrial zones tend to have a high pollution and air temperatures, leading to an uncomfortable thermal comfort condition. This shows proportion of green space is of importance for thermal comfort.

In city area, mostly proportion of green open space is limited to 30%, which is contrast to the proportion in rural area. Here, we analyze the thermal comfort conditions in North Sumatra, where development of city is on the line. Various indices have been used to assess thermal comfort including universal thermal climate index (UTCI) and physiologically equivalent temperature (PET). The universal thermal climate index (UTCI) is an index that accurately represents a wide range of climates, weather, and locations, which is widely applied worldwide (Grigorieva et al., 2023; Błażejczyk et al., 2012).

The objective of the study is to obtain an overview and determine the distribution of thermal comfort conditions in North Sumatra based on the Universal Thermal Climate Index (UTCI). Additionally, the study aims to identify variations in elevation and vegetation index in relation to thermal comfort by location, time, and land cover.

RESEARCH METHODS

Location and Data Source

The research area was in North Sumatra, which receives high annual rainfall (Darmawan et al., 2021). North Sumatra temperature ranges from 22.8°C to 32.2°C, an annual rainfall of 2,523 mm, average humidity of 77%, and average wind speed of 3.3 m/s based on the Climatology Station Deli Serdang (BPS, 2022). The peak of rainfall for Deli Serdang Regency was in May and October.

We used Climate Data Operator (CDO) for data processing, and ArcMap10.3 for image processing to describe the vegetation index and altitude and for visualization. The climate data used in the study was comprised of reanalysis and observed data. For the reanalysis, we employed daily air temperature, wind speed, solar radiation, and relative humidity data for 2011-2020, which were available from ERA5 (https://cds.climate.copernicus.eu/).

Then, we used daily observed climate (air temperature, wind speed, solar radiation, and relative humidity) from BMKG (Indonesian Agency for Meteorological, Climatological and Geophysics) observation online data for the same period (https://dataonline.bmkg.go.id/). To derive thermal temperature, we used Landsat-8 satellite image data (https://earthexplorer.usgs.gov/) for 2011-2020. The elevation data was available from gadm (https://gadm.org/).

UTCI Calculation

The reanalysis data was bias corrected to remove any potential biases with the observed climate data. We employed Piani approach to improve the distribution of reanalyzed data being closed to the observed data (Piani et al., 2010). The approach was widely used in the correction bias study (Ningrum et al., 2023; Sanusi et al., 2021; Kim et al., 2019; Sarvina et al., 2019). The corrected data then was processed to calculate the thermal comfort based on UTCI method.

The seasonal variation of UTCI was determined by grouping the data into four groups namely DJF, MAM, JJA, and SON. We determined the diurnal variation based on the UTCI values at 07:00, 14:00, and 18:00 GMT+7. UTCI was calculated using Equation 1 (Błażejczyk, 2011):

$$\mathrm{UTCI} = 3.21 + 0.872\ \mathrm{Ta} + 0.259\ \mathrm{Tmrt} + (-2.5078\ \mathrm{V}) + (-0.0176\mathrm{RH}) \quad (1)$$

where Ta is air temperature (ºC), Tmrt is mean radiation temperature (ºC), V is wind speed (m/s), and RH is Relative Humidity (%).

Estimation of Vegetation Index Value

The greenness of the area was calculated based on the normalized difference vegetation index (NDVI). This index was used to identify changes in vegetation cover both spatially and temporally, as well as changes caused by development (Sahebjalal and Dashtekian, 2013). The vegetation index was determined by measuring the greenness of vegetation through processing the digital data signal brightness values obtained from a combination of several bands (Vásquez et al., 2023; Xue and Su, 2017). NDVI was calculated using Equation 2:

$$\mathrm{NDVI} = \frac{(\mathrm{NIR-RED})}{(\mathrm{NIR+RED})} \quad (2)$$

where the NDVI value ranges from -1 to 1. The minimum value -1 refers to no vegetated land, while 1 represents high vegetation.

Thermal Comfort Value Mapping

The interpolation of thermal comfort values from several points was performed using the kriging method. This method was commonly used to interpolate parameters such as air temperature and rainfall (Li et al., 2020; Guhathakurta et al., 2013), particularly in areas with limited sample points (Munyati and Sinthumule, 2021; Mooney et al., 2020). However, the accuracy of the kriging interpolation method was higher in larger areas and decreases in smaller interpolated areas (Eldeiry et al., 2012).

Identification The Relationship between Thermal Comfort and Land Cover

Variations in spatial and thermal comfort were observed to assess their impact on altitude and land cover (Figure 1) in the study area. The thermal comfort map generated from maps of the area's elevation and land cover. The land cover classification of the study

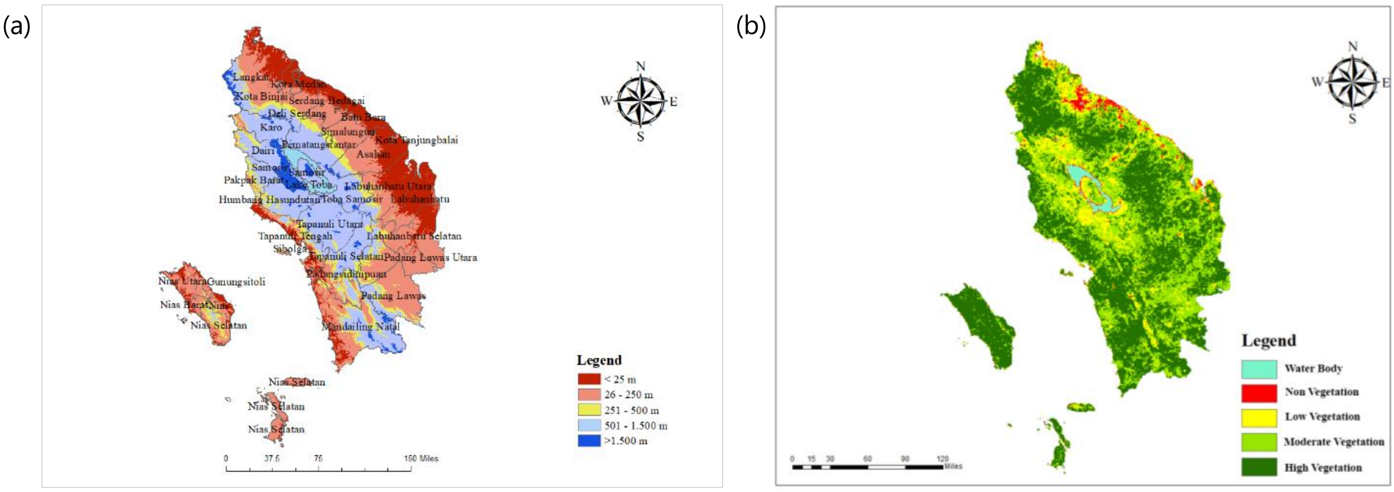

Figure 1. Spatial variation of (a) altitude (m a.s.l.) and (b) land cover for North Sumatra.

area was adjusted to align with the classification in Table 1. A graph of thermal comfort based on the area's altitude and land cover was analyzed and expressed in an XY plot. Moreover, an analysis of the effect of area elevation and land cover on UTCI thermal comfort was performed using a linear regression.

Table 1. NDVI classification based on Hardianto et al., 2021).

Range	Information
-1 – -0.03	Non-vegetated land
-0.03 – 0.15	Very low vegetation
0.15 – 0.25	Low vegetation
0.25 – 0.35	Medium vegetation
0.35 – 1.00	High vegetation

RESULTS AND DISCUSSION

Altitude and Land Cover of North Sumatra

Altitude of North Sumatra spans from east coast to the west coast of Sumatra with mountainous region (>500 m) in the centre. Low land areas were identified in surrounding coastal region with altitude below 25 m, that areas with equatorial rain patterns had rainy seasons in March-May and October-November. The vegetation density and built-up land influenced the air temperature in a particular area, resulting in an increased in heat stress. Consequently, areas with high concentrations of built-up land were more likely to had higher heat stress levels than those with more vegetation cover.

The study on North Sumatra's land cover was based on the NDVI value, where non-vegetated land was represented by water bodies and roads in Figure 1b. The non-vegetated land areas were primarily made up of the surface of Lake Toba, as well as several regions in the eastern part of North Sumatra showed in red color. Medan, being an urban area with a high concentration of buildings, was a prime example of such areas. Zaitunah et al., (2021) reported that in 2019, the maximum NDVI range in Medan City was between 0.1 to 0.2. Meanwhile, Nias Island was predominantly green color, indicating that it was an area with abundant vegetation. The region around Lake Toba and the areas of Mount Sibayak and Mount Sinabung also showed moderate to high vegetation cover. Based on the classification of vegetation index in percentage water bodies had the lowest vegetation class with an area of 1.3%. In contrast, the highest percentage of land cover based on the North Sumatra vegetation index was low vegetation, covering approximately 57.4% of the area.

Spatial Variation of North Sumatra Thermal Comfort

Figure 2a presents the average UTCI value from 2011 to 2020, showed North Sumatra's annual average UTCI value fell under the moderate heat stress category. The eastern region of North Sumatra had the highest heat stress value recorded, which reached 31°C. Conversely, with its high altitude area and low air temperature, Lake Toba resulted in lower heat stress values. Nias, on the other hand, had relatively high air temperatures of North Sumatra, as its location surrounded by sea, the average thermal comfort was categorized in the moderate heat stress. Zeng et al., (2020) noted a strong and significant positive correlation between air temperature and UTCI. Equation 1 highlights that high air temperature leads to high stress values. On a small scale, wind showed a negative correlation with UTCI, but on a larger scale, it showed a positive correlation.

Temporal Variation of Thermal Comfort

Many factors influenced the seasonal patterns in Indonesia, primarily attributed to its geographical position as a maritime nation straddling the equator, intersected by the Pacific Ocean and Indian Ocean, and

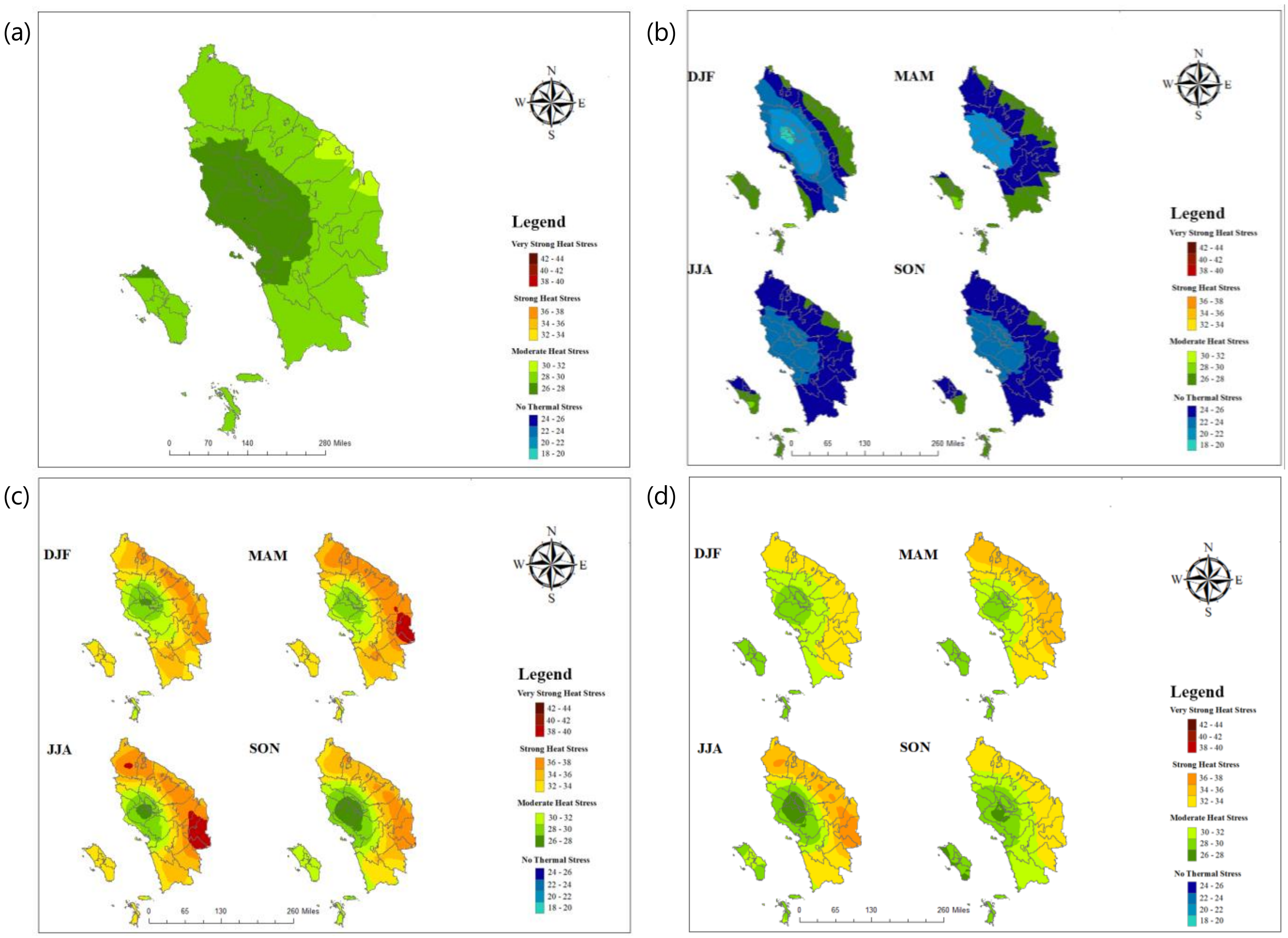

Figure 2. (a) Mean universal thermal climate index (UTCI) for 2011-2020, and diurnal temporal variation at: (b) in the morning 07.00 WIB; (c) the day 14.00 WIB; (d) the afternoon 18.00 WIB.

traversed by the Asia-Australia monsoon pathway. Among these factors, the monsoon played a pivotal role in shaping the distinct seasons, facilitated by variations in pressure cells. During December-January-February (DJF), the west monsoon wind blew from the high-pressure system over the Asian continent towards Australia. Conversely, in July-June-August (JJA), the eastern monsoon wind moved from Australia towards the Asian continent. These alternating monsoon winds contribute significantly to the seasonal shifts experienced in the country (Chen et al., 2020).

Low air temperature in the morning was due to the lack of solar radiation and the short duration of irradiation. The energy depletion at night due to the earth's reradiation process leaded to a low heat stress value. At 07.00 WIB, the average UTCI in the morning fell into the no thermal stress to moderate heat stress category. The maximum heat stress value during DJF was 29.1°C, with a minimum of 19.9°C, while during JJA, the maximum heat stress value was 30.1°C, with a minimum of 20°C. The SON had a similar UTCI variation to JJA, with a temperature distribution and different humidity ranging from 18.7°C - 26.9°C and 85% - 94%, respectively. The JJA had high heat stress due to the maximum air temperature brought about by the movement of dry air masses from mainland Australia to Asia. The sun's apparent movement also contributed to high temperatures during JJA as the sun was further from North Sumatra, resulting in maximum absorption of solar radiation due to sunny atmospheric conditions (Aulia et al., 2022; Fadholi, 2013).

The UTCI value at 14.00 WIB indicated a more varied diurnal UTCI pattern across North Sumatra's regions (Figure 2c). The rise in air temperature during the daytime resulted from increased solar radiation absorption by the surface, as per Tian et al., (2023). The UTCI in North Sumatra ranged from moderate to severe heat stress during the day, with the highest values occurring during JJA, the dry season. The highest heat stress value recorded during JJA was 39.9°C, and the lowest was 27.4°C. DJF period, on the other hand, had the lowest heat stress values, with the maximum value at 37.3°C and the minimum at 25.6°C. During the day, the area surrounding Lake Toba had a moderate heat stress category for comfort levels, despite having the lowest air temperature in North Sumatra. Samosir Island recorded an air temperature range of 19°C - 29°C. The UTCI in the afternoon was classified as having

Table 2. Mean diurnal thermal comfort for period 2011-2020 based on season and time of the day in North Sumatra.

Month	Time	Category	Area (%)	Month	Time	Category	Area (%)
DJF	Morning	No Thermal Stress	72.8	**JJA**	Morning	No thermal stress	90.5
		Moderate Heat Stress	27.2			Moderate Heat Stress	09.5
	Afternoon	Moderate Heat Stress	28.6		Afternoon	Moderate Heat Stress	22.9
		Strong Heat Stress	71.4			Strong Heat Stress	72.2
	Evening	Moderate Heat Stress	51.0			Very Strong Heat Stress	04.9
		Strong Heat Stress	49.0		Evening	Moderate Heat Stress	61.4
MAM	Morning	No Thermal Stress	67.8			Strong Heat Stress	38.6
		Moderate Heat Stress	32.2	**SON**	Morning	No thermal stress	92.7
	Afternoon	Moderate Heat Stress	40.7			Moderate heat stress	07.3
		Strong Heat Stress	59.3		Afternoon	Moderate Heat Stress	23.6
		Very Strong Heat Stress	00.0			Strong Heat Stress	68.9
	Evening	Moderate Heat Stress	34.8			Very Strong Heat Stress	07.5
		Strong Heat Stress	65.2		Evening	Moderate Heat Stress	61.4
						Strong Heat Stress	38.6

moderate to strong heat stress. The lowest heat stress values were observed during DJF, with a maximum of 35.5°C and a minimum of 27.7°C. Conversely, the highest heat stress values were recorded during JJA, with a maximum of 35.8°C and a minimum of 26°C. The higher air temperature during the afternoon was attributed to solar radiation and cloud cover (Pyrgou et al., 2019). Across the four seasons, the Lake Toba region and the Nias Islands were categorized as having moderate heat stress, while the west coast region was classified as having strong heat stress. In the morning, North Sumatra was categorized as having no thermal stress or being comfortable, as indicates in Table 2 and had moderate heat stress in all seasons.

Across all regions, no thermal conditions were prevalent. During the day, the heat stress category was primarily dominated by strong heat stress, followed by moderate and no thermal stress. This was because the sun was directly overhead the earth's surface during the day, leading to maximum solar radiation absorption. In the afternoon, North Sumatra was categorized as having moderate to strong heat stress. However, the heat stress category varied across different regions and seasons. The central part of North Sumatra, including Lake Toba and its surrounding areas, recorded lower heat stress values than other regions due to its lower temperatures and higher wind speeds.

Analysis of the Effect of Altitude and Land Cover on UTCI

The relationship between area elevation and thermal comfort can be analyzed through simple regression and the impact of land cover on UTCI thermal comfort. Figure 3a displays the regression trend equation between the altitude of a region and UTCI as $y = 2E\text{-}06x^2 – 0.0078x + 30.542$. In this equation, y represented the UTCI value, and x represented the region's altitude. According to the equation, there was a negative correlation between the altitude of the region and the UTCI value, meaning that if the altitude of the area increases, the resulting UTCI value will decrease, indicating lower heat stress conditions. However, since UTCI was not solely affected by air temperature, the regression coefficient value (R^2) generated from the region's altitude to UTCI in North Sumatra was only 0.78. This value showed that the effect of regional altitude on UTCI diversity was 78%.

Table 2 shows the regional variances in North Sumatra concerning heat stress classifications. In the morning, North Sumatra was classified as either free from thermal stress, denoting a comfortable environment, or as having moderate heat stress throughout all seasons. Across all regions, the prevalence of thermal conditions without stress was observed. Throughout the daytime, the dominant heat stress category was marked by intense heat stress, followed by moderate stress and the absence of thermal stress. This pattern can be attributed to the sun's direct positioning above the Earth's surface, resulting in maximum absorption of solar radiation. In the afternoon, North Sumatra was categorized as encountering moderate to strong heat stress. However, the heat stress classification exhibited variability across distinct regions and seasons. The central part of North Sumatra, encompassing Lake Toba and its surroundings, recorded lower heat stress values than other regions, attributable to lower temperatures and higher wind speeds.

The obtained regression equation for the effect of

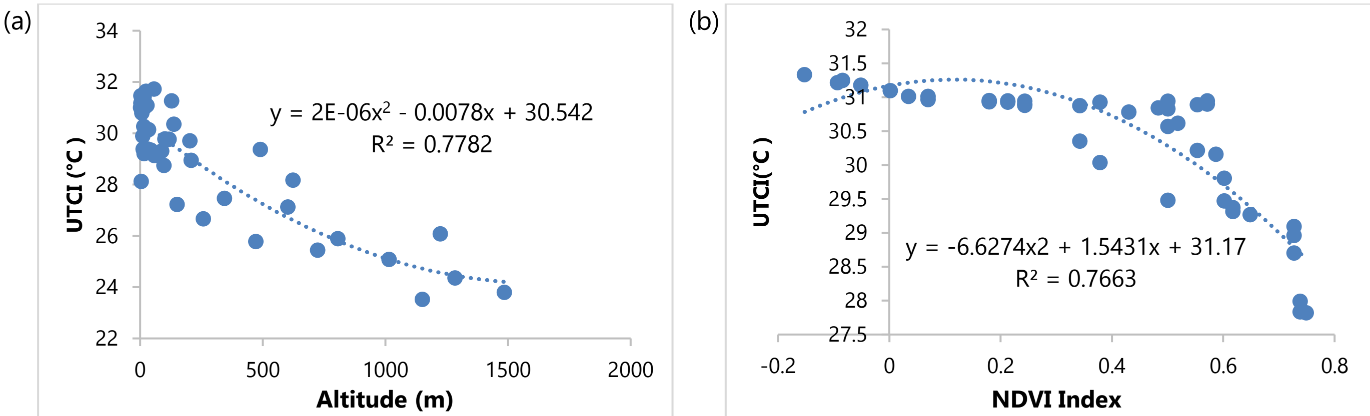

Figure 3. Universal thermal climate index (UTCI) as function of (a) Altitude (m) and (b) normalized difference vegetation index (NDVI) with regression lines for North Sumatra from 2011 to 2020.

land cover on UTCI was $y = -6.6274x^2 + 1.5431x + 31.17$, where y represented the UTCI value and x represented the NDVI value (Figure 3b). The equation shows a negative correlation, where the areas with higher vegetation index values or denser vegetation had lower UTCI values and therefore lower heat stress levels. Conversely, areas with lower vegetation index values had higher UTCI values and higher heat stress levels. The coefficient of determination (R^2) for this regression was 0.77, indicating that land cover accounted for 77% of the variation in UTCI diversity.

CONCLUSIONS

The study analyzed thermal comfort in North Sumatra Province using the UTCI method. On average, UTCI values in the region ranged from 27°C to 31°C, indicating a moderate heat stress category. The eastern region, with lowland topography and dominant urban land cover, had higher heat stress values than the mountainous mid to western regions with lower air temperatures. The diurnal distribution of UTCI values showed minimum heat stress values in the morning, with areas dominated by no thermal stress category, while maximum heat stress values occurred during the day.

Seasonal patterns showed that the lowest heat stress conditions occurred in DJF, categorized as no thermal stress. In contrast, the highest heat stress conditions occurred in JJA, categorized as moderate to very strong heat stress. The altitude of the region was found to had a significant influence on UTCI values, with higher regions showed lower UTCI values and a contribution of 78% to the diversity of UTCI. Land cover also had a substantial impact, contributing 77%. Higher vegetation index values were associated with lower heat stress, indicating that areas with more vegetation had less heat stress compared to water bodies and areas with little vegetation.

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