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Research article

Bioclimatic conditions of Vilnius city: a Universal Thermal Climate Index analysis (1993–2024)

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Abstract. This study examines bioclimatic conditions in Vilnius, Lithuania, from 1993 to 2024, using the Universal Thermal Climate Index (UTCI) to analyze trends in human thermal stress. RayMan software was employed to calculate UTCI data based on input parameters such as average air temperature, relative humidity, wind speed, and cloud cover. The Mann-Kendall trend test was applied to identify statistically significant changes in thermal stress over time. The second part of this research compares data from three different meteorological stations (located outside the city, north of the city centre, and within the city centre), focusing on extreme heat stress conditions from 2022 to 2024. Results show an increase in moderate and higher heat stress events, along with a decrease in strong and lower cold stress events. The variation in UTCI category frequencies over the years demonstrates a shift toward higher thermal stress levels and more instances of no thermal stress. A comparison of data from the three stations reveals that extreme heat stress conditions are more common in the city centre than in the northern part and outskirts of the city. These findings have implications for public health, urban planning, and climate adaptation strategies in Vilnius, highlighting the city's growing need for heat mitigation measures.

Keywords: *human health; heat stress; human thermal indices; Lithuania*

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INTRODUCTION

European cities are vulnerable to climate change impacts, such as rising temperatures and changing precipitation patterns (European Environment Agency 2024). Heat stress has increased everywhere, especially in cities where outdoor activities exceed critical thresholds (Bednar-Friedl *et al*. 2023). The first European Climate Risk Assessment (EUCRA) confirms rising average temperatures and more frequent heatwaves in Northern Europe (European Environment Agency 2024). Cities in this area are expected to face high to very high risks of pluvial flooding (Dodman *et al*. 2022).

Bioclimatic conditions are essential not only for human health and tourism but also for overall well-being in daily life, including living, working, and recreation (Charalampopoulos, Matzarakis 2022). Human heat exchange with the environment plays a key role in modern bioclimatic research (Błażejczyk 1994). Changes in bioclimatic zones are becoming more apparent, with a clear shift from colder, wetter conditions to hotter, drier ones (Sparey *et al*. 2023).

Climate change undermines comfort and introduces new challenges across various sectors (Matzarakis 2020; Rocha *et al*. 2022; Zhang *et al*. 2023). In urban areas, the main focus is on protecting human health and quality of life (Matzarakis 2021). In Northern Europe, buildings designed for cold winters often overlook the increasing frequency and severity of summer heat, which can cause health risks from overheating, especially for vulnerable groups. Urban planning measures, like increasing tree coverage and green spaces, can help reduce these impacts, particularly during heatwaves (Climate Change Committee 2022; European Environment Agency 2022, 2024).

Urban bioclimate is crucial due to a high concentration of people. Climate change, along with shifts in bioclimatic patterns, intersects with urban air pollution, urban heat island (UHI) effect, and limited green infrastructure (Matzarakis 2021; Misiune, Kažys 2022; Çelekli *et al*. 2023; Kuchcik *et al*. 2024). Increasing urbanization and aging populations are likely to worsen health risks from UHI, especially from heat exposure. Urban residents face higher health risks during hot weather than those in rural areas, with vulnerable groups being disproportionately affected (Heaviside *et al*. 2017). The UHI effect contributes to respiratory and cardiovascular problems and increases cities' ecological footprint (Piracha, Chaudhary 2022; Santamouris *et al*. 2015). Social factors such as urban development, planning practices, and interactions with ecosystems and biodiversity also significantly influence these risks (Heymans *et al*. 2019; Pineda Pinto, Steele 2025).

The most effective way to evaluate bioclimatic conditions is through human thermal indices, which are widely used to assess thermal environments (Staiger *et al*. 2019). These indices consider not only air temperature but also wind speed, humidity, mean radiation, metabolic heat production, and clothing insulation, creating a comprehensive system of human thermal perception (ASHRAE 2023). Thermal indices and related environmental parameters are generally comparable to meteorological conditions (Błażejczyk *et al*. 2012; Zare *et al*. 2018; Pantavou *et al*. 2024). Commonly used indices include Predicted Mean Vote (PMV) (Fanger 1970), Standard Effective Temperature (SET*) (Gagge *et al*. 1986), Physiologically Equivalent Temperature (PET) (Hoppe 1999), Perceived Temperature (PT) (Staiger *et al*. 2012), and Universal Thermal Climate Index (UTCI) (Jendritzky *et al*. 2012). These indices rely on complex numerical models (Chen 2023) and are supported by various software tools for urban microclimate simulations, such as RayMan (Matzarakis *et al*. 2007), ENVI-met (Bruse, Fleer 1998), SOLWEIG (Lindberg *et al*. 2008), and BioKlima (Błażejczyk 2017). Python-based libraries (Chen 2023; Gholami *et al*. 2024) and ERA5 reanalysis datasets (Di Napoli *et al*. 2020) are now available for calculations.

The Universal Thermal Climate Index (UTCI) has become one of the most widely used human bioclimatic indices worldwide (Zare *et al*. 2018; Kruger 2021; Romaszko *et al*. 2022; Zheng *et al*. 2025; Sargazi *et al*. 2026). It is applied in many fields, from general assessments of thermal conditions (Antonescu *et al*. 2021; Di Napoli *et al*. 2020; Zare *et al*. 2018; Li *et al*. 2025), to city microclimates (Park *et al*. 2014; Błażejczyk *et al*. 2016; Petralli *et al*. 2020; Yi *et al*. 2023; Barghchi *et al*. 2024; Kirschner *et al*. 2025), UHI studies (Pantavou *et al*. 2024; Parker *et al*. 2024; Silva *et al*. 2024), and planning (Błażejczyk, Twardosz 2023; Celekli *et al*. 2023; Tavares *et al*. 2024; Anders *et al*. 2025). It is also used in tourism (Kažys, Malunaviciute 2015; Kolendowicz *et al*. 2018; Rozbicka, Rozbicki 2021; Nam *et al*. 2024; Velea *et al*. 2024) and public health (Pappenberger *et al*. 2015; Błażejczyk *et al*. 2018; Di Napoli *et al*. 2018; Kuchcik *et al*. 2021; Urban *et al*. 2021; Khodadadi *et al*. 2022; Rozbicka *et al*. 2025) researches. Additionally, the UTCI is increasingly used for weather forecasts (Di Napoli *et al*. 2021; Kuzmanovic *et al*. 2024; Pantavou *et al*. 2024) and future bioclimate projections (Diah *et al*. 2021; Schwingshackl *et al*. 2021; Nam *et al*. 2024).

The UTCI is widely used in the Baltic Sea Region (BSR) studies focused on the bioclimatic features of the cities (Błażejczyk *et al*. 2016; De Luca *et al*. 2021; Kuchcik *et al*. 2021; Katavoutas *et al*. 2022; Błażejczyk, Twardosz 2023; Okoniewska *et al*. 2025; Owczarek, Krzyzewska 2025) and microclimates of built-up and vegetated environments (Lindberg *et al*. 2025; Lindner-Cendrowska *et al*. 2025; Negi *et al*. 2025; Czarnecka *et al*. 2026). Moreover, the UTCI is applied within atmospheric circulation analysis (Kolendowicz *et al*. 2018; Rozbicka, Rozbicki 2018; Owczarek 2021), recent climate change trends detection (Kažys, Malūnavičiūtė 2015; Krzyzewska *et al*. 2021; Tomczyk, Bednorz 2023; Deppisch 2023; Marmureanu *et al*. 2025; Okoniewska *et al*. 2025; Rozbicka *et al*. 2025), and future climate projections modelling (Brecht *et al*. 2020; Katavoutas *et al*. 2022; Nam *et al*. 2024; Negi *et al*. 2025; Hochebner *et al*. 2026).

Most research on temperature extremes in Lithuania concentrates on national-scale assessments (Bukantis, Valiuskeviciene 2005; Kažys *et al*. 2011; Rimkus *et al*. 2012; Jaagus *et al*. 2014; LHMT 2023; Klimavicius, Rimkus 2024). Some studies focus on climate change (Misiune, Kažys 2022; Ramanauskas *et al*. 2024), temperature extremes (Mirsanjari *et al*. 2021; Dailidiene *et al*. 2023), and the UHI effect (Bukantis, Urbanaviciute 2022; Bukantis, Klimavicius 2024; Tehrani *et al*. 2024) at the city level, linking these to human health impacts (Liukaityte, Rimkus 2008; Liukaityte 2011; Kažys 2012; Martinez *et al*. 2018; Tuniki *et al*. 2025). The UTCI has primarily been used for spatiotemporal assessments in Lithuania (Kažys 2012; Kažys, Malūnavičiūtė 2015; Kolendowicz *et al*. 2018; Kažys, Valiukas 2019). However, no research has yet applied the UTCI to analyze human bioclimatic conditions specifically for a city like Vilnius. Therefore, our research focuses on the various dynamics of UTCI values with a special focus on extreme heat and cold stress in a midlatitude midsized city. Additionally, it compares loads of heat in diverse environments (Local Climate Zone, LCZ types) in the city.

This research primarily aims to evaluate the current human bioclimatic conditions in Vilnius City using the UTCI. The objectives are: (1) to analyze the yearly, seasonal, and monthly UTCI trends from 1993 to 2024 concerning extreme conditions and (2) to compare UTCI values from the Trakų Vokė meteorological station with the data from two other stations (closer to the city centre) during extreme heat (95th percentile) events from 2022 to 2024.

STUDY AREA

This research evaluated the bioclimatic conditions of Vilnius, Lithuania's capital and largest city, in the eastern part of the country. The land area of Vilnius City Municipality is approximately 401 km². The population of Vilnius is 617,984 (State Data Agency 2026). The city features a humid continental climate (Köppen Dfb) characterized by warm summers, cold winters, and no dry season.

This research used three meteorological stations (Figs 1–2) in Vilnius City. The official Vilnius meteorological station in Trakų Vokė (TV station) (Fig. 1a) (54.625992, 25.107064, 160 m ASL) was the principal meteorological station for our research. This station is part of the Lithuanian Hydrometeorological Service (LHMT) network. The TV meteorological station is located in the southwest part of Vilnius, about 16 km from the city centre. The station is in an open terrain and free from tall buildings or obstructions. It is primarily surrounded by grass and some trees that do not block the measurement area.

Two other stations were only partially included in the research: Vilnius University meteorological station (VU station; Fig. 1b) (54.682817, 25.260648, 128 m ASL) and the station on the roof of the Lithuanian Hydrometeorological Service building (RS station; Fig. 1c) (54.702327, 25.274740, 109 m ASL), which have significantly different locations. The VU station is in the city centre, mainly surrounded by buildings and parked cars. The area includes grass and three tall trees nearby. The RS station is located north of the city centre, on the roof of the LHMT building in a residential zone. It has no grass around it and no tall trees nearby. Because of its placement, the RS station is higher above ground level than the other two stations. The TV station is the farthest from Vilnius city centre; it is almost in the suburbs. The other two stations are closer to the centre, but their surroundings serve different purposes – VU station is in the neighbourhood of Vilnius University's campus, and RS station is in residential neighbourhood. In Fig. 2, the LCZ (Local Climate Zone) classes are indicated. LCZ classes are a standardized way to classify landscapes based on surface cover, building structure, and materials that influence local climate, especially air temperature. They divide areas into urban types (e.g., compact high-rise, open low-rise) and natural types (e.g., forest, grassland, water) (Steward, Oke 2012). In this research, 3 classes appear: LCZ D (low plants), LCZ 6 (open low-rise), and LCZ 8 (large low-rise).

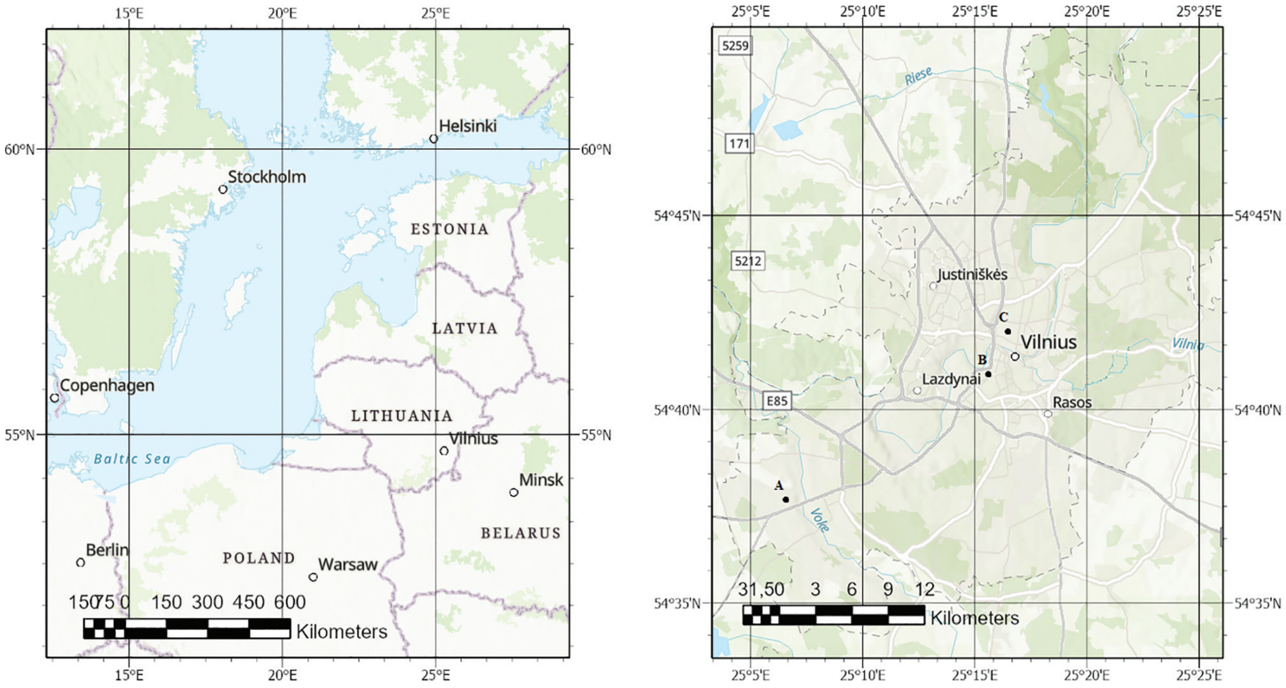


Fig. 1 Map of meteorology stations used in this research in Vilnius: A – TV station, B – VU station, C – RS station

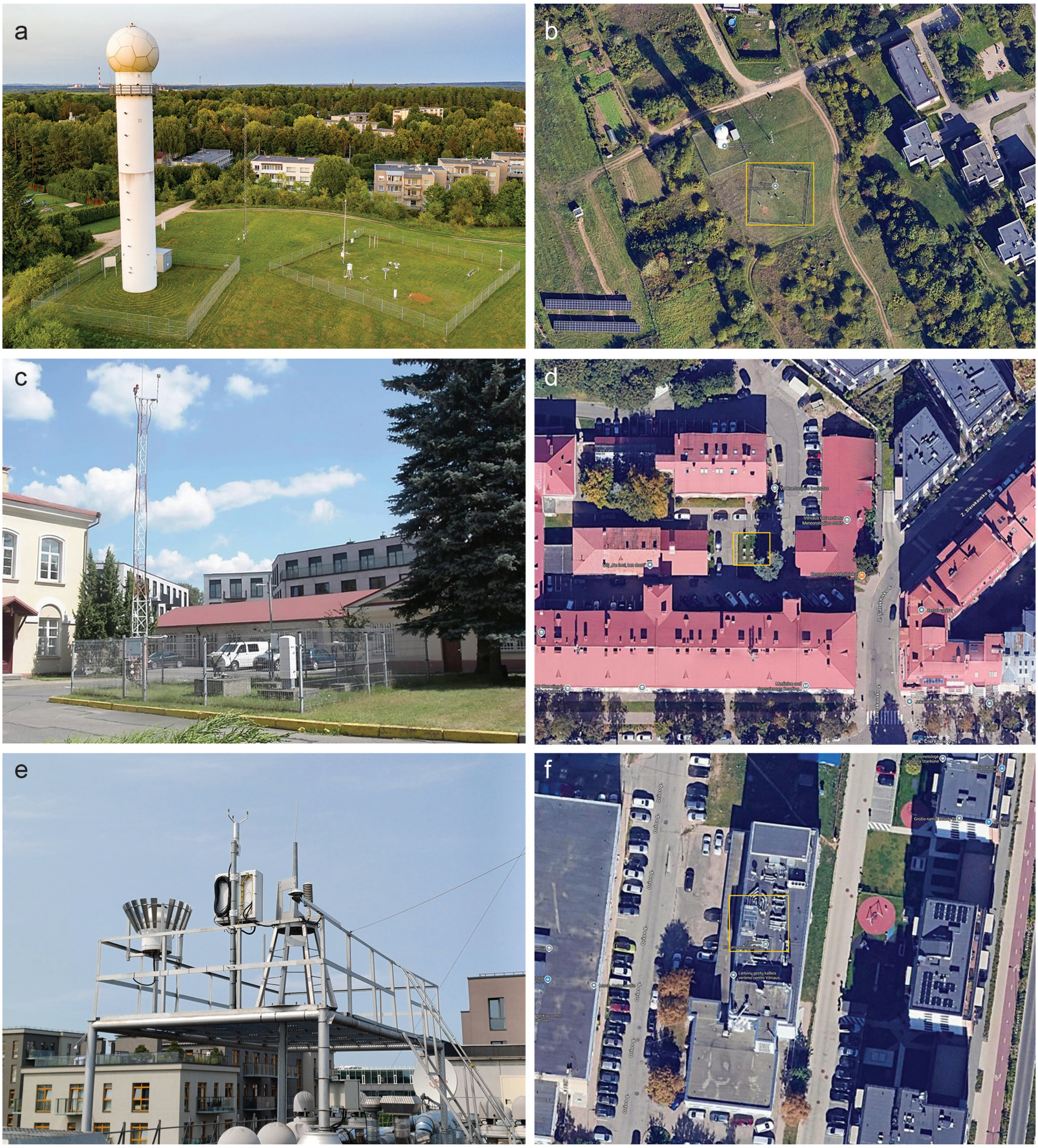


Fig. 2 TV station and its surrounding environment, LCZ D class (photo by A. Didžgalvis) (a), including aerial view (b); VU station and its surrounding environment, LCZ 6 class (photo by I. Kančys) (c), including aerial view (d); RS station and its surrounding environment, LCZ 8 class (photo by V. Mačiulyte) (e), including aerial view (f)

DATA AND METHODS

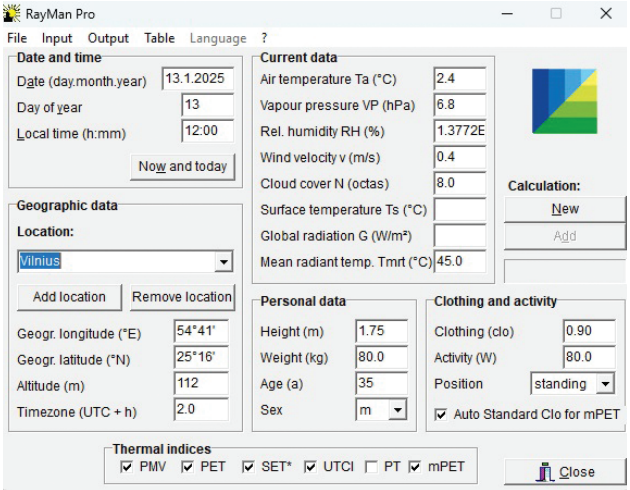
In this study, meteorological data from the TV station were collected every three hours from 1993 to 2024, including average air temperature (°C), air humidity (%), wind speed (m/s), and cloudiness (octas). Meteorological data from VU and RS stations were collected from 2022 to 2024. The VU station was used to measure the same parameters as the TV station was, while the data from the RS station included average air temperature (°C), humidity (%), wind speed (m/s), and solar radiation (W/m2).

The Universal Thermal Climate Index (UTCI) is calculated using a detailed physiological model that simulates how the human body responds to outdoor weather conditions (Błażejczyk *et al.* 2012). The UTCI combines multiple environmental factors: air temperature, wind speed, humidity, and radiant heat from the sun and nearby surfaces. These inputs are processed through a dynamic human body model, which considers clothing insulation and the person's activity level (sitting, standing, walking, working out, etc.). The result is expressed as an equivalent temperature that indicates a person's thermal stress (Błażejczyk *et. al* 2012). Although there isn't a straightforward formula for the UTCI, it is computed using specialized software or lookup tables created by biometeorology experts, providing a reliable measure of human thermal comfort across different climates. For this research, the UTCI was calculated for a standard person with a height of 1.75 meters, a weight of 80 kg, an age of 35, standing, with an activity level of 80 W. Clothing insulations changes depended on meteorological input data.

These UTCI values were calculated using the RayMan Pro version 3.1 beta (Fig. 3). This software version was developed around 2016. The TV station was the research base station, and calculations based on this station's data were the starting point for comparing three stations. After completing the UTCI calculations, the data analysis phase began. The UTCI is categorized into 10 groups (Table 1).

First, the chronological changes in the UTCI were calculated. Using daily data collected every three hours, the daily averages, minimums, and maximums of the UTCI were determined to observe how this index varied over the research period. Each three-hour measurement was counted as one event, so there were eight events per day. The average daily UTCI frequency was also calculated, and this data was compared across the entire period. Multi-year averages, minimums, and maximums of the UTCI were computed for different years, and the differences between these years were analyzed. The Mann-Kendall test was used to assess the statistical significance of the data trends. The trend is considered statistically significant when the *p*-value is less than 0.05.

Secondly, the same procedures were applied to data from the VU and RS stations. For this part of the study, the 95th percentile of UTCI minimum and maximum data from the TV station was calculated to identify dates (from 2022 to 2024) when the maximum UTCI and the highest minimum UTCI occurred. Some days within the 95th percentile were excluded because not all three stations' UTCI data were available due to missing meteorological information, and those days were omitted. Comparisons were made for these selected dates: 51 days for minimum and 53 days for maximum. This comparison was only performed when data from all three stations were available. A few dates from the 95th percentile were omitted because one station lacked data. The specific dates for the maximum UTCI were 14.08.2022, 24.08.2022, 25.08.2022, 27.08.2022, 28.08.2022, 29.08.2022, and 17.07.2023; for the minimum UTCI, the dates were 15.08.2022 and 28.08.2022. The 95th percentile data method was chosen to compare UTCI data across the three stations based on the TV station. The total of different UTCI categories was calculated to analyze how various Vilnius locations assess different thermal stress situations, showing how different places in Vilnius influence people's thermal comfort levels due to diverse surrounding environments.



Date and time
Date (day.month.year) 13.1.2025
Day of year 13
Local time (h:mm) 12:00

Geographic data
Location: Vilnius
Geogr. longitude (°E) 54°41'
Geogr. latitude (°N) 25°16'
Altitude (m) 112
Timezone (UTC + h) 2.0

Current data
Air temperature Ta (°C) 2.4
Vapour pressure VP (hPa) 6.8
Rel. humidity RH (%) 1.3772E
Wind velocity v (m/s) 0.4
Cloud cover N (octas) 8.0
Surface temperature Ts (°C)
Global radiation G (W/m²)
Mean radiant temp. Tmrt (°C) 45.0

Personal data
Height (m) 1.75
Weight (kg) 80.0
Age (a) 35
Sex m

Clothing and activity
Clothing (clo) 0.90
Activity (W) 80.0
Position standing
☑ Auto Standard Clo for mPET

Thermal indices
☑ PMV ☑ PET ☑ SET* ☑ UTCI ☐ PT ☑ mPET

Fig. 3 Rayman Pro software main window view

Table 1 UTCI equivalent temperature categorized in terms of thermal stress (Błażejczyk *et al*. 2013)

UTCI (°C) range	Stress Category	Category number
Above +46	Extreme heat stress	1
+38 to +46	Very strong heat stress	2
+32 to +38	Strong heat stress	3
+26 to +32	Moderate heat stress	4
+9 to +26	No thermal stress	5
+9 to 0	Slight cold stress	6
0 to –13	Moderate cold stress	7
–13 to –27	Strong cold stress	8
–27 to –40	Very strong cold stress	9
Below –40	Extreme cold stress	10

RESULTS

Vilnius is in a humid continental bioclimate, characterized by cold winters, warm summers, and strong seasonal contrasts, with mean temperatures around −5 °C in January and around +18 °C in July (LHMS information). Moderate precipitation is spread evenly throughout the year. Bioclimatic comfort is strongly seasonal: winter conditions often exceed cold-stress thresholds, while summer heat stress is generally moderate but can intensify during heatwaves. In terms of Local Climate Zones (LCZs), the city centre is dominated by LCZs 2–3 (compact mid-rise and compact low-rise), surrounded by extensive LCZs 5–6, 8 (open mid-rise and open low-rise residential areas (large low-rise), while large parks, forests, and river valleys correspond to natural LCZs (A–D) that help mitigate urban heat and improve thermal comfort.

UTCI values and trends in Trakų Vokė station

First, the frequency of UTCI categories was analyzed. Figure 4 shows that very strong cold stress (–27 to –40°C) was not observed during the 2014–2024 period. Meanwhile, moderate heat stress (+26 to +32°C) occurred more frequently than in earlier years. Before 2010, the frequency of moderate heat stress was about 4%, but from 2010 onward, it doubled to approximately 8%. Additionally, very strong cold stress (–27 to –40°C) did not occur in the TV station from 2014 onward. In this data, only the slight cold stress category (0 to 9°C) is not statistically significant ($p = 0.18$). All other categories show statistically significant trends: increasing trends in no thermal stress (9 to 26°C), moderate heat stress (26 to 32°C), and strong heat stress (32 to 38°C) and decreasing trends in moderate cold stress (0 to –13°C), strong cold stress (–13 to –27°C), and very strong cold stress (–27 to –40°C) ($p < 0.05$).

When analyzing the data on TV station's moderate and higher heat stress (26–46°C) as well as strong and lower cold stress (–13 to –40°C) counts over different years (see Fig. 5), it was found that from 2010 onward, moderate heat stress and increased heat discomfort occurred much more frequently than in previous years. Before 2010, there were about 121 thermal heat discomfort events on average; after 2010, this number nearly doubled to approximately 235 events. The number of strong cold stress and colder events decreased nearly every year. Before 2010, these cold discomfort events averaged 84 times annually, but after 2010, the number dropped to about 31. In a way, the data shows that in earlier years, heat and cold thermal stress events were roughly equal in number. However, in later years, these stresses diverged. With this trend, it is possible that in the next 50 years or so, strong or lower cold stress will decrease significantly or disappear entirely. Both data trends are statistically significant ($p < 0.05$).

When examining changes over different years (data is statistically significant, $p < 0.05$), it was observed that the UTCI was gradually rising during the research period, and minimum UTCI values have

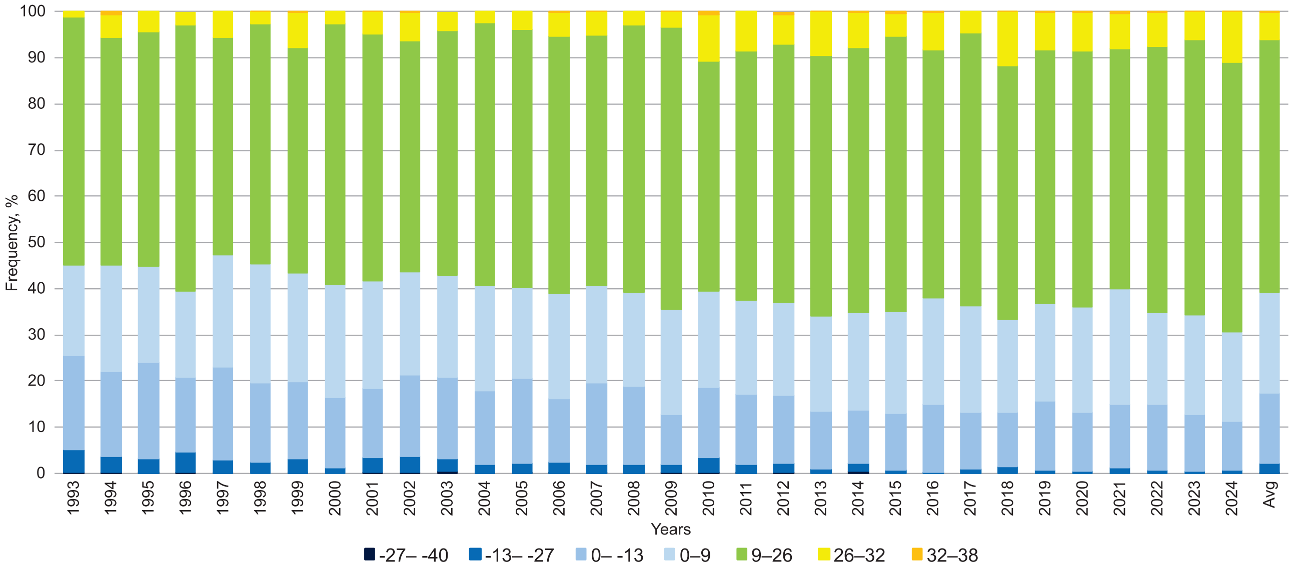


Fig. 4 UTCI categories frequency (%) in Trakų Vokė station for 1993–2024 and the average

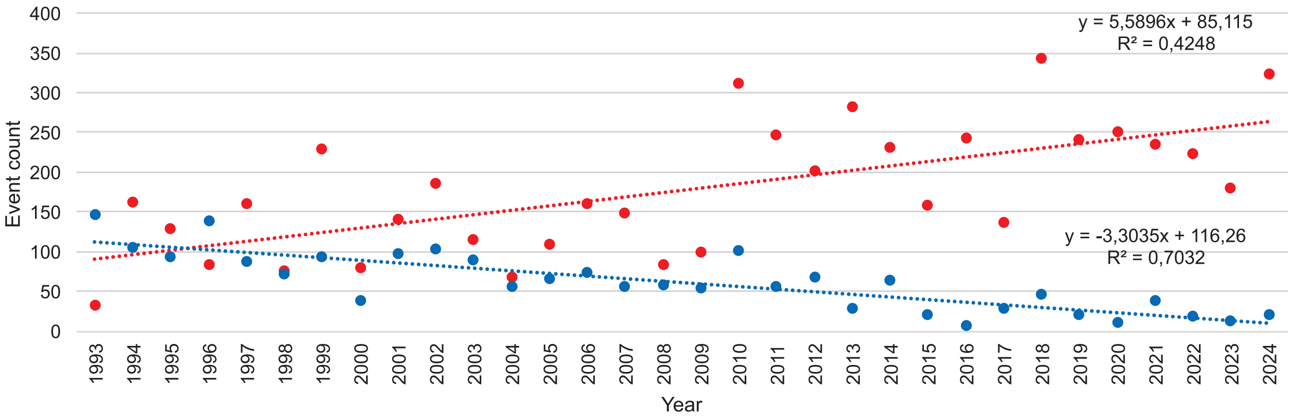


Fig. 5 Event count with moderate/higher heat stress (red) and strong/lower cold stress (blue) in Trakų Vokė station, 1993–2024

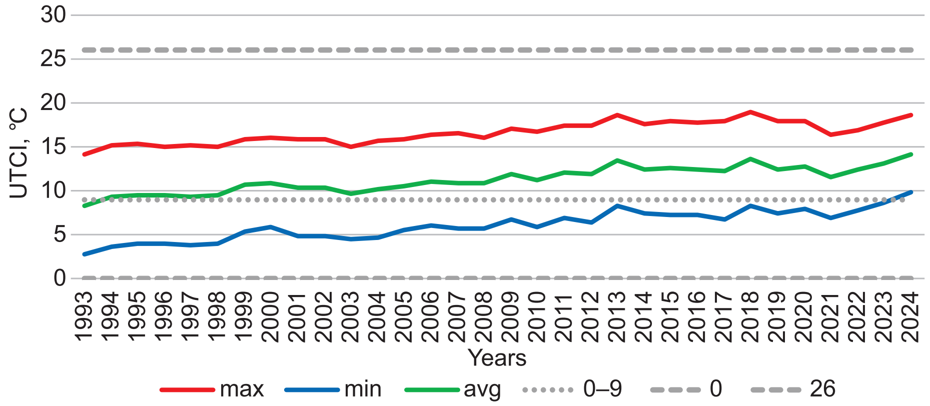


Fig. 6 Mean UTCI yearly data (min, max, avg) distribution, 1993–2024

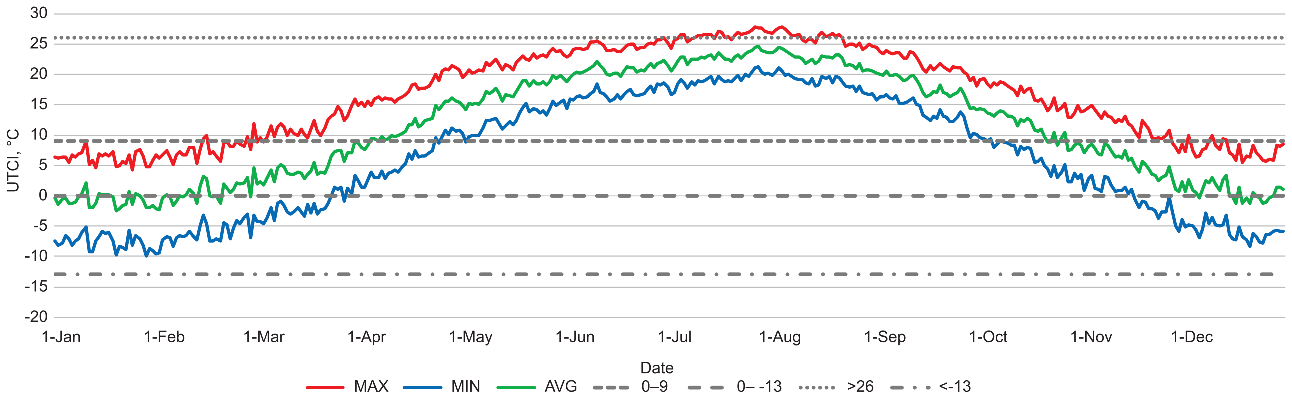


Fig. 7 Mean UTCI daily data (min, max, avg) distribution, 1993–2024

even shifted from slight cold stress to no thermal stress (Fig. 6) in recent years. The maximum UTCI temperature increased by nearly 3 degrees Celsius from 1993 to 2024. If this trend continues, the UTCI temperature is likely to stay comfortable for people, with no thermal stress in the Vilnius suburbs.

The calculation of the same-day averages each year shows how the UTCI is spread across different days of the year. Figure 7 illustrates that various parts of the year fall into different UTCI categories. On average, from 1 December to 1 April, people in Vilnius experienced moderate to slight cold stress. Starting in mid-April, no thermal stress "window" began. While thermal discomfort did not occur in late spring, summer and early autumn, moderate heat stress was observed when calculating maximum values in July and August. After the beginning of October, minimum UTCI values entered the slight cold stress category (0 –9°C). From 1 November, the average UTCI data also fell into the slight cold stress category, and from 1 December, cold stress was present in all UTCI data.

When analyzing changes in seasonal UTCI maximum values over different years, it was found that during winter months (December, January, February), lower average UTCI values were recorded in earlier research periods (Fig. 8a). As we move toward more recent data, the UTCI values become less negative. All trends shown in Figs. 8 and 9 are statistically significant ($p < 0.05$). Figures 8 c and d show that the maximum UTCI increases yearly in summer and autumn. This suggests that meteorological conditions in summer and autumn significantly impact people's comfort. Autumns are becoming milder, with slower temperature drops after hotter, less humid summers.

Changes in seasonal UTCI minimum values are even more significant, especially during winter and autumn (Fig. 9 a, d). During winter months, average minimum UTCI data shifted from about –10°C (in 1993) to roughly –5°C (in 2024). In autumn, the change from the start to the end of the study period is even greater. In spring, the minimum UTCI data changed less than in other seasons (Fig. 9 b). Overall, there is a rising trend in both the minimum and maximum UTCI data throughout the research period.

Comparison of extreme heat events between 3 stations

When comparing three different stations in Vilnius city, some differences in the UTCI appeared (Table 2). The highest UTCI recorded from the TV station (the station that is farther away from Vilnius centre than the other two) showed that 87% of the events were moderate heat stress (category 4). In contrast, the VU station's events mostly fell into strong heat stress (category 3). Only one day among these 95th percentile

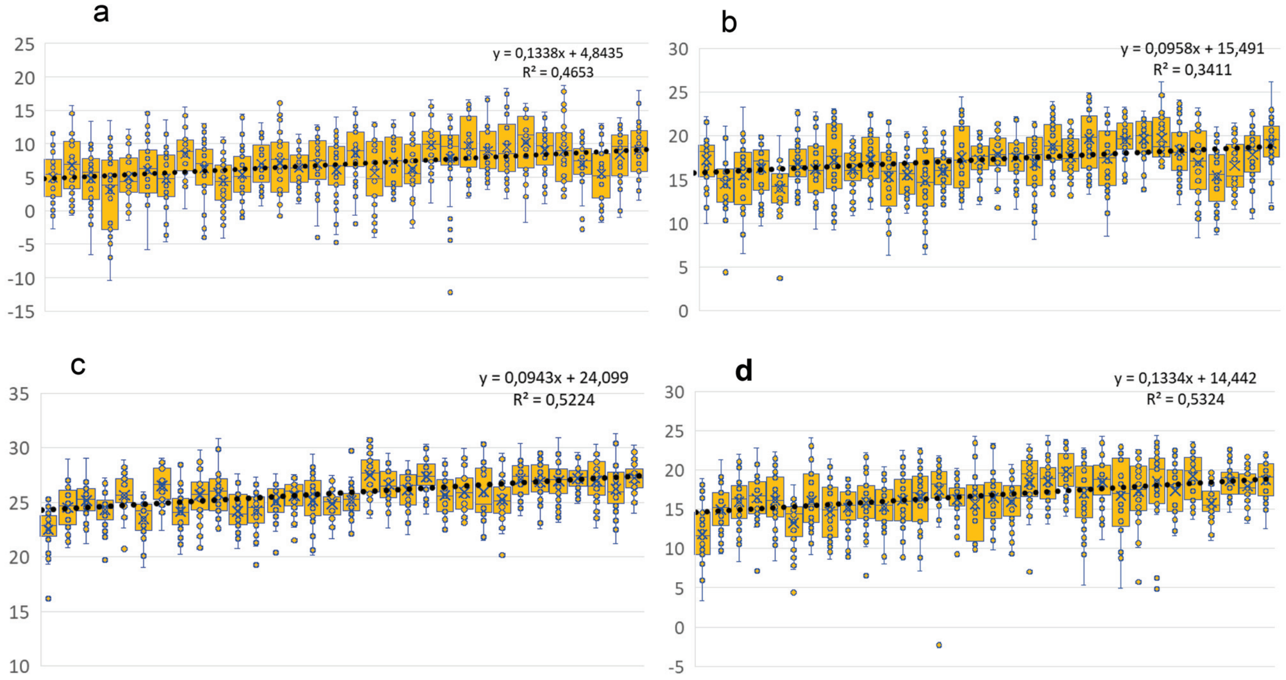


Fig. 8 Maximum daily average winter (a), spring (b), summer (c), and autumn (d) UTCI data during the research period (1993–2024)

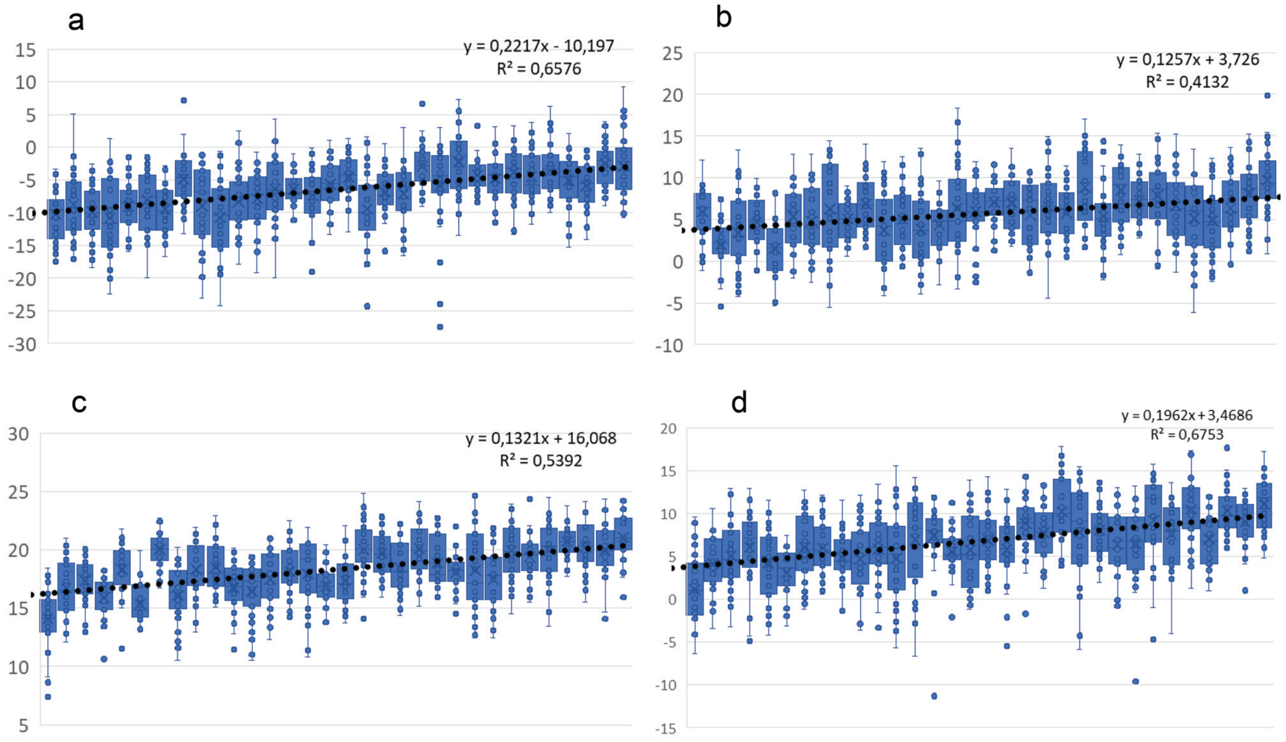


Fig. 9 Minimum daily average winter (a), spring (b), summer (c), and autumn (d) UTCI data during the research period (1993–2024)

days had lower category events, indicating that the city centre heats up more than the suburbs. The RS station, located on the LHMS roof in a residential area, produced results in the middle compared to the same days. Categories 3 and 4 were nearly evenly split in this area, about 50:50. On average, the maximum UTCI calculated from the VU station's data is by about 11% higher than that from the TV station's data, while the RS station's data is by approximately 3% higher. The difference in minimum UTCI values is less significant – around 0.5% to 1%.

The minimum UTCI data shows a relatively similar distribution across the stations. VU station's minimum UTCI data mostly fall into the 4th category (~ 88%),

Table 2 Comparison of UTCI at TV, VU, and RS stations on the 95th percentile hottest events

MAX				MIN			
Date	TV	VU	RS	Date	TV	VU	RS
2022-06-24	29.8	32.3	30.4	2022-06-24	24.4	28.5	25.7
2022-06-25	30.4	33.5	31.0	2022-06-25	25.1	26.1	24.0
2022-06-26	31.5	34.4	31.7	2022-06-26	26.6	27.3	25.5
2022-06-27	31.2	34.7	32.5	2022-06-27	27.8	28.6	25.3
2022-06-28	31.7	35.5	32.5	2022-06-28	27.3	29.3	28.2
2022-06-29	33.2	35.7	33.0	2022-06-29	27.2	28.9	27.3
2022-06-30	30.7	33.9	31.5	2022-07-01	25.5	29.3	28.3
2022-07-01	30.5	34.6	32.1	2022-07-04	24.3	27.7	27.3
2022-07-02	29.9	35.3	32.0	2022-07-22	26.3	27.8	29.2
2022-07-04	30.7	33.4	30.3	2022-08-05	25.3	25.4	24.7
2022-07-22	32.2	34.9	32.4	2022-08-16	24.8	30.6	27.5
2022-08-04	30.8	32.6	30.7	2022-08-17	24.8	27.2	26.8
2022-08-05	31.4	34.5	33.2	2022-08-18	25.9	27.9	25.0
2022-08-06	30.0	34.2	30.4	2022-08-19	25.8	28.9	26.8
2022-08-16	29.8	32.5	32.3	2022-08-23	25.5	26.9	24.4
2022-08-17	30.5	34.6	31.8	2023-06-16	24.2	25.7	21.8
2022-08-18	32.3	35.4	32.5	2023-06-18	25.4	28.5	26.6
2022-08-19	30.0	33.7	31.8	2023-06-20	26.0	27.9	27.1
2022-08-23	30.7	34.5	31.0	2023-06-21	25.0	29.2	25.6
2023-06-21	31.7	32.9	30.5	2023-08-06	24.1	27.8	25.9
2023-07-16	31.2	32.8	33.5	2023-08-16	25.2	30.2	30.0
2023-08-06	31.9	35.5	31.7	2023-08-17	26.9	30.2	29.8
2023-08-15	31.2	36.2	33.0	2023-08-18	26.5	29.9	27.9
2023-08-16	31.1	36.1	33.8	2023-08-19	25.5	29.0	26.5
2023-08-17	33.9	38.0	35.2	2023-08-20	26.6	32.6	28.2
2023-08-18	31.2	35.3	32.7	2023-08-27	24.8	30.0	27.0
2023-08-19	30.1	34.5	32.1	2024-05-19	24.5	21.3	23.8
2023-08-20	31.2	35.4	33.0	2024-05-26	24.2	26.9	25.8
2023-08-26	29.8	34.4	32.1	2024-06-26	25.2	28.9	26.4
2023-08-30	32.0	34.8	33.4	2024-06-37	26.2	26.6	24.8
2024-06-27	31.3	35.9	32.6	2024-06-28	26.2	27.9	27.3
2024-06-28	31.0	36.0	33.1	2024-07-12	24.1	28.9	24.5
2024-07-09	30.0	32.1	30.8	2024-07-13	25.3	29.0	27.7
2024-07-11	30.4	34.5	32.3	2024-07-14	24.8	28.8	25.7
2024-07-12	30.4	33.7	31.7	2024-07-16	25.9	28.0	24.9
2024-07-13	31.8	35.8	32.0	2024-07-21	25.6	27.1	26.1
2024-07-16	30.4	35.3	31.6	2024-07-22	24.3	27.4	25.7
2024-07-17	31.1	33.6	31.3	2024-07-23	26.1	27.6	26.0
2024-07-22	30.2	32.3	30.5	2024-07-27	24.3	30.0	25.4
2024-08-08	29.9	31.5	30.2	2024-08-06	24.1	29.6	26.7
2024-08-17	31.4	33.5	30.6	2024-08-15	24.3	25.0	23.5
2024-08-18	32.1	35.4	32.0	2024-08-17	26.4	29.7	27.8
2024-08-19	31.2	33.9	32.0	2024-08-18	25.4	28.6	27.6
2024-08-29	30.5	35.1	31.9	2024-08-19	24.9	30.3	27.3
2024-08-30	32.4	34.8	32.4	2024-08-20	24.1	27.3	26.0
2024-09-02	30.4	32.6	30.9	2024-08-21	25.2	28.3	27.9
				2024-08-30	26.8	27.5	25.8
				2024-09-04	24.2	25.9	22.4
				2024-09-12	24.5	25.5	25.2
Moderate heat stress (4 cat)	86.96%	2.17%	54.35%	No thermal stress (5 cat)	73.47%	12.24%	40.68%
Strong heat stress (3 cat)	13.04%	97.83%	45.65%	Moderate heat stress (4 cat)	26.53%	87.76%	59.32%

while TV station's data indicates no thermal stress during these dates for 73% of the research. When comparing max data to min data, some patterns emerge. When strong heat stress is calculated (maximum UTCI) on the same day, the minimum UTCI drops by one category; some days even drop two categories to no thermal stress. This pattern illustrates how different environments cause territories to cool down at different rates.

At the RS station, the minimum UTCI data indicates an increase in the 4th category. This station is located in a residential area, and the minimum UTCI data may rise due to changes in car traffic, different building materials, and varying underlying surfaces.

DISCUSSION AND CONCLUSIONS

Our findings show that, on average, humans do not experience any thermal stress more than half the time (55%) in Vilnius. Generally, bioclimatic changes lead to more frequent heat stress events and fewer cold stress days (Okoniewska *et al*. 2025). At the same time, they affect the yearly percentage of optimal (no thermal stress) conditions in cities (Katavoutas *et al*. 2022), which we have already observed in Vilnius (Fig. 4). Despite improved thermal comfort (no stress), cold stress still makes up 39% of all UTCI events.

We observed significant opposite sign changes in the maximum (+168 hrs./decade) and minimum (–99 hrs./decade) UTCI event frequencies in Vilnius city (Fig. 5). Rozbicka *et al*. (2025) reported similar clear positive trends for UTCI heat stress categories and a decrease in cold stress in Poland. These climate change trends have also been observed in the Baltic Sea Region. Gecaite and Rimkus (2023) found that absolute winter air temperature minimums and maximums increased over the 1951–2020 period. Meanwhile, the number of extremely warm days roughly doubled during the 1951–2021 period (Jaagus *et al*. 2024).

It was not surprising that we observed a significant increase in UTCI values (Fig. 6) in Vilnius from 1994 to 2024, since Europe has been warming at twice the rate of the global average, making it the fastest-warming continent on Earth (since the mid-90s +0.53 °C per decade) (C3C 2025). However, the UTCI is not just air temperature; it is a comprehensive bioclimatic index (equivalent temperature) that measures human thermal stress, accounting for wind speed, humidity, and solar radiation (Brode *et al*. 2012). Consequently, UTCI trends are reaching even higher levels: the average UTCI increase is 1.4 °C per 10 years. A recent study by Okoniewska *et al*. (2025) identified a UTCI trend of 0.61 °C per 10 years for Poland. Additional research also shows increasing UTCI trends in the Baltic Sea Region (Každys, Malunaviciute 2015; Kolendowicz *et al*. 2018; Katavoutas *et al*. 2022, Nam *et al*. 2024). There is more evidence of changing human bioclimatic conditions in the south-eastern part of the Baltics analyzing standard air temperature records (Basarin et al. 2020; Dailidiene *et al*. 2023; Gecaite, Rimkus 2023; Jaagus *et al*. 2024; Ramanauskas *et al*. 2025) and PET values (Tomczyk, Matzarakis 2023).

In Vilnius, the highest increase is observed in minimum (nighttime) UTCI values (Figs 6, 9): 1.7 °C per decade. Kuchcik *et al*. (2021) observed similar trends in Poland, with a 1.33 °C per decade rise in minimum UTCI values. Seasonal analysis in Vilnius shows that UTCI values are increasing at different rates: during the daytime (maximum values), the steepest rise occurs in summer and autumn (Fig. 8), while at night (minimum values), the greatest increases are in winter and autumn (Fig. 9). Autumn is becoming the most comfortable season with no thermal stress. However, rising UTCI values in summer are likely to cause more moderate or severe heat stress events in the future. Changes in thermal conditions will be a significant environmental and public health concern in Vilnius (Ramanauskas *et al*. 2024), and the decrease in cold-related mortality does not outweigh the rise in heat-related deaths (Martinez *et al*. 2018).

The average comfortable conditions (no thermal stress) in Vilnius last for nearly 7 months (see Fig. 7): from the end of March to the end of October; this is similar to what is observed in Polish cities (Tomczyk, Bednorz 2023; Rozbicka *et al*. 2025). Každys, Malunaviciute (2015) found that comfortable conditions along the Baltic Sea coast for the period 1980–2009 lasted between 100 and 140 days, depending on the region. However, in Vilnius, minimum UTCI values reach the comfortable zone only for about 5 months (from May to September), and from early June until the second decade of August (almost 2 months), maximum UTCI values rise into the "moderate heat stress" zone. Therefore, the most comfortable bioclimatic conditions for humans in Vilnius are experienced in May, June, and September. A similar yearly UTCI distribution (though with lower minimum values) was found by Rozbicka, Rozbicki (2021) in Warsaw for the period 1980–2016.

We have already experienced 2023 and 2024 as the hottest years in Lithuania's temperature records since 1770. Approximately 47,700 heat-related deaths occurred in Europe in 2023 and around 61,700 in 2022, serving as strong indicators of the increasing frequency and severity of heatwaves (C3C 2025). According to LHMT data, from 1961 to 2023, a total of 34 heatwaves were recorded in Lithuanian cities (Vilnius, Kaunas, and Klaipeda). The number of hot days (≥ 30 °C) in Vilnius rose from 1.6 days per year (1961–1990) to 5.3 days per year (1991–2020) (Ramanauskas *et al*. 2024). Urban environments experience much stronger heat effects compared to rural areas due to the Urban Heat Island effect (UHI) (Błażejczyk *et* *al*. 2016; Matzarakis *et al*. 2016; Pecelj *et al*. 2021; Li *et al*. 2023), and the UTCI is a universal tool for describing the impact of thermal stress on the human body (Di Napoli *et al*. 2021; Romaszko *et al*. 2022). Bukantis and Klimavicius (2024) found that seven heatwaves occurred in 2022–2023 in the Vilnius city centre (VU station), while only three heatwaves were recorded in Vilnius Airport area. Similar UHI effects on central *vs*. suburban parts were found in various Polish cities (Półrolniczak *et al*. 2018; Sachindra *et al*. 2023; Kuchcik *et al*. 2024; Hajto *et al*. 2025; Tasan *et al*. 2025). We analyzed the 95th percentile of maximum and 5th percentile of minimum UTCI daily values from 2022 to 2024 in Vilnius (Table 2). On average, maximum UTCI values at the VU station, which most accurately represents the city centre (Figs 1, 2), were higher compared to the RS (residential area) and TV (suburban) stations, with differences of 2.4 °C and 3.4 °C, respectively. Smaller but still significant differences were observed in the minimum UTCI values (1.9 °C and 2.7 °C, respectively). Similar UTCI value distributions within cities have been found in Warsaw (Błażejczyk *et al*. 2016; Rozbicka, Rozbicki 2021; Kuchcik *et al*. 2024) and Stuttgart (Matzarakis *et al*. 2016).

The TV station, LHMT's official meteorological station, is situated on the outskirts of Vilnius city (see Fig. 1). Our data shows (see Fig. 3) that, due to the UHI effect, UTCI values can vary by as much as 5.4 °C (on 02.07.2022). Most often (85%), maximum UTCI values at the VU station fall into the "strong heat stress" category, which can significantly impact human health and well-being. Several factors influence UTCI distribution in cities, including proximity to the city centre, building materials, building density, sky view factor, green space ratios, and more. A comparison among three different Vilnius areas shows how thermal stress varies across different locations. Rural areas experience less thermal stress because of abundant greenery, fewer crowded buildings, and less dense environments. Conversely, the city centre faces a higher thermal stress due to limited greenery, many buildings, pavements, and restricted air flow, all of which reduce cooling and decrease comfort for residents. At night, these areas generally cool down by at least one category. However, in residential areas near the RS station, cooling is less effective.

Despite significant findings, our research has a few limitations. First, the TV meteorological station is situated on the outskirts of the city (LCZ D) and has more rural landscape features. Therefore, the analysis only presents the generic conditions and tendencies of the UTCI. Secondly, the VU and RS meteorological stations, respectively, LCZ 6 and LCZ 8, do not fully represent the local climates, because the VU station is located in a closed inner yard and the RS station is on the rooftop of the building. It might be the over(under-)estimation of the extreme UTCI values depending on the specific microclimatic conditions. Thirdly, due to the limitations in UTCI calculation (Brode *et al*. 2012; Nie *et al*. 2022; Brode, Kampmann 2023; Chen *et al*. 2025; Sargazi *et al*. 2026), such as fixed metabolic rate, adjusted clothing insulation, and sensitivity limitation (wind velocity), it is difficult to determine real heat stress impacts on the most vulnerable members of society, different sex and age groups, various physical activities and abrupt weather changes. Therefore, a complex and holistic approach by integrating the LCZ concept (Langer *et al*. 2021; Lehnert *et al*. 2021; Kuchcik *et al*. 2024; Hajto *et al*. 2025; Muhlbauer 2025) and other human bioclimatic indices, such as PET and PMV (Matzarakis *et al*. 2014; Zare *et al*. 2018; Basarin *et al*. 2020; Gatto *et al*. 2020; Eslamirad *et al*. 2023; Pantavou *et al*. 2024; Sargazi *et al*. 2026), the modelling of urban environments (Frohlich, Matzarakis 2020; Chen 2023; Silva *et al*. 2025; Gregorčič *et al*. 2026), and connecting with air pollution (Davtalab, Bycenkiene 2026) and health (Romaszko *et al*. 2022; Vanos *et al*. 2023) concepts could create a deeper understanding of heat stress impacts on human well-being within the cities.

One promising way to reduce the UHI effect is greening urban areas (Błażejczyk *et al*. 2016; Antoszewski *et al*. 2022; Yi *et al*. 2023; Parker *et al*. 2024; Silva *et al*. 2024; Lindberg *et al*. 2025; Lindner-Cendrowska *et al*. 2025; Negi *et al*. 2025; Ramanauskas *et al*. 2025). In the near future, a more detailed analysis of UTCI distribution across different urban environments and LCZs will be necessary to better understand human thermal conditions in Vilnius.

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