Spatiotemporal Assessment of Outdoor Thermal Comfort Regimes in Urban Plazas of Chicago

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ABSTRACT: Unique microclimates in urban plazas around tall buildings impact people's presence, which is driven by the Outdoor Thermal Comfort (OTC) levels. Increasing interest in OTC studies due to their significant contribution to the UN Sustainable Development Goal SDG11 has led to the development of advanced OTC indices. Urban designers and planners strive to gain knowledge in assessing their outdoor public space designs through these indices, thus understanding the impact of such developments on people's social lives. Microclimate CFD simulation is a popular method commonly employed on this topic. This study uses CFD simulation using ENVImet to model microclimates and OTC indices for five urban plazas in downtown Chicago with Dfa climate zone. The study adopts a spatiotemporal approach to assess three OTC indices, namely, Physiological Equivalent Temperature (PET), Standard Effective Temperature (SET*), and Universal Temperature Climate Index (UTCI). Using physiological thermal stress levels as a basis for comparison, the spatial approach involves the distribution of comfort regimes in the plazas, while the temporal approach uses the mean values of the OTC indices to address the research objectives, which are (a) comparing 'neutral' comfort regimes of PET, SET*, & UTCI during a peak lunch hour of the summer solstice day, (b) exploring spatial distribution of neutral regimes of these indices, (c) temporal analysis of PET thermal stress categories and microclimatic variables between 12-2 pm, and (d) spatiotemporal analysis of the same within and between the plazas. The findings show that SET* and UTCI lack granularity around neutral thermal stress regimes, unlike PET, which limits the understanding of finer thermal conditions that may exist in the plazas and could be critical in the success of the plaza. The other key findings of this study highlight the importance of the spatial distribution of thermal stresses in assessing the thermal conditions of an outdoor environment.

KEYWORDS: outdoor thermal comfort, microclimate, urban plazas, cfd, thermal stress

INTRODUCTION

Microclimate creates a thermal environment that impacts people's presence in outdoor public spaces (Tsitoura, Tsoutsos, and Daras 2014), thus contributing to the quality of life in cities, both from an economic and social viewpoint (Stathopoulos 2009). Humans perceive the thermal environment through thermal comfort. Outdoor Thermal Comfort (OTC) studies over the past few decades have gained momentum due to their direct contribution to the UN Sustainable Development Goal SDG11 (United Nations Department of Economic and Social Affairs 2023). Numerous OTC models and indices have been developed during this period. These studies are also critical to understanding human physiological thermal stress levels. Extremities in microclimates could increase stress levels, which are found to be hazardous to human health (Luber and McGeehin 2008). Hence, OTC indices and their associated thermal stresses become an important area of study for public space design. Recent interest in the OTC topic has led to many studies exploring the OTC models and their thermal perceptions, which are based on subjective models developed through people's perceptions of their comfort levels (Potchter et al. 2018; Cheung and Jim 2017). Thermal stresses and their comfort perceptions in certain models associated with a temperature range could provide a basis for comparison. The continuous surge in world population has led to an increase in tall urban scenarios in cities, which create unique microclimates. These climatic conditions impact the outdoor urban spaces in such cities. Architects and urban planners strive to gain knowledge in outdoor public space designs to ensure sustainable development. James Parakh, in his work, stresses the relationship between tall buildings and open spaces by stating-

> One of the key ways that tall buildings contribute to the public realm is by framing and creating open spaces at their base. (Parakh 2015).

Moreover, a lot of work has been done on OTC and outdoor public spaces in mid-rise urban conditions in temperate climate zones, unlike the case in US cities with tall buildings in the continental climate zone of the Koppen climate classification (Kumar and Sharma 2020; Khan, Azari, and Stephens 2020). One such case is Chicago city with its "Dfa" hot summer humid continental climate. The city of Chicago has a rich history of tall buildings. The definition of 'tall' is usually relative to the average building heights of the urban context as defined by the Council of Tall Buildings and Urban Habitat (CTBUH). Per this definition, a building with 150m and above height is considered a tall building in Chicago (CTBUH 2019). A comprehensive study on the public spaces around tall buildings in Chicago shows that out of 116 tall buildings (150m+ height), around 56 have public spaces at the ground level (Khan and Du 2020). Not all these spaces are successful or popular in terms of people's attendance. One of the likely reasons could be microclimates, which could be significantly different given their urban morphological conditions. This research is an effort to fill this knowledge gap in this area.

1.0 LITERATURE REVIEW

1.1. OTC indices and research question

OTC indices are a function of varied climatic factors that impact human behavior in outdoor spaces. These include temperature, humidity, solar radiation, and wind velocity. Studies show that perception of thermal environment, created by these microclimatic variables, also involve physiological and behavioral variables, namely metabolic rates and clothing levels respectively (Nikolopoulou and Steemers 2003; Chen and Ng 2012). The assessment of OTC perception has resulted in numerous indices. It ranges from simple models that were adapted from indoor thermal comfort models to advanced ones that include heat stress or energy balance models comprising of all the variables discussed earlier in this section. Some of the most commonly used indices are PET (Physiological equivalent temperature) by Hoppe in 1992 (Höppe 1999), SET* (Standard Effective Temperature) by Gagge et al. (Gagge, Fobelets, and Berglund 1986) and PMV (Predicted Mean Vote) by Fanger in 1972 (Fanger 1982) (Honjo 2009). However, the unit of PMV is an actual vote, unlike the rest, which uses temperature as a unit. Because of this, PMV is excluded from the discussion in this research. Nevertheless, the other three indices offer a high level of sophistication and have been compared in various studies through different lens (Zare et al. 2018; Potchter et al. 2018; Coccolo et al. 2016).

A comprehensive study of more than 160 OTC indices uses an evaluation score through six criteria namely comprehensiveness (number of variables), scope (range of environmental conditions), sophistication (conceptual merits), transparency (clarity in rationale), usability (application), and validity (reliability) to sort them for an easy use (de Freitas and Grigorieva 2017) (refer to Table 1). One of the criteria, which is the lowest for all the three indices, considers computational procedure, standard data, and easy output as a structure for evaluation. This research explores this criterion further within these models by applying the logic on five plazas in Dfa Climate zone city i.e. Chicago.

Table 1: Five assessment criteria to rate PET, SET*, UTCI. Source: (Extracted from the comprehensive list from (de Freitas and Grigorieva 2017))

Index	Comprehensiveness	Scope	Sophistication	Transparency	Usability	Validity	Total
PET	5	5	5	5	3	3	26
SET*	5	3	5	5	3	5	26
UTCI	5	5	5	5	3	4	27

Thermal perceptions defined through the human physiological stress levels of outdoor thermal conditions provide wholistic understanding of OTC indices. These stress levels are categorized using levels which are set in temperature units in certain indices namely PET, SET*, and UTCI. This study uses thermal stress as a basis of comparing the three indices. Several studies exist where thermal stress thresholds for different indices are documented and discussed at length (Coccolo et al. 2016; Zare et al. 2018). Table 2 is developed from these studies to reflect the stress levels, and threshold for the studies OTC indices.

Table 2: Thermal Stress Categories for PET, SET*, UTCI. Source: (Adopted from (Zare et al. 2018))

	PET (°C)	SET (°C)	UTCI (°C)
extreme cold	<4		<-40
very cold			-40 to -27
cold	4 to 8		-27 to -13
moderate cold	8 to 13	<17	-13 to 0
slight cold	13 to 18		0 to 9
comfortable (neutral)	18 to 23	17 to 30	9 to 26
slightly warm	23 to 29		
warm	29 to 35	30 to 34	26 to 32
hot	35 to 40	34 to 37	32 to 38
strong heat			38 to 46
very hot	>41	>37	> 46

1.2. CFD modeling of microclimates

The continued interest in microclimates and OTC research has increased the use of Computational Fluid Dynamics (CFD) simulation as a popular research methodology on this topic. One of the biggest advantage of this approach is the ease in controlling the outdoor environment which is dynamic and challenging in real life (Toparlar et al. 2015; 2017). Amongst various software, ENVImet provides a comprehensive package of tools to simulate and visualize meteorological data, urban environments, vegetation, and soil types. It also includes Biomet that computes OTC indices PET, SET*, UTCI and PMV for these environments (Bruse 2018). The possibility of finer grid resolutions have been explored in many OTC studies (Maleki et al. 2014; Reinhart, Dhariwal, and Gero 2017). Typical OTC studies using CFD simulation focus on the values of OTC indices and their alignment with the benchmarks set for the investigation. Limited work has been done on the frequency of spatial distribution of these values in space. This study explores the novel approach of spatiotemporal distribution of OTC values and their associated thermal stress levels to answer following research questions: (1) How do the three OTC indices (PET, SET* & UTCI) differ in five different Plazas of Chicago when assessed using their mean values at 12 pm on a summer solstice day?, (2) What is the spatial distribution of neutral regime for PET, SET*, & UTCI in each plaza? , (3) What is the trend observed in microclimatic variables and PET thermal stresses when analyzed temporally during the mid-day break from 12pm to 2 pm?, and (4) What is the spatiotemporal distribution of PET thermal stress within and between the Plazas during this mid-day break?

2.0 RESEARCH METHODOLOGY

2.1. Study area

Five outdoor public plazas in downtown Chicago are considered for this research. These plazas are located in the urban blocks enclosed between W. Randolph, Clark, Dearborn, and W Jackson streets. Each plaza is at the ground level of an iconic tall building. These are 197.5m tall Rachard Daley Center (1965) housing (01) the Daley Plaza, 264.5 m tall Chase tower (1969) housing (02) the Chase Plaza, 173.9 m tall One South Dearborn (2005) housing (03) the Dearborn Plaza; and 171.3 m tall Kluczynski Federal center (1974) housing (04) the Federal NE (Northeast) Plaza and (05) Federal SW (Southwest) Plaza (refer to Figure 1). Other adjacent buildings around these plazas range from 15m to 100m.

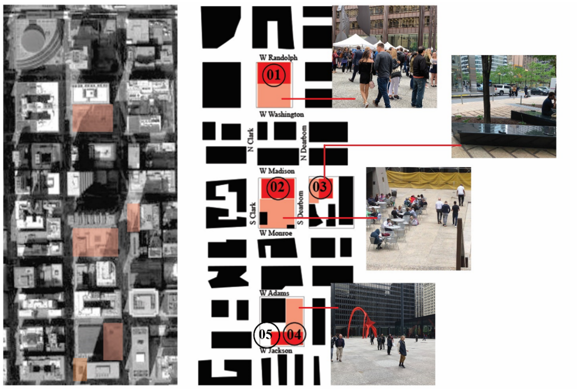

Figure 1: Location of five plazas of Chicago. Source: (Author 2021)

2.2. Microclimate modelling using ENVImet.

The research methodology involves microclimate modeling using ENVI-met software to conduct simulations. The selected day for the simulation was June 21, a summer solstice in 2019. The total simulation time was set to three hours, with the initializing hour starting at 11 am. The context was modeled in ENVImet Monde World Editor using the Daley Center, Chicago coordinates. The digitized model used information from an open street map, Google views, and CTBUH skyscraper center. The vectorized model is then exported to a raster-based .INX file for simulation. Three spatial domains consisting of five plazas were exported from this model using settings shown in Table 3. Instead of nesting grids, the model was expanded by real grid cells. This paper uses an open lateral boundary condition (where grid values closest to the border are copied to the next ones in each time step) with Simple Forcing for temperature and relative humidity at an hourly interval. Other input parameters (listed in Table 4) are taken from the diurnal meteorological conditions collected from a nearby weather station located 325m from the Daley Plaza. The site roughness selected for the simulation is 0.1, representing dense urban conditions.

Table 3: Spatial domain settings for ENVImet simulations. Source: (Author 2024)

Model Geometry	model dimension (no. of grids)			grid cell sizes (m)			highest building in domain	3D model top height	min. distance between bldgs & model border
	x	y	z	dx	dy	dz	(m)	(m)	
Federal NE Plaza & Federal SW Plaza	96	105	100	4	4	4	178	400	18 grids
Chase Plaza & One S Dearborn Plaza	97	108	109	4	4	4	265	547	15 grids
Daley Plaza	95	107	105	4	4	4	230	463	13 grids

Table 4: Initial Meteorological conditions for simulations. Source: (Author 2024)

Initial Meteorological Conditions	
Wind Speed (m/s)	6.26
Wind Direction (Deg)	90 East
Roughness Length at Measurement Site	0.1
Minimum Temperature of Atmosphere (°C)	11.67
Maximum Temperature of Atmosphere (°C)	22.22
Minimum Relative Humidity (%)	43
Maximum Relative Humidity (%)	75

3.0 RESULTS

The data analysis uses a spatiotemporal approach to compare the three OTC models to derive the results. The temporal approach uses the mean values of the OTC index and its associated thermal stress categories, while the spatial approach uses a percentage of space under different stress categories as a metric for comparison. The three OTC models are compared using their thermal sensation thresholds for comfort conditions.

3.1. Comparative analysis of PET, SET*, & UTCI at 12 pm

Statistical test ANOVA (analysis of variation) single factor was performed for all the five plazas to analyze the difference between the means of PET, SET*, and UTCI values. The results revealed that there was a statistically significant difference in means of all the three indices in the listed plazas ($F(2, 510) = [132.9]$, $p < 0.05$) for Federal NE plaza; ($F(2, 231) = [21.1]$, $p < 0.05$) for Federal SW plaza; ($F(2, 357) = [38.6]$, $p < 0.05$) for Dearborn plaza; ($F(2, 1005) = [72.5]$, $p < 0.05$) for Chase plaza; and ($F(2, 1053) = [314.6]$, $p < 0.05$) for Daley plaza. The box plots comparisons in Figure 2 show the distribution of data used in these analyses for five plazas.

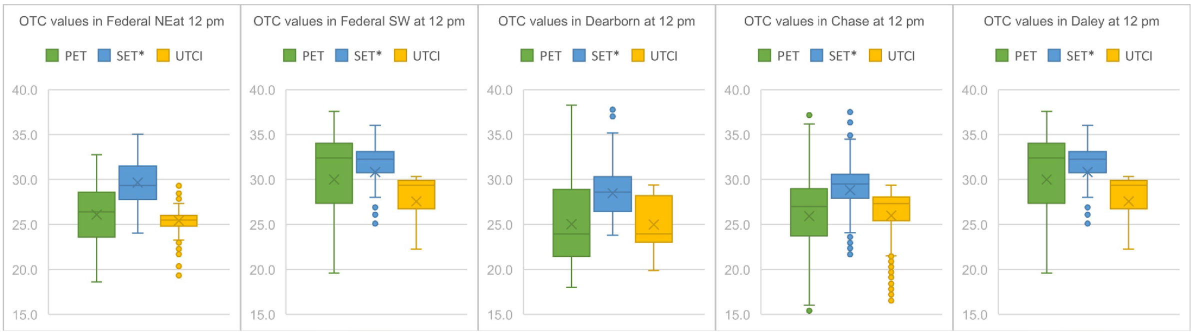

Figure 2: Box plots showing the PET, SET*, and UTCI in five plazas of Chicago. Source: (Author 2024)

The comparative analysis of the three OTC indices: PET, SET*, and UTCI mean values, and the corresponding thermal stress at 12 pm in the five plazas are presented in Table 2. It was found that the thermal conditions of Daley Plaza are under the neutral physiological thermal stress category for the three indices, whereas Federal SW Plaza is under the warm thermal stress category. This implies that Daley Plaza is likely to be the most preferred plaza in summer noon. Moreover, the high granularity in PET thermal stress categories creates a better understanding of thermal conditions in these plazas. For instance, the slightly warm conditions in Federal NE, Dearborn, and Chase Plaza help to distinguish them from others, unlike the case SET* or UTCI indices. However, this gravely impacts the spatial distribution of PET-neutral regimes in the plazas. Hence, for the sake of comparison, an "extended comfort sensation" is considered that increases the comfort thresholds to include neutral, slightly warm, and slightly cold categories for PET, which matches the thresholds of the next stress categories around neutral regimes for SET* & UTCI (refer to Table 5).

Table 5: Mean and standard deviation values of OTC indices PET, SET*, and UTCI and their corresponding thermal stress levels. Source: (Author 2024)

OTC indices at 12 pm		PET (°C)	Thermal stress	SET* (°C)	Thermal stress	UTCI (°C)	Thermal stress
Federal NE Plaza	Mean	26.2	slightly warm	29.8	neutral	25.6	neutral
	SD	3.2		2.7		1.6	
Federal SW Plaza	Mean	30.6	warm	31.5	warm	28.2	warm
	SD	4.6		2.3		2.4	
Dearborn Plaza	Mean	25.2	slightly warm	28.7	neutral	25.2	neutral
	SD	4.7		2.8		2.8	
Chase Plaza	Mean	26.0	slightly warm	28.9	neutral	26.0	neutral
	SD	4.5		2.9		3.1	
Daley Plaza	Mean	19.4	neutral	24.5	neutral	20.4	neutral
	SD	2.8		1.9		3.6	

3.2. Spatial distribution of neutral regime for PET, SET*, & UTCI at 12 pm

The comparative analysis of the PET, SET*, and UTCI neutral regime spatial distribution in the five plazas was initiated with ANOVA single factor test. The results demonstrated a statistically significant difference in the values of the five plazas with ($F(4, 10) = [4.4]$, $p = 0.03$). The comparison is further presented in Figure 3 charts. The top row shows the spatial distribution of neutral regime in the five plazas. Daley Plaza shows the highest distribution of for all the three indices. Moreover, the comparison within the groups shows PET has the lowest distribution for all five plazas which can be explained by its lower threshold values for this regime unlike the other two (refer to Table 1). This case is reversed when the comparison is made using the "extended comfort sensation" for these indices. PET demonstrates the highest spatial distribution amongst the three. These findings open a discussion on if an intermediate stress category is required between neutral and warm stresses for SET* and UTCI, and neutral and moderate cold for SET*. It is recommended to have one since the results may not be indicative of its given cause and proposes conducting an onsite survey to confirm the thermal stress thresholds for each OTC index.

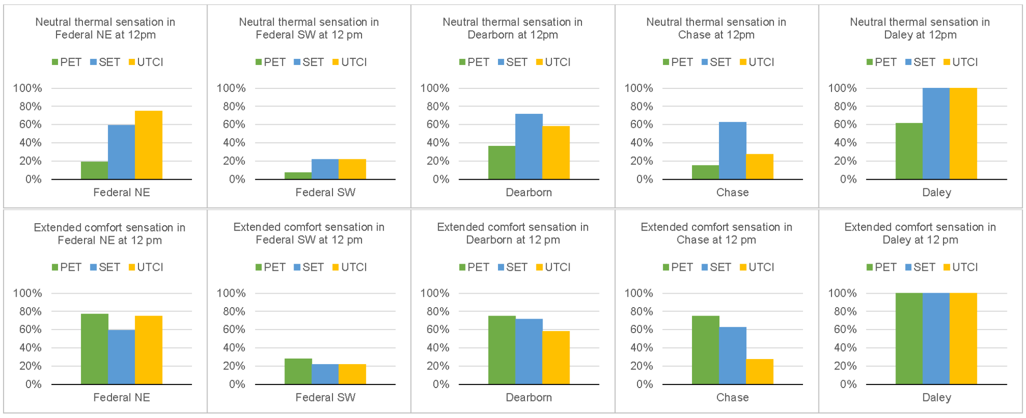

Figure 3: Spatial distribution of neutral regime (top row),and extended comfort regime (bottom row) of PET, SET*, and UTCI in five plazas of Chicago. Source: (Author 2024).

3.3. Temporal analysis of microclimatic variables and PET thermal stresses during mid-day break

A midday break with a 12 – 2 pm time block is considered for assessing thermal comfort variations and their corresponding thermal stresses. Table 6 presents the mean values for PET at 12 pm, 1 pm, and 2 pm for five plazas. It is found that PET thermal stress remains consistent during this period except for Federal NE and Federal SW plazas. The former gets warmer while the latter gets cooler at 2 pm. This could be further explained by the trend in microclimatic variables during this time block (refer to Figure 4). These variables, namely Temperature (°C), Mean Radiant Temperature (°C), Relative Humidity (%), and Wind Speed (m/s), are presented in Table 7. The data trend for Relative Humidity shows a decrease from 58% to 53% in the Federal NE Plaza and an increase from 54.1% to 58.1% in the Federal SW Plaza. The temperature trend is reversed, showing an increase from 16.4°C to 17.4°C in Federal NE Plaza and a decrease from 17.3°C to 16.4°C. The increasing MRT and the constant wind speed trends for both plazas do not seem to contribute to the change in the thermal stresses from 1 to 2 pm.

Table 6: Mean and standard deviation of PET and its corresponding thermal stress levels in five plazas. Source: (Author 2024)

	PET	12 pm	Thermal stress	1 pm	Thermal stress	2 pm	Thermal stress
Federal NE Plaza	Mean	26.2	slightly warm	26.2	slightly warm	29.6	warm
	SD	3.2		3.5		6.1	
Federal SW Plaza	Mean	30.6	warm	31.8	warm	25.7	slightly warm
	SD	4.6		4.9		5.2	
Dearborn Plaza	Mean	25.2	slightly warm	25.7	slightly warm	23.8	slightly warm
	SD	4.7		6.8		6.5	
Chase Plaza	Mean	26.0	slightly warm	27.3	slightly warm	26.9	slightly warm
	SD	4.5		4.6		5.6	
Daley Plaza	Mean	19.4	neutral	20.6	neutral	22.4	neutral
	SD	2.8		2.9		2.7	

Table 7: Mean and standard deviation values of microclimatic variables for five plazas. Source: (Author 2024)

		W (m/s)			RH (%)			MRT (°C)			T (°C)		
		12 pm	1 pm	2 pm	12 pm	1 pm	2 pm	12 pm	1 pm	2 pm	12 pm	1 pm	2 pm
Federal NE Plaza	Mean	0.9	0.9	0.9	58.0	55.9	53.8	48.3	47.4	52.6	16.4	16.9	17.4
	SD	0.8	0.8	0.8	0.2	0.2	0.3	6.8	8.3	11.6	0.1	0.1	0.1
Federal SW Plaza	Mean	0.6	0.6	0.6	54.1	56.0	58.1	42.9	55.4	54.0	17.3	16.9	16.4
	SD	0.2	0.2	0.2	0.1	0.1	0.1	8.9	8.1	7.8	0.0	0.0	0.0
Dearborn Plaza	Mean	1.1	1.1	1.1	53.8	55.9	57.9	41.7	46.7	47.9	17.3	16.9	16.4
	SD	1.0	0.9	0.9	0.2	0.1	0.1	9.9	10.0	9.4	0.0	0.0	0.0
Chase Plaza	Mean	1.0	1.0	1.0	53.8	55.9	57.9	52.3	54.0	49.3	17.7	17.5	17.1
	SD	0.7	0.7	0.7	0.2	0.2	0.2	10.6	7.4	8.8	0.8	1.1	1.3
Daley Plaza	Mean	3.4	3.4	3.4	53.5	55.6	57.8	58.7	54.0	51.2	17.5	17.0	16.5
	SD	0.7	0.7	0.7	0.3	0.3	0.3	8.1	8.8	8.4	0.1	0.1	0.1

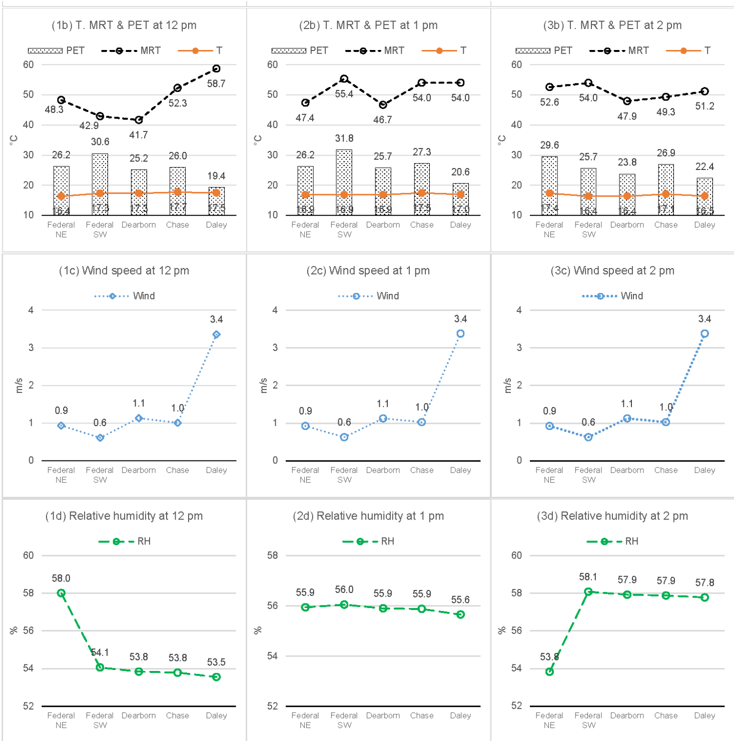

Figure 4: Microclimatic variables during mid-day break of a summer solstice in five plazas of Chicago. Source: (Author 2024).

3.4. Spatiotemporal distribution of PET thermal stress during mid-day break

A spatiotemporal distribution of PET thermal stress categories in five plazas provides insight into the relative frequencies of thermal stress data (a) within each plaza and (b) across five plazas for 12 pm, 1 pm, and 2 pm (refer to Figure 5). The results for Chase Plaza demonstrate the spatial distribution of five thermal stress categories for all three hours. The other Plazas showing similar patterns are Dearborn Plaza for 1 pm and 2 pm, and Federal NE/SW Plazas for 2 pm. Further, Dearborn at 1 pm and Federal NE at 2 pm show even distributions, suggesting the Plazas offer varied choices of thermal conditions for people. This also explains the shift in the average PET values and its corresponding thermal stress from 1 pm to 2 pm as discussed in the previous section (refer to Table 3). The pattern of Daley Plaza is unique when compared to the other plazas. It is the only plaza with the highest neutral thermal stress category, with 61% at 12 pm and 55% at 1 pm. This implies that the Plaza will be preferred by people during the summer afternoons.

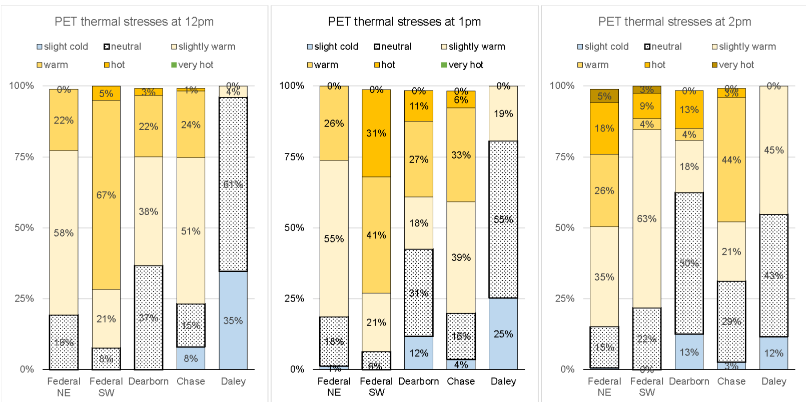

Figure 5: Spatiotemporal distribution of PET thermal stresses in five plazas of Chicago. Source: (Author 2024).

4.0 DISCUSSION

The paper presented a spatiotemporal comparative analysis of outdoor thermal comfort conditions using five plazas with different morphological conditions in Chicago. The findings show that three indices, namely PET, SET*, and UTCI, demonstrate different outputs exhibiting their limitations in thermal stress levels, which must be considered in future studies. These findings are further elaborated in the sections below.

The findings from a comparative analysis of PET, SET*, and UTCI in these plazas at noon of summer solstice day provide the expected mean values of OTC indices, which can be used in designing plazas in Chicago or cities with

Dfa climate region. The associated thermal stress with these values highlights a key limitation in SET* and UTCI in assessing the thermal conditions of a Plaza. The two indices lack granularity around neutral thermal stress regimes, unlike PET. This limits the understanding of finer thermal conditions that may exist in the plazas and could be critical in the success of the plaza. It becomes more decisive when multiple design elements contribute to the microclimates of a plaza.

The findings from the spatial distribution of the neutral regime and the extended comfort conditions provide further insight into this issue. The results could be misleading in this analysis since PET with finer thresholds will always show lower spatial distribution compared to SET* and UTCI. To make a fair argument, an “extended comfort condition” is considered, which aligns with the next thermal stress category common to all three indices. The results show that PET has the highest spatial distribution. Although the results are purely based on the simulations, it is recommended to conduct another study investigating people’s behavior and their thermal perception through onsite surveys.

OTC thermal stresses and microclimatic variables in the five plazas are further explored temporally in a 12-2 pm mid-day break period using mean PET values and their corresponding thermal stress for each hour. The findings show a thermal stress category variation in Federal NE & SW plazas at 2 pm. This variation is also observed in the microclimatic variables namely Relative Humidity and Temperature. Further study is required to investigate the interrelationships between these variables and PET values. The other three plazas do not exhibit any change in their thermal stresses. However, the spatiotemporal analyses of all the plazas demonstrate interesting findings around their thermal condition assessments. The findings pose a question on whether assessing thermal comfort through mean values is an appropriate approach, given the fact that there exist other thermal stress categories that are not captured. Thus, the assessment does not provide a comprehensive view of the thermal conditions. For example, the temporal analysis using mean PET values shows a constant thermal stress category, “slightly warm” in Chase Plaza. But the spatiotemporal distribution at 2 pm shows that 44% of the plaza exhibits “warm” thermal stress category. The same is also true for Dearborn Plaza at 2 pm, where 50% of the plaza exhibits “neutral” thermal stress category. Hence, it is important to consider the spatial distribution of thermal conditions.

These analyses also open a discussion on including thermal stress(es) as one of the design criteria for outdoor environments. While it would be ideal to have plazas dominated by neutral thermal stress, it is often challenging to achieve this condition temporally due to the dynamic nature of the outdoor climatic environment. Even if it is achieved at a specific time of the day, the real question would be whether such an environment would be ideal for people with different social-cultural characteristics. For example, a recent study shows that thermal perceptions differ based on gender (Jin, Liu, and Kang 2020). Hence, creating micro-environments within plazas exhibiting microclimatic variations could be a better solution, giving people choices to either adopt or to embrace change to retain their comfort levels.

It is also important to highlight one limitation of this study. The findings from temporal analysis comparing differences in mean PET values between different time blocks are limited due to the smaller sample size of temporal data. For example, the results for Dearborn, Chase, and Daley Plazas do not show much variation during the simulated period. However, this could be different if a larger sample set was used. Hence, it is recommended to address the issue in future studies. Moreover, the study assumes that thermal stress identified in the three indices are the same; however, few studies show that thermal stresses depend on multiple factors, namely climatic, socio-cultural, and psychological factors impacting its assessment (Schweiker et al. 2018).

CONCLUSION

The paper presented a spatial and temporal approach to compare three OTC indices namely PET, SET* and UTCI. The study was conducted for Chicago with the Dfa climate zone in Koppen Climate Classification. The indices were studied for five plazas in downtown Chicago with tall building urban conditions. ENVImet – a CFD microclimate modeling tool was used as a research methodology to derive the data for findings. The results showed that that SET* and UTCI lack granularity around neutral thermal stress regimes, unlike PET. This limits the understanding of finer thermal conditions that may exist and could be critical to the success of the plaza. The other key findings of this study highlight the importance of spatial distribution of thermal stresses in assessing the thermal conditions of an outdoor environment. The significance of this research is towards creating well designed outdoor public spaces that contribute to sustainable communities and improved public health as outlined in the UN SDG-11.

REFERENCES

Bruse, Michael. 2018. “Technical References on EnviMet.” *Envi_Met.* https://envi-met.info/doku.php?id=root:start.

Chen, Liang, and Edward Ng. 2012. “Outdoor Thermal Comfort and Outdoor Activities: A Review of Research in the Past Decade.” *Cities* 29 (2): 118–125. https://doi.org/10.1016/j.cities.2011.08.006.

Cheung, Pui Kwan, and C. Y. Jim. 2017. “Determination and Application of Outdoor Thermal Benchmarks.” *Building and Environment* 123 (October): 333–350. https://doi.org/10.1016/j.buildenv.2017.07.008.

Coccolo, Silvia, Jérôme Kämpf, Jean-Louis Scartezzini, and David Pearlmutter. 2016. “Outdoor Human Comfort and Thermal Stress: A Comprehensive Review on Models and Standards.” *Urban Climate* 18 (December): 33–57. https://doi.org/10.1016/j.uclim.2016.08.004.

CTBUH (Council on Tall Buildings and Urban Habitat). 2019. “The Skyscraper Center.” *CTBUH, Number of 150m+ Completed Buildings*. 2019. https://www.skyscrapercenter.com/cities.

Fanger, P. O. 1982. Thermal Comfort : Analysis and Applications in Environmental Engineering. Malabar, FL : R.E. Krieger Publishing Company.

Freitas, C. R. de, and E. A. Grigorieva. 2015. "A Comprehensive Catalogue and Classification of Human Thermal Climate Indices." *International Journal of Biometeorology* 59 (1): 109–20. https://doi.org/10.1007/s00484-014-0819-3.

———. 2017. "A Comparison and Appraisal of a Comprehensive Range of Human Thermal Climate Indices." *International Journal of Biometeorology* 61 (3): 487–512. https://doi.org/10.1007/s00484-016-1228-6.

Gagge, A P, A P Fobelets, and L G Berglund. 1986. "A Standard Predictive Index of Human Response to the Thermal Environment." *ASHRAE Transactions* 92 (2B): 23.

Honjo, Tsuyoshi. 2009. "Thermal Comfort in Outdoor Environment." *Global Environmental Research* 13: 43–47.

Höppe, P. 1999. "The Physiological Equivalent Temperature - a Universal Index for the Biometeorological Assessment of the Thermal Environment." *International Journal of Biometeorology* 43 (2): 71–75. https://doi.org/10.1007/s004840050118.

Jin, Hong, Siqi Liu, and Jian Kang. 2020. "Gender Differences in Thermal Comfort on Pedestrian Streets in Cold and Transitional Seasons in Severe Cold Regions in China." *Building and Environment* 168 (January): 106488. https://doi.org/10.1016/j.buildenv.2019.106488.

Khan, Zahida, Rahman Azari, and Brent Stephens. 2020. "Outdoor Thermal Comfort (OTC) In Human Interaction-Based Studies: An Overview of Reviews." In *2020 Building Performance Analysis Conference and SimBuild*, 600–609. Atlanta: ASHRAE and IBPSA-USA. https://www.techstreet.com/standards/outdoor-thermal-comfort-otc-in-human-interaction-based-studies-an-overview-of-review?product_id=2198869#jumps.

Khan, Zahida, and Peng Du. 2020. "Typologies of Outdoor Public Spaces at Street Level of Tall Buildings in Chicago." *Prometheus* 04, 90–97. IIT Architecture Chicago, Buildings, Cities, and Performance II.

Kumar, Pardeep, and Amit Sharma. 2020. "Study on Importance, Procedure, and Scope of Outdoor Thermal Comfort – A Review." *Sustainable Cities and Society* 61 (October). https://doi.org/10.1016/j.scs.2020.102297.

Luber, George, and Michael McGeehin. 2008. "Climate Change and Extreme Heat Events." *American Journal of Preventive Medicine*, Theme Issue: Climate Change and the Health of the Public, 35 (5): 429–435. https://doi.org/10.1016/j.amepre.2008.08.021.

Maleki, Aida, Kristina Kiesel, Milena Vuckovic, and Ardeshir Mahdavi. 2014. "Empirical and Computational Issues of Microclimate Simulation." In *ICT-EurAsia 2014*, vol. 8407, 78–85. Bali, Indonesia: Springer. https://doi.org/10.1007/978-3-642-55032-4_8.

Nikolopoulou, Marialena, and Koen Steemers. 2003. "Thermal Comfort and Psychological Adaptation as a Guide for Designing Urban Spaces." *Energy and Buildings* 35 (1): 95–101. https://doi.org/10.1016/S0378-7788(02)00084-1.

Parakh, James. 2015. "The Network of Urban Spaces Surrounding Tall Buildings." *Proceedings of the CTBUH 2015 International Conference*. Chicago, IL: Council on Tall Buildings and Urban Habitat.

Potchter, Oded, Pninit Cohen, Tzu-Ping Lin, and Andreas Matzarakis. 2018. "Outdoor Human Thermal Perception in Various Climates: A Comprehensive Review of Approaches, Methods and Quantification." *Science of The Total Environment* 631–632 (August): 390–406. https://doi.org/10.1016/j.scitotenv.2018.02.276.

Reinhart, Christoph F., Jay Dhariwal, and Katy Gero. 2017. "Biometeorological Indices Explain Outside Dwelling Patterns Based on Wi-Fi Data in Support of Sustainable Urban Planning." *Building and Environment* 126 (December): 422–30. https://doi.org/10.1016/j.buildenv.2017.10.026.

Schweiker, Marcel, Gesche M. Huebner, Boris R. M. Kingma, Rick Kramer, and Hannah Pallubinsky. 2018. "Drivers of Diversity in Human Thermal Perception – A Review for Holistic Comfort Models." *Temperature: Multidisciplinary Biomedical Journal* 5 (4): 308–42. https://doi.org/10.1080/23328940.2018.1534490.

Stathopoulos, Ted. 2009. "Wind and Comfort." In *European & African Conferences on Wind Engineering*. Florence, Italy.

Toparlar, Y., B. Blocken, B. Maiheu, and G.J.F. van Heijst. 2017. "A Review on the CFD Analysis of Urban Microclimate." *Renewable and Sustainable Energy Reviews* 80 (December): 1613–40. https://doi.org/10.1016/j.rser.2017.05.248.

Toparlar, Y., B. Blocken, P. Vos, G.J.F. van Heijst, W.D. Janssen, T. van Hooff, H. Montazeri, and H.J.P. Timmermans. 2015. "CFD Simulation and Validation of Urban Microclimate: A Case Study for Bergpolder Zuid, Rotterdam." *Building and Environment* 83 (January): 79–90. https://doi.org/10.1016/j.buildenv.2014.08.004.

Tsitoura, Marianna, Theocharis Tsoutsos, and Tryfon Daras. 2014. "Evaluation of Comfort Conditions in Urban Open Spaces. Application in the Island of Crete." *Energy Conversion and Management* 86 (October): 250–58. https://doi.org/10.1016/j.enconman.2014.04.059.

United Nations Department of Economic and Social Affairs. 2023. *The Sustainable Development Goals Report 2023: Special Edition*. The Sustainable Development Goals Report. United Nations. https://doi.org/10.18356/9789210024914.

Zare, Sajad, Naser Hasheminejad, Hossein Elahi Shirvan, Rasoul Hemmatjo, Keyvan Sarebanzadeh, and Saeid Ahmadi. 2018. "Comparing Universal Thermal Climate Index (UTCI) with Selected Thermal Indices/Environmental Parameters during 12 Months of the Year." *Weather and Climate Extremes* 19 (March): 49–57. https://doi.org/10.1016/j.wace.2018.01.004.