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著者(和文)	JINXIAO, VarquezAlvin Christopher Galang, 伊坪徳宏, 神田学
Authors(English)	Xiao Jin, Alvin C. G. Varquez, Do Ngoc Khanh, Tomohiko Ihara, Norihiro Itsubo, Manabu Kanda
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URBANIZATION AND CLIMATE CHANGE EFFECTS ON FUTURISTIC THERMAL COMFORT OF THREE MEGACITIES: SSP370 SCENARIO

Xiao JIN[1], Alvin C.G. VARQUEZ[2], Do Ngoc KHANH[3], Tomohiko IHARA[4]
Norihiro ITSUBO[5] and Manabu KANDA[6]

[1] Dept. of Transdisciplinary Science and Engineering, Institute of Science Tokyo
(2-12-1 Ookayama, Meguro, Tokyo, 152-8550, Japan)
E-mail: jin.x.ac@m.titech.ac.jp (Corresponding Author)
[2] Associate Professor, Dept. of Transdisciplinary Science and Engineering, Institute of Science Tokyo
(2-12-1 Ookayama, Meguro, Tokyo, 152-8550, Japan)
E-mail: varquez.a.aa@m.titech.ac.jp
[3] Member of JSCE, SIT Research Laboratories, Shibaura Institute of Technology
(3-7-5 Toyosu, Koto, Tokyo, 135-8548, Japan)
E-mail: khanhdn@shibaura-it.ac.jp
[4] Associate Professor, Graduate School of Frontier Sciences, The University of Tokyo
(5-1-5 Kashiwanoha, Kashiwa, Chiba, 277-8563, Japan)
E-mail: ihara-t@k.u-tokyo.ac.jp
[5] Professor, Dept. of Science and Engineering, School of Creative Science and Engineering, Waseda University
(3-4-1 Okubo, Shinjuku City, Tokyo, 169-8555, Japan)
E-mail: itsubo-n@waseda.jp
[6] Professor, Dept. of Transdisciplinary Science and Engineering, Institute of Science Tokyo
(2-12-1 Ookayama, Meguro, Tokyo, 152-8550, Japan)
E-mail: kanda.m.aa@m.titech.ac.jp

Rising climate hazards in urban areas, driven by global climate change and intensified by urbanization, are increasing extreme thermal stress, posing significant risks to thermal comfort and socioeconomic well-being. This study projects high-resolution future urban climate and thermal stress for 2050 under the SSP370 scenario, a high-emission, low-mitigation pathway from the Coupled Model Intercomparison Project Phase 6 (CMIP6). In this research, hourly 1.5 × 1.5-km projections of meteorology and Universal Temperature Climate factor (UTCI) were generated, incorporating urbanization effects (future urban morphology and anthropogenic heat emissions change) across three major cities: Tokyo, Cairo, and Jakarta. Under SSP370, both UTCI and air temperature increase substantially across all cities, with UTCI showing stronger responses. Urban change effects vary distinctly across cities: Tokyo shows cooling due to reduced anthropogenic heat emissions, with air temperature responding more strongly than UTCI, while Cairo and Jakarta experience warming from continued urban development. Despite these differences, the magnitudes of urban change effects are inversely correlated with background temperature across all cities. Analysis of feature importance through machine-learning reveals that urban change-induced UTCI responses are radiation-dominated in Tokyo and Cairo, contrasting with ventilation-dominated responses in humid Jakarta.

Key Words: *UTCI, Urban climate, SSP370, Urbanization, Anthropogenic heat emissions*

1. INTRODUCTION

Global warming and rapid urbanization are intensifying heat exposure and reducing thermal comfort for urban populations worldwide. While urban surface temperature increases have been extensively studied, the spatiotemporal patterns of human thermal comfort and their driving mechanisms remain underexplored in urban thermal assessments[1].

To address these gaps, this study employs high-resolution regional climate modeling to project future urban climate and thermal stress for 2050 under the high-emission SSP370 scenario. We use an enhanced Weather Research and Forecasting (WRF) model coupled with the Single-Layer Urban Canopy Model (SLUCM) that explicitly incorporates urban morphology and anthropogenic heat emissions to capture urban change effects and accurately project future

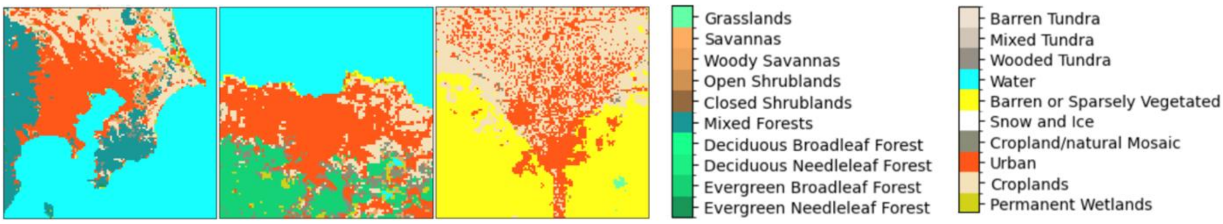

Fig. 1 Land cover classification of WRF Domain3 for Tokyo, Jakarta, and Cairo in 2022 (from left to right)

urban climate changes across three climatically diverse megacities: Tokyo with humid subtropical climate, Cairo with hot desert climate, and Jakarta with tropical rainforest climate. Thermal stress is quantified using the Universal Thermal Climate Index (UTCI), which comprehensively reflects human thermal comfort by integrating multiple meteorological factors. Additionally, machine learning analysis is applied to identify the dominant environmental drivers of thermal stress changes across different urban contexts. Accordingly, the objectives of this study are:

- To project urban climate and thermal stress (UTCI) changes by 2050 under the SSP370 scenario in Tokyo, Jakarta, and Cairo, incorporating urban change effects.
- To explore how thermal comfort and temperature responses vary across cities with distinct climatic backgrounds and future urbanization trajectories, including changes in built form and anthropogenic heat emissions.
- To examine the divergence between urban change-induced temperature and UTCI changes, and assess the relative contributions of key meteorological variables to this discrepancy.

2. METHODOLOGY

This study assesses future urban climate and thermal stress in Tokyo, Jakarta, and Cairo for 2050 under the SSP370 scenario, with 2022 simulations for model validation. The methodology comprises: (1) modified WRF–SLUCM simulation incorporating urban morphological parameters and anthropogenic heat emission (AHE); (2) UTCI estimation using the UTCI–Fiala model; and (3) feature importance analysis using LightGBM.

(1) Modified WRF-SLUCM Simulation with Urban Morphology and Anthropogenic Heat

This study utilizes the WRF model (v4.6) coupled with the SLUCM[3], incorporating spatially distributed urban parameters (**Fig. 1-2**) and externally prescribed AHE derived from the AH4GUC dataset[2] (**Fig. 2**). The AH4GUC is a global 1-km hourly dataset for urban climate applications, covering present-day and future scenarios. Each city was simulated at 1.5 km resolution using the innermost domain of a three-level WRF nesting system centered at 35.582° N, 140.16° E (Tokyo); 6.12° S, 107.00° E (Jakarta); and 30.47° N, 31.2358° E (Cairo). The simulation setup and domain configurations follow those described in previous work[1].

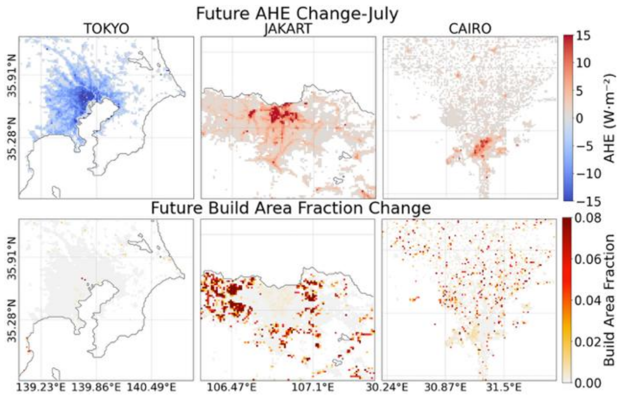

Fig. 2 Future changes in urban morphological parameters. (e.g., build area fraction) and anthropogenic heat emissions (AHE; July shown as an example) for Tokyo, Jakarta, and Cairo, comparing 2022 and 2050. Other variables and months show similar patterns.

ERA5 reanalysis data (hourly, 0.25°) were used as initial and boundary conditions for present-day simulations and as the baseline for future projections using the pseudo-global warming (PGW) method, adding climate change signals from global climate models to current weather data to project future conditions, with CMIP6-based deltas superimposed onto the ERA5 baseline[4]. To derive these deltas, monthly mean changes in key climate variables, including atmospheric temperature, horizontal wind, 2-m relative humidity, geopotential height, 2-m air temperature, sea surface temperature, and surface skin temperature, were calculated by comparing the 2015–2024 and 2045–2055 climatologies using outputs from 26 Global Climate Models (GCMs) from CMIP6 under SSP370 scenario, with ensemble averaging across all GCMs using the r1i1p1 member from each model. For each city, three WRF simulations were conducted by combining two climate forcings (2022 baseline and 2050 SSP370) with two urbanization assumptions: (1) static present-day urban conditions (pu), and (2) dynamic future urban configurations (fu) that incorporate projected changes in urban morphology and AHE. The difference between the fu and pu simulations under the same climate forcing (SSP370) defines the ΔUP signal, which isolates the effects of urbanization on thermal stress while holding climate conditions constant.

(2) UTCI-Fiala Thermal Stress Estimation

The Universal Thermal Climate Index (UTCI) is defined as the equivalent air temperature in a standardized reference environment that would elicit the same physiological response as actual outdoor thermal conditions[5)]. UTCI is based on the UTCI-Fiala model, a multi-node thermoregulatory framework that simulates dynamic physiological responses to environmental conditions[5)]. In this study, we used the empirical version of UTCI, developed by Bröde et al. (2012)[8)], which approximates the original UTCI-Fiala model through a regression equation derived from extensive simulations. This version retains sensitivity to the key meteorological drivers (air temperature, wind speed, humidity, and mean radiant temperature) while improving computational efficiency, making it suitable for long-term, high-resolution climate simulations. Required input variables were obtained from WRF model outputs.

(3) Feature Importance Analysis with LightGBM

To identify the key meteorological drivers of future urban change-induced thermal stress, we utilize the Light Gradient Boosting Machine (LightGBM) algorithm[7)] to conduct a feature importance analysis. LightGBM is a high-efficiency gradient boosting method capable of capturing nonlinear relationships and interactions among variables. Compared to analyzing terms in the UTCI regression formula, this approach offers a flexible, data-driven way to quantify variable contributions under diverse conditions.

The target variable, ΔUTCI (ΔUP), represents urban change-induced UTCI changes attributable to urbanization. It was computed as the difference between two SSP370 simulations: one with projected changes in urban morphology and AHE, and another with present-day urban settings. Correspondingly, the input features consisted of urban change-induced changes in four key meteorological variables: near-surface relative humidity (ΔRH2), wind speed (ΔWNDSPD), 2-m air temperature (ΔT2), and mean radiant temperature (ΔTmrt), each computed as the difference between the same pair of simulations. This setup isolates the urbanization effects on thermal stress and climate under constant climate forcing.

For each city, the data were grouped by meteorological seasons, or by rainfall category in Jakarta, which has wet and dry seasons instead of four seasons. For each subset, LightGBM regression models were trained with an 80/20 train–test split. Input features were standardized using StandardScaler prior to model fitting. Model training employed early stopping (patience = 50 rounds), with RMSE as the objective function. Predictive performance was evaluated on the test set using R^2, MAE, and RMSE. Feature importance was assessed using the gain metric, which quantifies the total reduction in training loss attributed to each variable across all tree splits. The gain values were extracted from each trained model and used to evaluate the relative influence of input features within each city and seasonal (or rainfall-based) grouping. This approach enabled the identification of dominant meteorological drivers contributing to urban change-induced UTCI changes across different climate and temporal contexts.

3. RESULTS AND DISCUSSION

(1) Model verification

Simulated present-day climate was compared with observational data. Hourly simulated 2-m air temperature (T2) and 10-m wind speed were compared with corresponding observations from the NOAA Integrated Surface Database (ISD), as shown in **Fig. 3**. Only stations that reported data continuously for 2022 were selected.

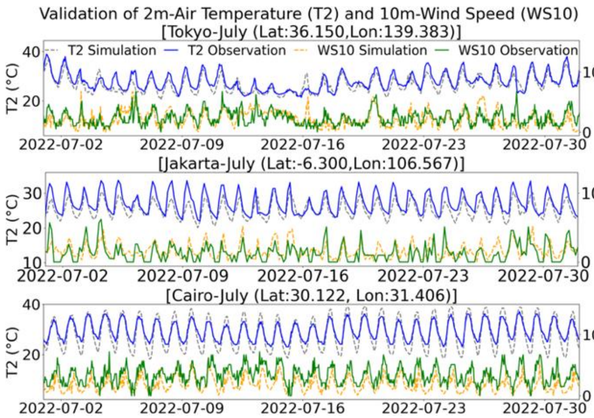

Fig. 3 Validation of simulated and observation data for 2022; July is shown as an example.

The validation results demonstrate reliable model performance across all three cities shown in **Table 1**. The spatial resolution mismatch between station locations and model grids contributes to some discrepancies in the validation metrics. Temperature predictions show good accuracy with low mean bias and high correlations for Tokyo and Cairo, though Jakarta exhibits lower correlation due to tropical climate complexity. Wind speed predictions, while showing higher uncertainty due to the inherent complexity of turbulent wind fields, remain within acceptable ranges, which demonstrates the reliability of our modeling approach. Moreover, since future projections are analyzed as anomalies relative to present simulations, any residzal bias is minimized. The model is therefore considered reliable for evaluating urban change-induced impacts on thermal stress.

Table 1 Model Validation Metrics for 2m-Air Temperature and 10m-Wind Speed for the year 2022.

	Tokyo		Jakarta		Cairo	
	T2	WS10	T2	WS10	T2	WS10
Mean Bias	-0.65 °C	2.27 m/s	-1.37 °C	1.46 m/s	-0.93 °C	0.45 m/s
MAE	1.96°C	2.38 m/s	1.88 °C	1.65 m/s	1.91 °C	0.80 m/s
RMSE	2.52°C	2.92 m/s	2.40 °C	2.07 m/s	2.38 °C	1.06 m/s
R^2	0.89	0.34	0.49	0.24	0.88	0.47

(2) Inter-City Variations in UTCI and Temperature Responses to SSP370 climate forcing, future urbanization (morphology and AHE change)

Fig. 4 indicates by 2050, both UTCI and T2 will experience substantial increases under the SSP370 scenario, with distinct magnitudes and temporal patterns emerging across the three cities based on spatially averaged monthly data.

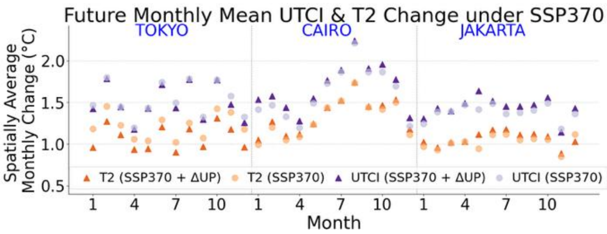

Fig. 4 Projected spatially averaged monthly changes in UTCI (purple) and T2 (orange) in 2050 under SSP370 for Tokyo, Cairo, and Jakarta. Light circles represent climate forcing only; dark triangles indicate climate forcing plus future urban changes (ΔUP).

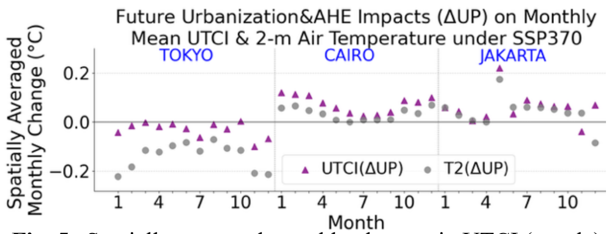

Fig. 5 Spatially averaged monthly changes in UTCI (purple) and T2 (gray) projected for Tokyo, Cairo, and Jakarta driven by future urban changes (ΔUP) under SSP370.

Cairo displays the most dramatic seasonal variation, with UTCI increases reaching their zenith during August at over 2.0°C above current levels. The warming trajectory follows a pronounced annual cycle: beginning with moderate increases in December, the temperature rise intensifies progressively through January and February, then moderates during March and April before building toward its summer peak. This pattern reveals substantial intra-annual variability in the city's thermal stress response. Jakarta exhibits its remarkably stable UTCI increases throughout the year, with warming consistently maintained between 1.25 and 1.75°C above present-day levels and minimal month-to-month fluctuation. This consistency reflects the city's characteristically stable equatorial climate conditions. Tokyo shows moderate monthly variations in UTCI warming, more variable than Jakarta but less seasonally concentrated than Cairo's extreme summer peaks. Notably, across all cities, T2 follows similar seasonal patterns to UTCI but consistently shows lower warming magnitudes, suggesting that UTCI provides a more sensitive indicator of thermal stress changes than traditional air temperature measurements alone.

The impacts of future urban changes, here referring to urbanization, encompassing both morphological and AHE changes, on future climate and thermal comfort differ across three cities based on spatially averaged monthly data, as demonstrated in **Fig. 5-6**. Tokyo shows a cooling pattern throughout most of the year from urbanization effects, with the most pronounced cooling during winter months when T2 decrease s reach approximately -0.1 to -0.2°C and UTCI shows smaller negative changes around -0.05°C, demonstrating that temperature is more sensitive to reduced AHE than UTCI. This counterintuitive pattern stems from Tokyo's status as a highly mature urban environment with minimal future urban morphological change and substantial reduction in AHE due to declining population, as illustrated in **Fig. 2**. **Fig. 6a** also shows cooling effect diminishes during warmer months. The temperature-dependent nature of this cooling effect is consistent with previous research showing that AHE has a greater relative impact on urban thermal conditions during colder seasons when solar radiation is weaker[6]. With the projected reduction in AHE for Tokyo, this cooling benefit is most evident during winter months when anthropogenic heat sources play a larger role in the urban thermal balance, whereas the effect becomes less pronounced during warmer seasons when solar radiation dominates the energy budget and diminishes AHE's relative contribution.

Cairo demonstrates a warming pattern following the same underlying mechanism. As a developing city with ongoing urban morphological change and increasing AHE, Cairo shows warming effects with city-wide UTCI increases reaching over 0.1°C during peak months. The most significant increases occur during colder months (January to March) when solar radiation is weaker, while the effect becomes less pronounced during warmer seasons. This temperature-dependent relationship is clearly illustrated in **Fig. 6a**, which shows the inverse correlation between background temperature and urban change effects across cities. Jakarta shows urban change-induced warming effects comparable to Cairo, with city-wide UTCI increases consistently ranging between 0.1-0.2°C across all months. Spatially, extreme UTCI and T2 changes were commonly found at urban expansion areas such as western Jakarta. However, unlike the clear seasonal patterns observed in Tokyo and Cairo, Jakarta exhibits no discernible monthly pattern due to its tropical equatorial location. This geographic position results in consistently high temperatures throughout the year and a very narrow annual temperature range of approximately 26-28°C that potentially masks the underlying temperature-dependent relationship. When analyzed within the broader temperature framework, as demonstrated in **Fig. 6b**, Jakarta's urbanization effects actually follow the same underlying mechanism. Despite the narrow temperature range, most data points align well with the fitted temperature-dependent relationship (R^2 ranging from 0.74 to 0.9), confirming that the same physical principles governing Tokyo's cooling and Cairo's seasonal warming also apply to Jakarta. However, several months show anomalous behavior as outliers from this relationship, which correspond to periods with relatively higher precipitation levels (**Fig. 6c**), indicating that local climatic factors such as rainfall patterns can modulate the standard temperature-dependent urbanization effects in tropical environments where the temperature signal is constrained by the narrow seasonal temperature variation.

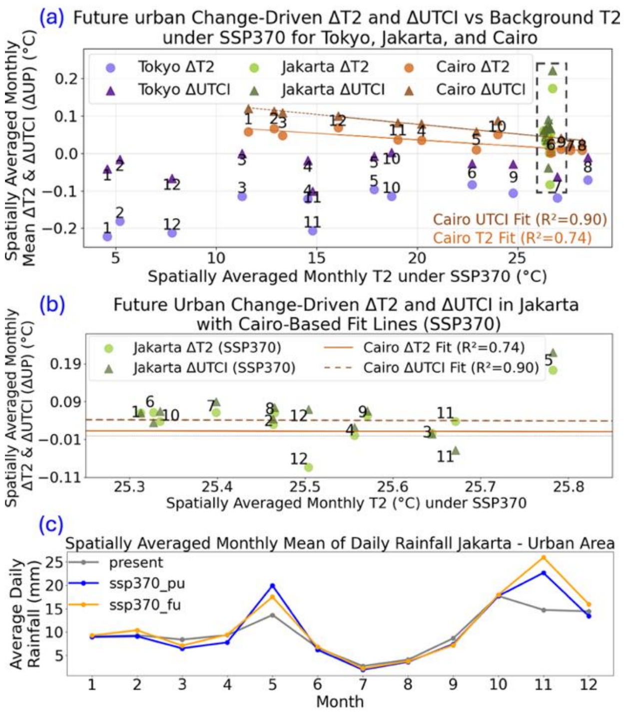

Fig. 6 Urbanization-driven T2 and UTCI changes versus background temperature under SSP370 (all data represent spatially averaged monthly means). (a) ΔT2 (ΔUP) and ΔUTCI (ΔUP) versus background T2 for Tokyo, Jakarta, and Cairo; (b) detailed zoom-in of dashed box in (a); (c) Jakarta's monthly rainfall.

(3) Discrepancy between Temperature and Thermal Stress Responses and the Role of Key Meteorological Drivers

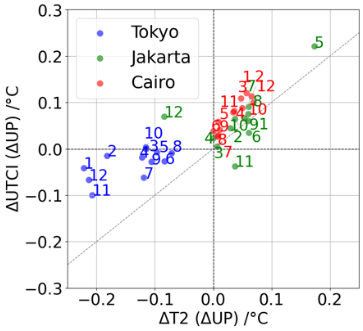

Fig. 7 Comparison of monthly spatially averaged ΔT2 and ΔUTCI in response to urban change (ΔUP) under SSP370. Numbers indicate months of the year

The monthly-scale relationship between spatially averaged changes in 2-meter air temperature (ΔT2) and heat stress index (ΔUTCI) in response to future urban morphological and AHE changes (ΔUP) under the SSP370 scenario shows different response patterns among three cities (**Fig. 7**). Most data points for Tokyo are distributed above the 1:1 line, indicating that ΔUTCI (ΔUP) are generally smaller in magnitude than ΔT2 (ΔUP), suggesting that UTCI is less sensitive than temperature to future urban changes, more precisely the reduced anthropogenic heat emissions. Cairo's data points are primarily distributed above the diagonal, where ΔUTCI (ΔUP) exceed ΔT2 (ΔUP), implying that heat stress is more sensitive to urban modifications than air temperature. The differential response patterns of T2 and UTCI to urban modifications may be explained by their varying sensitivity to mean radiant temperature. Jakarta's data points show the greatest scatter and are roughly distributed along the reference line, but with notable deviations in certain months (e.g., November and December), revealing potentially more complex nonlinear response mechanisms between temperature and heat stress changes.

To further elucidate the driving mechanisms behind the T2-UTCI response differences, this study employed a LightGBM regression model[8)] to predict ΔUTCI induced by ΔUP, with input features including ΔRH2, ΔWindSpeed, ΔT2, and ΔTmrt (all driven by ΔUP). Model performance evaluation demonstrated high accuracy across all cities. Tokyo and Cairo achieved R^2 (Test) >0.95 across seasons, with minimum MAE of 0.05°C and maximum RMSE <0.63°C. Jakarta achieved R^2 (Test) of 0.989 and 0.974 for high and low precipitation groups respectively, with RMSE <0.07°C. The extracted feature importance scores provide quantitative evidence for identifying meteorological factors dominating urban change-induced UTCI changes.

Despite different climate zones, Tokyo and Cairo both exhibit radiation-dominated responses to urbanization (**Fig. 8**). Tokyo shows urban-induced radiative temperature changes as the primary factor across spring, summer, and autumn, most prominently in summer, indicating radiative heat load's decisive role under urban development. Winter shows increased importance of urban-induced air temperature changes while radiative effects decrease, but UTCI response remains limited due to constrained radiation variation. Cairo presents similar patterns, with urban change-induced radiative temperature changes dominating spring, summer, and winter UTCI responses, while autumn shows air temperature changes as the primary factor. Wind speed and humidity remain marginal variables year-round, indicating urban change-induced heat stress enhancement occurs primarily through radiative effects. In contrast, Jakarta's UTCI response to urban change centers on urban change-induced wind speed changes. Wind speed modifications dominate during high precipitation periods, while urban change-induced air temperature and radiative temperature changes serve as secondary factors. During low precipitation, urban change-induced air temperature changes slightly predominate but remain secondary to wind speed modifications. Overall, Jakarta's urban change-induced UTCI response is primarily governed by ventilation effects.

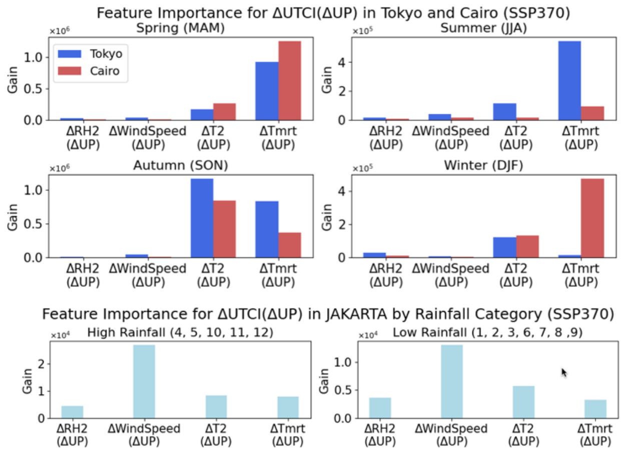

Fig. 8 Feature importance in predicting urbanization-induced heat stress changes (ΔUTCI) for Tokyo, Cairo by season, and Jakarta by rainfall category under SSP370 scenario.

4. CONCLUSION

This study projected high-resolution future urban thermal stress under SSP370, revealing significant inter-city differences in urbanization impacts. Two key findings emerge:

- Under SSP370, UTCI exceeds air temperature increases across cities. Cairo shows a seasonal variation, Jakarta experiences uniform warming, while Tokyo shows variable warming patterns.
- Effect of urban changes on monthly conditions varies across cities: Tokyo shows cooling from reduced AHE, with air temperature being more sensitive than UTCI; Compared with Jakarta, Cairo showed a more UTCI increase than air temperature increase with with urban expansion. The intensity of increases of UTCI and air temperature, were found to be inversely correlated with the actual background temperature of cities.
- Air temperature and UTCI show divergent responses to future urban changes across cities. Feature importance analysis reveals drivers of urban change-induced UTCI variations: Tmrt-dominated in Tokyo and Cairo versus wind-speed-dominated in humid Jakarta. Further investigation is underway for other future scenarios and parameterizations of the urban effect.

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