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The Effects of Urban Morphology on Enriching Thermal Experience:

Microclimates of Courtyard Spaces in Cambridge

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Abstract

The microclimate shaped by urban form is one of the critical determinants for the success of public spaces. To date, hundreds of studies have revealed the potential of mitigating heat and cold stresses by spatial-enclosure strategies to reduce thermal discomfort. However, most of them have placed more emphasis on taming the thermal extremes, rather than on enriching the microclimatic context to benefit the thermal experience. A rich thermal context with varied, mild thermal stress would enhance psychological adaptation, affording flexibility and meeting different thermal preferences of sun, shade, wind and stillness. Therefore, we aim to investigate the morphological effects on these thermal qualities, and to compare not only the cooling performance of geometries but also the microclimatic diversity and hourly fluctuation in thermal stress. More than a hundred fully enclosed courtyards (n=107) were selected across 31 colleges and 10 teaching sites at the University of Cambridge. We have completed 20-hour microclimate simulations at 33 domains with boundary conditions near the summer solstice and the ENVI-met simulation results were fed back into the heatmap through Urbano, Dragonfly and Ladybug plugs-in in Grasshopper. We found much stronger morphological effects on the variations of sun and wind than on air temperature and humidity. The inferential statistical analysis has also shown that the compacity of building shades and the vegetation configurations play crucial roles in taming thermal extremes and enriching the urban thermal contexts at the human scale.

Keywords: *Microclimatic Diversity, Thermal Variability, Enclosure Form, Multi-spatial Scales, Numeric Simulation*

I. INTRODUCTION

1.1 Thermal qualities of enclosed outdoor spaces

The outdoor thermal qualities are multifaceted. It is not only measured by the maximum summer cooling performance but also via microclimatic diversity, which significantly contributes to occupants' thermal autonomy in finding their desired variety of thermal conditions. Compact (semi)enclosed outdoor spaces provide pleasant thermal transitions and great social opportunities for indoor occupants and pedestrians. (Reynolds 2002) demonstrates with the example of two Spanish patios with the same side opening at the ground level, that although the overall thermal condition of a deep patio is cooler than a shallow one, the latter can provide more choices in sun and wind conditions. Furthermore, the thermal quality of enclosed and semi-enclosed outdoor spaces is reflected in more stability and less fluctuation than the climate outside from which they provide shelter (Sinou and Steemers 2004). Building and vegetation configurations are both key factors for improving these thermal qualities by defining the form of enclosure. The evapotranspiration from the leaves adjusts the local day and night temperature and humidity – they are efficient climate moderators that produce oxygen and thermal delight (Heschong 1979, de Dear 2004). Without vegetation, it is a challenging task to balance all of these thermal qualities. Although mutual shading between walls in a compact courtyard contributes to preserving the coolth and heat, too much shading can lead to undesired consequences in winter. Likewise, a huge courtyard without green would give more space for longwave radiation, which exacerbates the heat losses at night and is more likely to bring thermal extreme scenarios

(Javanroodi and Nik 2020). Hence, a deeper understanding of the dynamic thermal contexts in enclosed outdoor spaces both with and without the presence of vegetation is required (Shashua-Bar and Hoffman 2004, Almhafdy, Ibrahim et al. 2013).

The degree of the enclosure of outdoor spaces has been investigated in the past (Steemers, Ramos et al. 2004, Zamani, Heidari et al. 2018), but here we narrow down the study scope to focus solely on the fully enclosed courtyard and other morphological variables (Muhaisen and Gadi 2006).

1.2 Study area

We have reviewed past research projects on outdoor thermal comfort and environmental performance in Cambridge, UK (Nikolopoulou and Steemers 2003, Ratti, Raydan et al. 2003), where the climate is considered to be temperate. The ubiquitous and traditional courtyard spaces at Cambridge possess a variety of morphological characteristics, extending from the old town to West Cambridge where new teaching sites were built up (Fig. 1). Most of these courtyards are only open to the members of colleges except for 17 public ones. Apart from their unique architectural values, we set out to investigate three thermal qualities of the courtyard spaces across the university: ***1) cooling performance, 2) microclimatic diversity*** (Stephanopoulos 2012, Chatzipoulka, Steemers et al. 2020) ***and 3) thermal fluctuation*** (Sinou and Steemers 2004).

The study area comprises 33 simulation domains sized from 120m² up to 375m². Each domain contains one to ten courtyard samples adding up to the total sample size of 107. The universal thermal climatic index (UTCI) is one of the standardised thermal indices widely adopted to evaluate human thermal sensation (Jendritzky, de Dear et al. 2012, Li, Niu et al. 2020, Okoniewska 2020) along with air temperature (TA), relative humidity (RH), mean radiant temperature (MRT) and wind velocity (U). With the support of spatial analytical tools, we can either describe the dynamic thermal contexts by means of urban heatmap or estimate the morphological effects through statistical approaches.

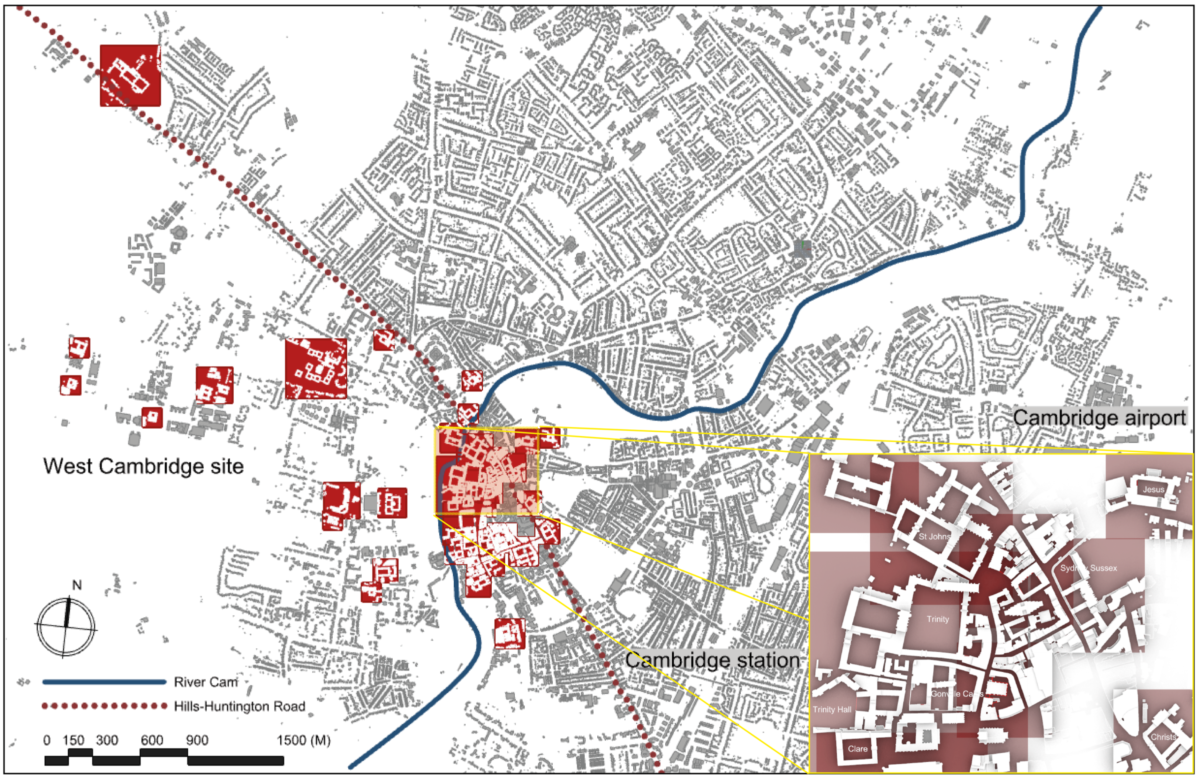

Figure 1. *A master plan shows 107 courtyard samples framed in 33 red-shaded simulation domains across the University of Cambridge. The detailed building configurations in the core area can be viewed in more detail in the bottom right corner.*

II. METHODOLOGY

Numeric simulation enables simultaneous measurements of many spatial samples at a district scale. The CFD-based program ENVI-met can provide a comprehensive model of the dynamic sun, wind and thermal stress (Perini, Chokhachian et al. 2017). In this study, the simulation is combined with spatial analysis by parametric tools such as Urbano in Grasshopper and the descriptive & inferential statistics in RStudio (Figure 2).

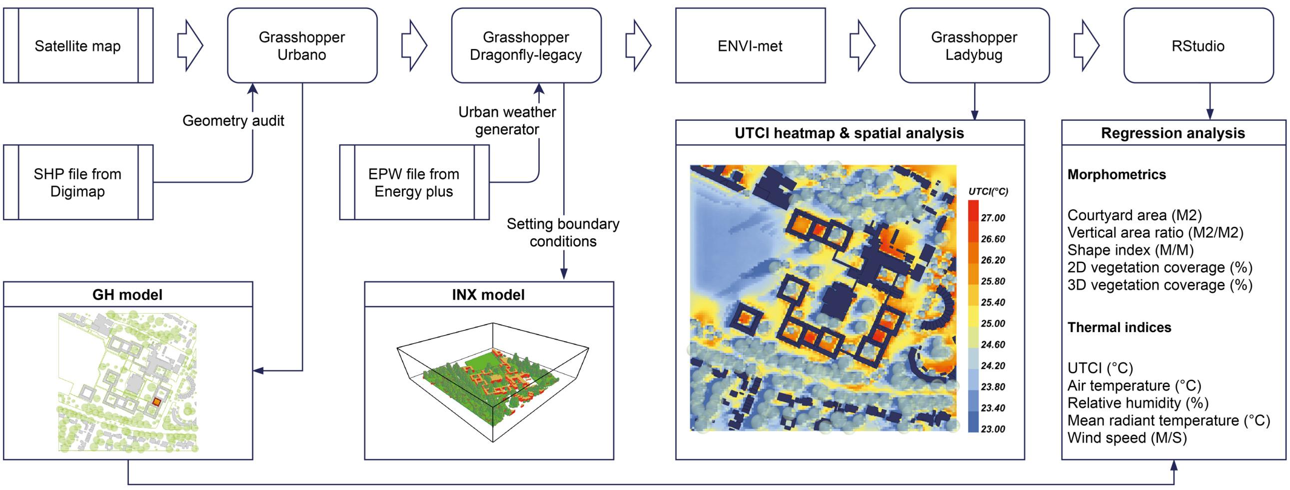

Figure 2. *The framework combines microclimate simulation and statistical analysis, taking Churchill College as example*

2.1 Measuring the courtyard form

Many simulations and in-situ monitoring experiments have revealed the significant thermal influence of courtyard design variants (Soflaei, Shokouhian et al. 2017, Zamani, Heidari et al. 2018). We have chosen five morphological variables including coverage, volume, compactness, horizontal aspect ratio, and long axial orientation from the building parameters, also adding four uncommonly used greening variables regarding the grass and tree coverage, both within and surrounding the enclosed regions of the courtyards (Table 1).

Table 1. Morphometrics for the courtyard form (Bardhan, Debnath et al. 2018)

Acronyms	Morphometrics	Formulas and definitions	Unit
CA	Courtyard area	***CA = SIGMA(a)*** where *a* is the area of each grid within a courtyard region	M^2
VAR	Vertical area ratio	***VAR = VA/CA*** where *VA* is the area of vertical surfaces enclosing the region	M^2/M^2
SI	Shape index	***SI = P/[4*SQRT(CA)]*** where *P* is the perimeter of the courtyard region	M/M
HAR	Horizontal aspect ratio	***HAR = L/W*** where *L* is the length of the long axis and *W* the short axis	M/M
LAT	Long axial tilt	***LAT = THETA(L)*** where *THETA* is the degree clockwise for the long axis tilted from the North	Deg. (°)
VC_c_2d; VC_s_2d	2D vegetation coverage ratio within/surrounding the courtyard region	***VC_c_2d = VA_2d/CA; VC_s_2d = VA_2d/SA*** where *VA_2d* is the ground area covered by shrubs, bushes, and grass; *SA* is the area of the simulation domain	%
VC_c_3d; VC_s_3d	3D vegetation coverage ratio within/surrounding the courtyard region	***VC_c_3d = VA_3d/CA; VC_s_3d = VA_3d/SA*** where *VA_3d* is the ground area covered by trees higher than 2 metres, e.g., oak trees, sycamores	%

2.2 Describing dynamic thermal conditions and the regression method

The dynamics of thermal quality can be described in terms of the average intensity (AVG, spatial means), the heterogeneity (SD, standard deviation) and the stability (OR, oscillation ratio) of the thermal conditions within a courtyard region (Table 2). For example, AVG (UTCI) indicates the cooling performance, SD (UTCI) the microclimatic diversity and OR (UTCI) the hourly fluctuation of the thermal stress. These outputs are then regressed with the geometric parameters to explain the morphological effects on the microclimatic elements.

Table 2. Temporal-spatial analysis and regression method

Spatial analytics	Output resolution	Input resolution	Formulas and definitions	Units
Spatial means (AVG)	1 region; 1 hour	1 grid; 1 hour	***AVG(R_t) = SIGMA (Gij_t)/N*** Where *Gij_t* is a grid value at the hour of *t* calculated by thermal indices; *ij* denote the coordinates of the grid; N is the total number of the grids within a courtyard region.	°C; %; M/S
Spatial variance (SD)	1 region; 1 hour	1 grid; 1 hour	***SD(R_t) = SQRT (SIGMA [(Gij_t - AVG(R_t)^2]/N)*** This is a standard deviation equation.	°C; %; M/S
Oscillation ratio (OR)	1 region; 1 hour	1 region; T hours	***OR(R_T) = SIGMA{ABS[AVG(R_t) - AVG(R_T)]}/(T-1)*** Where *AVG(R_T)* averages all values from *AVG(R_t)* with a total hour of *T* across the daytime.	°C/h; %/h; M/S*h
Multivariate linear regression				
Independent variables Xn	CA; VAR; SI; HAR; ; VC_2d; VC_3d		***Y= b1*X1 + b2*X2 + … + bn*Xn + res.*** Where *X1, X2 … Xn* are the morphometrics as independent variables, corresponding to the coefficient vectors *b1, b2… bn*; *Y* is the spatial analysis result from the microclimate simulations, and *res.* means residuals.	M²; M/M; %; M²/M²; Deg.(°)
Dependent variable Y	AVG(); SD(); OR()			°C; %; M/S (h)

2.3 Setting the boundary conditions for the microclimate simulation

The meteorological records around the summer solstice are compared to select a date for the microclimate simulation in ENVI-met. We have chosen 28 Jun, the least cloudy day with fairly stable wind, according to the airport weather files formatted in the typical meteorological year (TMY) since 1994. The raw TMY data are pre-processed by the urban weather generator (UWG) in Dragonfly (Table 3(a)) to consider the urban heat island effect. The UWG files (Figure 3) then define the boundary conditions for simulation (Table 3(b)).

Table 3. Generating the urban weather profile to define boundary conditions

(a) Urban weather generator (UWG) settings in Dragonfly			
Building parameter	Building age	Floor to floor distance	Waste Heat fraction from the HVAC system
	Pre – 1980's	3.5M	0.5
Traffic parameter	Sensible heat ratio	Weekday Schedule	Weekend Schedule
	4 W/ M²	[20%, 90%]	[20%, 50%]; [20%, 40%]
Vegetation parameter	Albedo	Evapotranspiration from trees	Evapotranspiration from grass
	0.3	0.7	0.5
Pavement parameter	Albedo	Thickness	Conductivity
	0.1	0.5M	1W/M*K

(b) Material settings in ENVI-met	
Facades	Bricks_0000B3
Roofs	Tile_0100R1
Pavements	Concrete_0000PG
Trees_XL	Quercusrobur_0000B3
Trees_L	Platanus&acerifolia_0000B8
Trees_M	Acercampester_0000A9
Trees_S	Betulapendula_0000B7
Grass	50CM_0000LG

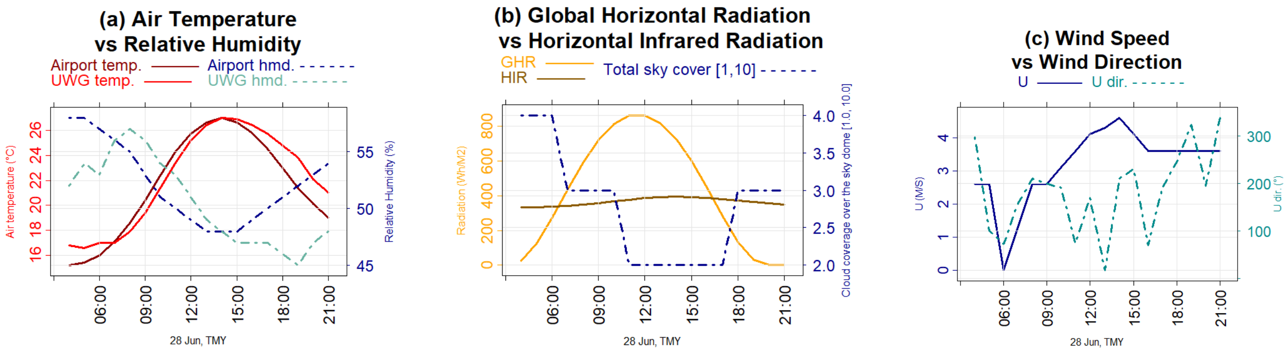

Figure 3. *(a) The urban weather generator (UWG) transfers the airport temperature and humidity into an urban context; (b,c) The raw radiation and wind data from the airport are used due to very little difference between the urban and rural.*

III. RESULTS

3.1 Descriptive statistics

The distribution of each morphological variable has been represented in the density plot (Figure 4). Some of them are left-skewed, such as the (a) court area, (b) vertical area ratio, (c) shape index and (d) horizontal aspect ratio. This indicates the outliers of oversized, overly deep, extremely irregular, or overstretched courtyard forms, and they are excluded from the regression for better estimation performance. There are also non-negligible numbers of samples with no 2D or 3D vegetation. Finally, 107 courtyard samples were retained for further analysis.

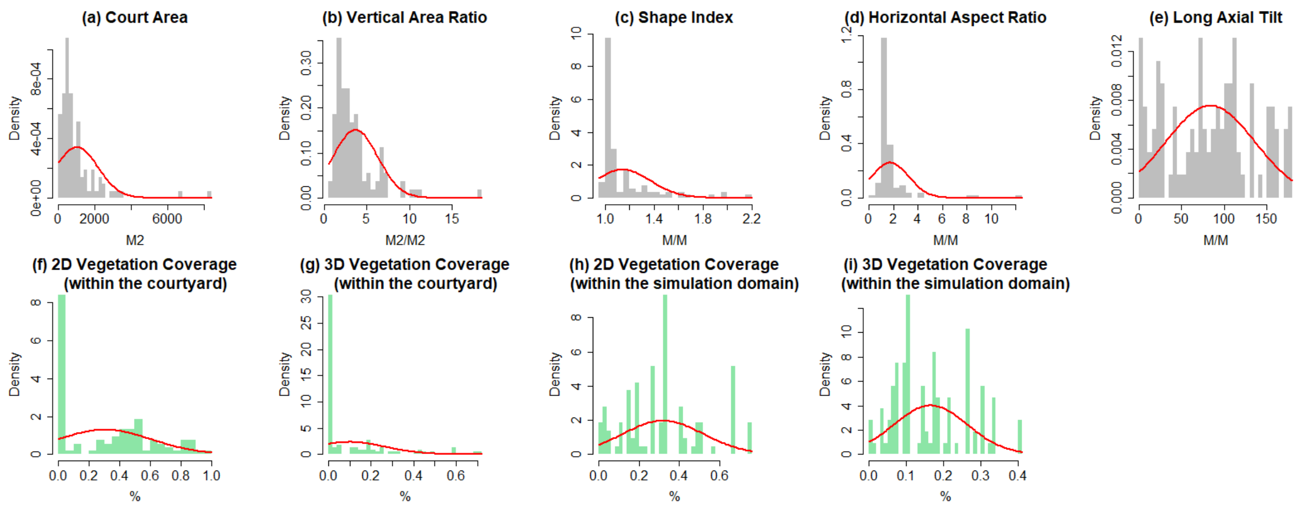

Figure 4. *Histograms of the building and vegetation parameters by sampling courtyard spaces at Cambridge*

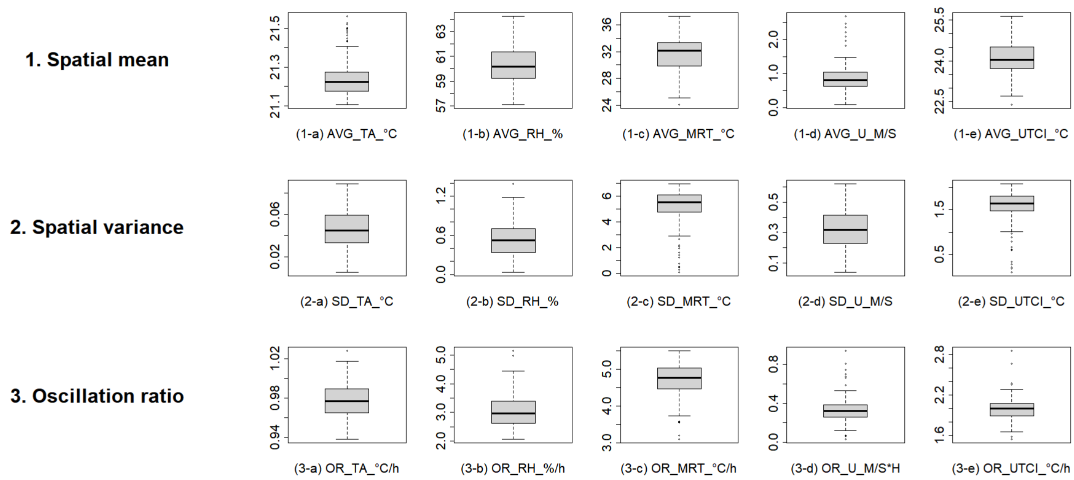

*Figure 5. The simulation results of the diurnal spatial mean (1-a,b,c,d,e), diurnal spatial variance (2-a,b,c,d,e) and hourly oscillation ratio (3-a,b,c,d,e) scaled by air temperature (Ta), relative humidity (Rh), mean radiant temperature (MRT), wind velocity (U) and UTCI among 107 courtyard samples. The box plots compare the diurnal means and dynamic ranges of thermal indices, after completing the 20-hour microclimate simulations on all 107 samples at 33 simulation domains. The spatial variances of air temperature and humidity (2-a, 2-b) are less than 0.1°C and 1%, compared to their hourly oscillation ratios (3-a, 3-b) at around 1°C/h and 5%/h. The variabilities of sun, wind and overall thermal sensation are much more obvious, where the diurnal spatial variance of MRT can reach up to 6°C within a courtyard (2-c), and sometimes the wind vibrates at a rate of 1.8M/S*h (2-e).*

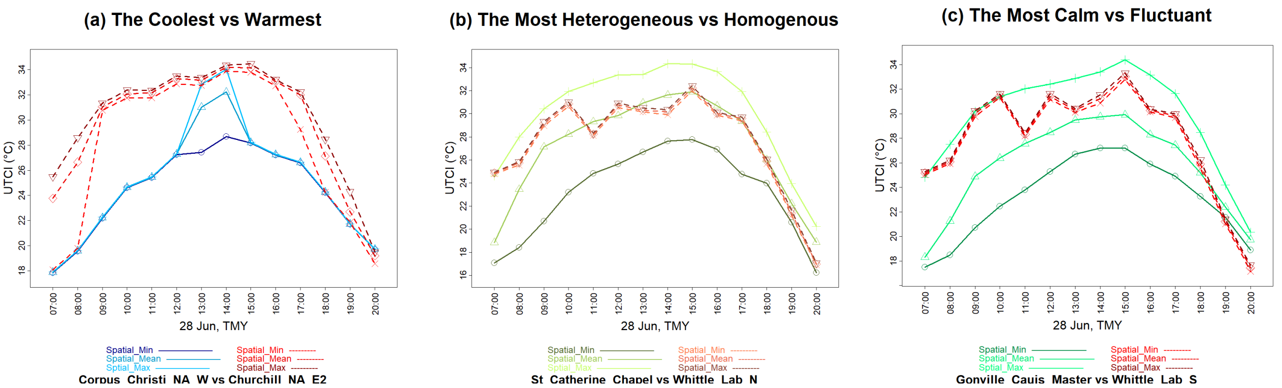

Figure 6. *The daytime UTCI results are marked with min, mean, and max values in three pairs of extreme courtyards measured by the cooling performance, microclimatic diversity and thermal fluctuations: the coolest (Corpus Christi), the warmest (Churchill), the most heterogeneous (St Catherine) and calm (Gonville Caius) versus the most homogenous and fluctuant (West Cam Lab). See the Appendix for all results.*

3.2 Inferential statistics

The multivariate regression findings corroborate the previous descriptive analysis between the microclimate simulation and courtyard form which better explains the variation of sun and wind than the air temperature and humidity. More than 30% coefficient vectors show good reliability ($p < 0.05$) with 9 morphological regressors (Table 4). For the building parameters, the spatial scale, volume and compacity yield higher validity than the horizontal aspect ratio and axial orientation. The overall cooling performance is more dependent on the coverage of the trees than on the building shade. The 3D green coverage surrounding the courtyard also significantly contributes to the spatial-temporal variance of the thermal context inside.

Table 4. Multivariate linear regression (Sample size N=107; *, **, * to mark significance levels *P* <.05, *P* <.01, *P* <.001; the variance inflation factor (VIF) is reported for each independent variable to test for heteroscedasticity)**

Xn / Yn	Multiple R	Adjusted R^2	CA b1	VAR b2	SI b3	HAR b4	LAT b5	VC_c_2d b6	VC_c_3d b7	VC_s_2d b8	VC_s_3d b9
AVG(UTCI)	**0.81**	**0.62**	**0.00*****	**-0.12*****	0.02	**-0.11*****	**0.00****	-0.08	**-2.18*****	1.34***	0.13
SD(UTCI)	0.52	0.20	0.00	0.00	**0.48****	0.02	0.00	0.09	**0.92*****	0.27	-1.27**
OR(UTCI)	**0.74**	**0.51**	0.00	-0.03***	-0.07	-0.01	0.00	-0.05	**-0.74*****	-0.05	0.36**
AVG(TA)	**0.80**	**0.61**	**0.00****	0.00	0.03	-0.01	0.00	**-0.06****	0.03	0.42***	0.03
SD(TA)	0.65	0.37	0.00***	0.00***	0.00	0.00	0.00	0.00	0.03***	0.01	0.01
OR(TA)	0.52	0.20	0.00	0.00	0.00	0.00	0.00	-0.01	0.02	**0.04*****	-0.01
AVG(RH)	**0.77**	**0.56**	**0.00****	-0.14***	0.87	-0.07	**0.01*****	0.61	-0.05	-1.6**	**12.3*****
SD(RH)	0.65	0.37	0.00***	0.00***	0.00	0.00	0.00	0.00	0.03***	0.01	0.01
OR(RH)	0.52	0.20	0.00	0.00	0.00	0.00	0.00	-0.01	0.02	**0.04*****	-0.01
AVG(MRT)	**0.77**	**0.56**	0.00	0.00	0.00	0.00	0.00	-0.01	0.02	**0.04*****	-0.01
SD(MRT)	**0.70**	**0.45**	**0.00*****	-0.03***	**0.49*****	-0.01	**0.00*****	**0.15***	**0.04*****	-0.36***	**0.93*****
OR(MRT)	**0.88**	**0.76**	**0.00****	**-0.07*****	0.10	-0.03	0.00	-0.05	**-2.62*****	-0.10	0.85**
AVG(U)	0.66	0.38	0.00***	-0.07***	0.08	-0.04	0.00	0.09	-0.32	-0.83***	2.26***
SD(U)	**0.79**	**0.59**	**0.00*****	**-0.02*****	**0.29*****	-0.01	0.00	**0.14*****	**-0.11***	-0.04	0.15
OR(U)	0.61	0.32	0.00	-0.03***	0.04	0.00	0.00	0.04	-0.16*	-0.23***	0.54***
VIF	N/A	N/A	1.51	1.52	1.54	1.51	1.07	1.60	1.19	1.71	1.85

IV DISCUSSIONS & CONCLUSIONS

The descriptive and inferential findings have revealed a variety of morphological effects of the courtyard on its cooling performance, microclimatic diversity and hourly thermal fluctuation. We have identified 2 efficient morphological approaches to enrich thermal textures: **(1) increasing the shape index of the courtyard; (2) increasing the tree coverages within and outside the courtyard**, where the second method can be twice as than the first (b7=0.92, b9=0.93 vs b3=0.48) and perform better in moderating the thermal extreme. Other approaches are also proved to be valid to diversify individual microclimatic elements. For example, increasing the vertical area ratio can contribute to shielding the strong wind and growing the mild breezes. A courtyard with an E-W oriented axis would experience more variations in sun and shade than with an N-S oriented axis.

This study has some limitations in the area of simulation and statistics. Firstly, we have excluded the variable of courtyard locations, for it is not the targeted item to investigate in this study, and it may add complexity to the regression model at a later stage. Therefore, identical boundary conditions have been applied to all 33 simulation domains across a range of urban density. This gives rise to more ideal but less realistic simulations without considering the intra-urban temperature variations. Secondly, while the small sample size leads to a rough estimation through multivariate linear modelling, it still effectively tests the sensitivity of each morphological variables to do with the variability of microclimatic elements.

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APPENDIX

The three-bar plots triangulate the college rankings of ‘cooling performance vs microclimatic diversity (left), ‘microclimatic diversity vs hourly thermal fluctuation’ (centre), and ‘hourly thermal fluctuation vs cooling performance’ (right). They are scaled by the diurnal spatial means, diurnal spatial variance and hourly oscillation ratio of the universal thermal climatic index (UTCI) values.