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Planning strategies for roadside tree planting and outdoor comfort enhancement in subtropical high-density urban areas

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ABSTRACT

Hot summers in the subtropics cause thermal discomfort, which is intensified by the urban heat island effect in heavily built-up areas. Use of urban greenery has been proposed as a mechanism for microclimate regulation. In this study, the microclimatic effect of urban trees was investigated in the context of high-density cities in subtropical hot and humid climates. Measurements were conducted in urban areas with sky view factors (SVF) ranging from 0.2 to 0.8, and mean radiant temperatures were calculated. The measurements show that the effects of urban trees are related to SVF and that the impact of building morphology is more evident under cloudy conditions than under sunny conditions. In heavily built-up areas, the mean radiant temperature (T_{mrt}) was reduced to a comfortable level (33 °C) by roadside trees in the early afternoon. Simulation results indicate that roadside trees reduce the physiological equivalent temperature (PET) to 29 °C in urban areas with SVFs of 0.2 under cloudy conditions. The SVF-oriented planning method was tested using the existing building geometry of two high-density districts of Hong Kong, Mong Kok and Sham Shui Po, and site-specific design strategies for tree planting were developed. The study results show that a comfortable microclimate can be provided by roadside trees in heavily built-up urban environments in subtropical cities for nearly 70% of the summer. Design suggestions for refining the Green Master Plans of Hong Kong in future planning are provided.
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1. Introduction

1.1. Challenges in climatic planning for urban greenery in subtropical high-density cities

In the past half century, rapid population growth and extensive urbanization have taken place in the world's tropical and subtropical regions [1]. With some of the world's major cities turning into megacities, high-density development is becoming irreversible [2]. Urban heat island (UHI) magnitudes of up to 4 °C have been reported in tropical and subtropical regions, as a result of high population densities and highly developed urban environments [3,4]. Cities in hot regions are at higher risk of being affected by climate change [5]. Recent studies [6,7] in (sub)tropical cities have shown that UHI effects are associated with urban thermal discomfort and heat-related human health issues. Between 1997 and 2005, 4764 deaths from heat stroke occurred among Hong Kong's elderly population on summer days with maximum temperatures of 30.4 °C or above [8]. A recent study [9] conducted in Hong Kong showed that every 1 °C temperature increase above 29 °C was associated with a 4% rise in mortality in areas where profound UHI effects were observed. A study in Guangzhou showed that a 15.5% increase in heat-related mortality occurred when the air temperature increased from 30 to 32 °C [10].

Givoni [11] noted that one of the objectives of urban design in hot humid regions is minimizing thermal discomfort and reducing the heat island effect in densely built urban areas. However, less systematic research has been conducted on climatic urban planning and design for hot climates, particularly hot humid climates, than for other climate types. Urban climate studies for the (sub)tropical

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regions account for less than 20% of those in the field. Moreover, the existing studies reveal a bias toward examination of conditions under dry, clear skies for these areas [12]. In large parts of the subtropical regions where hot humid climates are found, the sky is often partially cloudy [11]. Urban greenery has been proposed as a mitigation measure for the UHI effect in these areas [13–15]. Macro-scale intra-urban measurements have shown a 2–4 °C air temperature difference between urban areas and green areas in (sub)tropical cities [4,16,17]. In the interest of improving environmental quality, studies on the minimum site coverage of greenery in urban areas have been conducted, and planning suggestions have been made [18,19]. However, in many high-density cities, urbanization generates significant tension concerning land for greenery [20,21]. Tree planting has been accorded a low priority in many highly developed urban areas, and the existing green coverage is often much lower than the recommended value [22,23]. In addition, studies of urban greenery in temperate climates with urban sprawl may not be fully applicable to subtropical areas [24], and there is a lack of design guidance for selecting suitable planting locations for specific urban sites [25]. Planners should seek solutions that optimize the planning of tree planting within the context of the built environment and local climate [14,15,26]. Site-specific planning for tree planting in high-density cities with subtropical hot humid climates was investigated in this study to fill the gap in the research to date [27,28].

1.2. Urban morphology and greenery in built environments

The sky view factor (SVF) has been shown to be a key parameter in the impact of building morphology on urban microclimate. Unger [29] studied the relationship between intra-urban temperature differences and areal SVF means, and noted that area-averaged SVF values predicted temperature differences between sites better than point-based SVF values. Studies in tropical and subtropical areas have shown that the SVF influences the thermal performance of building groups [30]. A 1% reduction in the SVF was found to reduce the daytime UHI intensity by 1%–4% in subtropical Hong Kong [31]. Chen et al. [32] studied the relationship between the area-averaged SVF and the daytime air temperature increase in urban sites and noted that the influence of the SVF varied with building density. Yang et al. [33,34] studied the effect of the sky view factor on the retrieval of emissivity and the surface temperature in urban areas. The sky view factor has been found to be negatively related to the effective emissivity of an urban canopy, because of multiple scattering and reflection caused by buildings. He et al. [35] evaluated the effect of SVF on air temperature and specific humidity and investigated the correlation between SVF and the physiological equivalent temperature (PET) in a temperate climate. Studies have also shown that SVF is closely related to outdoor thermal comfort in (sub)tropical cities. Lin et al. [36] studied seasonal and annual outdoor thermal perceptions for various SVFs in a subtropical city. Krüger et al. [37] found a strong correlation between SVF and differences between the air temperature and mean radiant temperature (T_{mrt}).

Several studies have investigated the cooling of vegetation in an urban context and have concluded that the thermal effects of trees on the urban environment are related to the influence of buildings. It has been reported that in streets with aspect ratios of 0.2–0.6, a 2.3 °C cooling in air temperature resulted from increasing the tree coverage to 64% [38]. Ali-Toudert and Mayer [39] revealed that, compared to the cooling effect on air temperature, the reduction in T_{mrt} due to vegetation was more sensitive to the building morphology of the site. Morakinyo et al. [40] increased the range of tested aspect ratios to 1–3 to study the cooling effect of roadside trees in dense urban environments, and their results showed that there is high impact of shadow cast from bounding buildings in deep canyons. Yahia and Johansson [41] conducted parametric studies to assess the thermal effects of trees in streets with different orientations in a hot dry city. Shashua-Bar et al. [42] observed that the cooling efficiency of vegetation in an urban canyon was highly related to canopy coverage, but recent studies [43–45] in the tropics and subtropics have shown that in addition to the tree canopy cover, the structural characteristics of various tree species and the design of the spatial distribution of trees should also be considered to achieve desired heat mitigation outcomes. Zhao et al. [46] investigated optimization approaches for placing trees that provide maximum benefits to a building structure, taking into account the influence of adjacent buildings. However, their work needs to be extended to urban-site scale.

In summary, greenery is typically accorded a low priority in highly developed urban areas. With limited land available for urban greenery, it is necessary to understand the thermal behavior of roadside trees in built environments, plan tree planting using appropriate methods, and identify suitable planting locations. SVF is closely related to the outdoor microclimate and thermal comfort. This study was conducted to investigate the thermal effects of trees planted under different SVFs formed by buildings and their performance in improving outdoor comfort. Tree planting in urban areas with compact morphology and profound UHI effects were studied, and site-specific planning strategies for heavily built-up districts were developed.

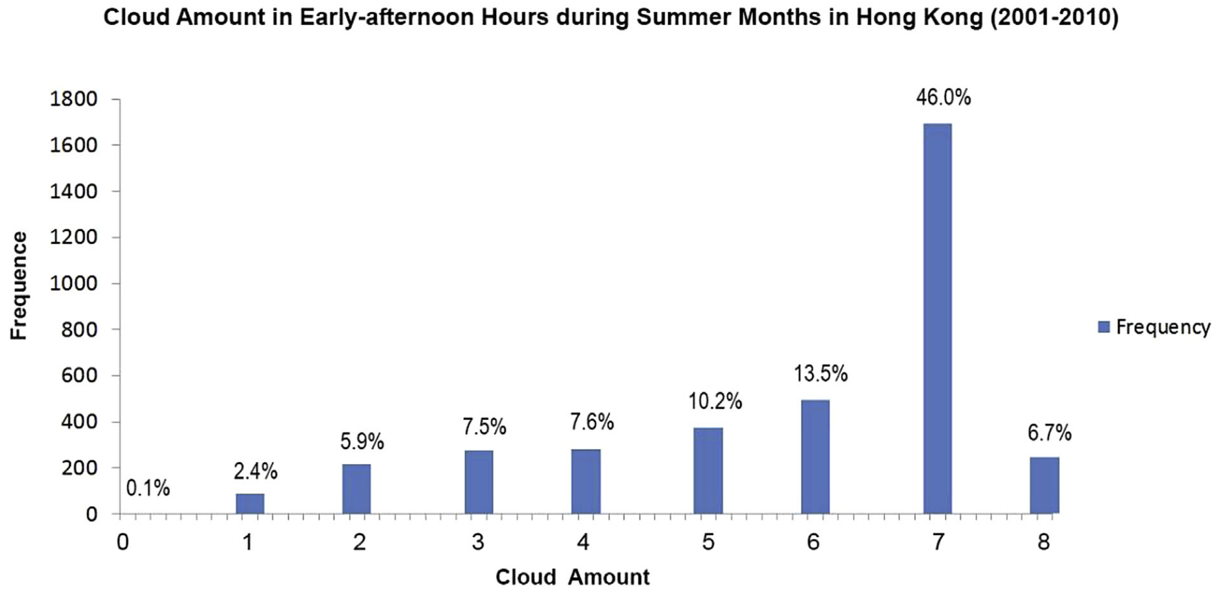
2. Study area and climatic conditions

Hong Kong is a subtropical city with a hot humid climate (Hong Kong Observatory, 2015). The mean daily maximum air temperature is approximately 31 °C in July and August. During the summer months, the daily mean relative humidity remains high (above 80%), with values usually exceeding 85% during the nighttime. Because of the high humidity, cloudy conditions dominate the weather during the summer in Hong Kong, especially in the early afternoon [47]. According to 2001–2010 data from the Hong Kong Observatory, the sky is cloud nearly 70% of the time during the summer between the hours of 12:00 and 15:00, with cloud cover reaching 6 oktas or more (Fig. 1). Increasingly frequent occurrences of both extreme hot weather and low-level clouds are expected in the subtropics because of climate change [48]. given the critical and prevailing thermal issues in hot humid subtropical cities [2], this study was conducted to investigate the thermal effects of urban trees under both sunny and cloudy conditions.

In a large part of the Kowloon Peninsula in Hong Kong, building density is high, and many districts are classified as “highly developed with high thermal load” [49]. Images of air temperature derived from ASTER data show that the highest nocturnal temperatures occur in the heavily built-up urban areas of the Kowloon Peninsula [50]. Therefore, the Kowloon Peninsula was selected to be our study area (Fig. 2). Research in the tropics and subtropics has shown that the comfort range in these regions differs from that in temperate climates and has a higher threshold [51]. For people to remain comfortable in subtropical outdoor environments during hot humid summers, the PET should not exceed 32 °C, and T_{mrt} should not exceed 34 °C [52,53]. These comfort thresholds were adopted in the study for use in assessing different planning methods for roadside tree planting from the perspective of pedestrian comfort enhancement.

3. Methodology

In this study, the microclimatic effects of trees under low and high SVFs were first compared by means of site surveys. Based on



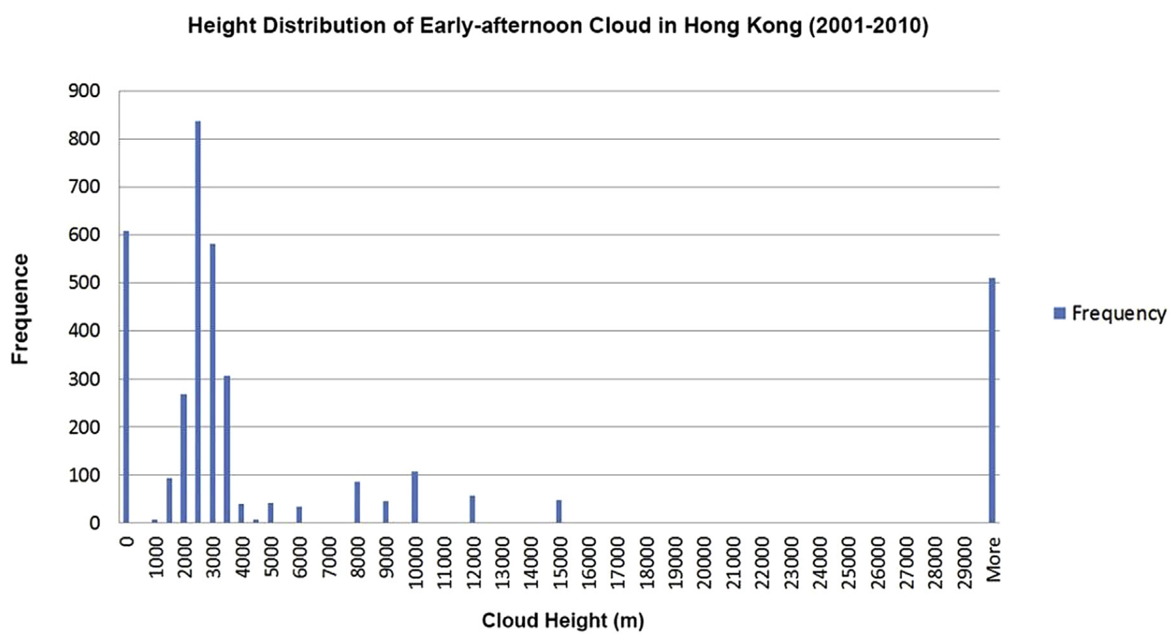


Fig. 1. Occurrence frequency of conditions with different total cloud amounts (upper plot) and distribution of cloud heights during early afternoon (lower plot) in summer months (June–August) in Hong Kong (2001–2010).

the measurement results, an SVF-based planning method was examined by means of parametric studies, using simplified building block array geometries. For two demonstration cases, the SVF-based planning method was tested for the existing compact urban morphology of Hong Kong, and site-specific climatic planning strategies were developed.

3.1. Measurement methodology

Small-scale site surveys were conducted to assess the thermal impact of urban trees under low and high SVFs. Urban areas in Kowloon Peninsula with SVFs ranging from 0.2 to 0.8 were selected as sites to be measured. For each pair of low and high SVF sites that were compared, the studied trees had similar solar transmissivity ratios (estimated by the ratio of downward radiation under a canopy and on an exposed location, measured using a thermopile-type pyranometer). Environmental variables were measured under the tree canopy and on a nearby exposed reference point at a height of 1.5 m [54–56]. A mobile measuring unit containing an HOBO sensor and Testo400 measuring instrument was set at each measuring point to record the downward solar radiation (Fig. 3), air temperature, relative humidity, and wind speed at a 10-sec sampling interval, and the data were averaged for subsequent analyses. The globe temperature was also measured with a standard globe thermometer (diameter D = 0.15 m, emissivity $\varepsilon = 0.95$) using a 5-min mean [57]. T_{mrt} values were then calculated from the recorded measurements [52,57]. The measurements were conducted from 12:30–14:00 under both clear and cloudy conditions in July and August 2014. As the measurements were conducted on different days, several criteria were established to ensure that representative

Fig. 2. Measurement sites in the urban areas of Kowloon Peninsula, Hong Kong.

Fig. 3. Measurement equipment.

data were obtained. 1) The background radiation was constrained to be within the same range for each measured weather type. For sunny conditions, the globe radiation amounts were in the range of 800–1000 W/m^2, and the range of diffuse radiation was at a low level of approximately 100–200 W/m^2. For cloudy conditions, the diffuse radiation accounted for a large fraction and remained at high levels within the range of 350–400 W/m^2. 2) The solar radiation was constrained to be within a constant range 30–60 min before measurements and during the measurement period (based on solar radiation records from the Hong Kong Observatory). 3) To exclude the effect of upwind signals, only data collected under weak wind conditions (wind speeds <1.5 m/s) were used for analysis.

3.2. Parametric study

3.2.1. Model validation and sensitivity test

Parametric studies were conducted by numerical modeling to investigate the thermal effects of roadside trees in densely built urban areas. The three-dimensional microclimate model ENVI-met was used in the parametric studies to simulate the micro-scale interactions among trees, urban surfaces, and the atmosphere. The accuracy of the ENVI-met model in simulating the thermal effects of trees under different weather conditions was validated by two sets of measured data collected on 4 June 2014 (sunny) and 13 June 2014 (cloudy). For each tree studied, an estimated leaf area density (LAD) profile was developed using 1) fisheye lens images captured under the tree canopy and 2) frontal images showing the vertical configuration of the tree [58,59]. The LAD profiles were then input into the plant database of ENVI-met for calculation purposes (Fig. 4). The simulation results and the measured data were compared in terms of T_a, T_s, T_{mrt}, and PET values. The intensity of the incident radiation and the surface albedo both affect the reflected radiation in an urban space and thus influence the T_{mrt} value [57]. A test run was performed to demonstrate the sensitivity of the ENVI-met model to surface albedo values [60]. Two wall

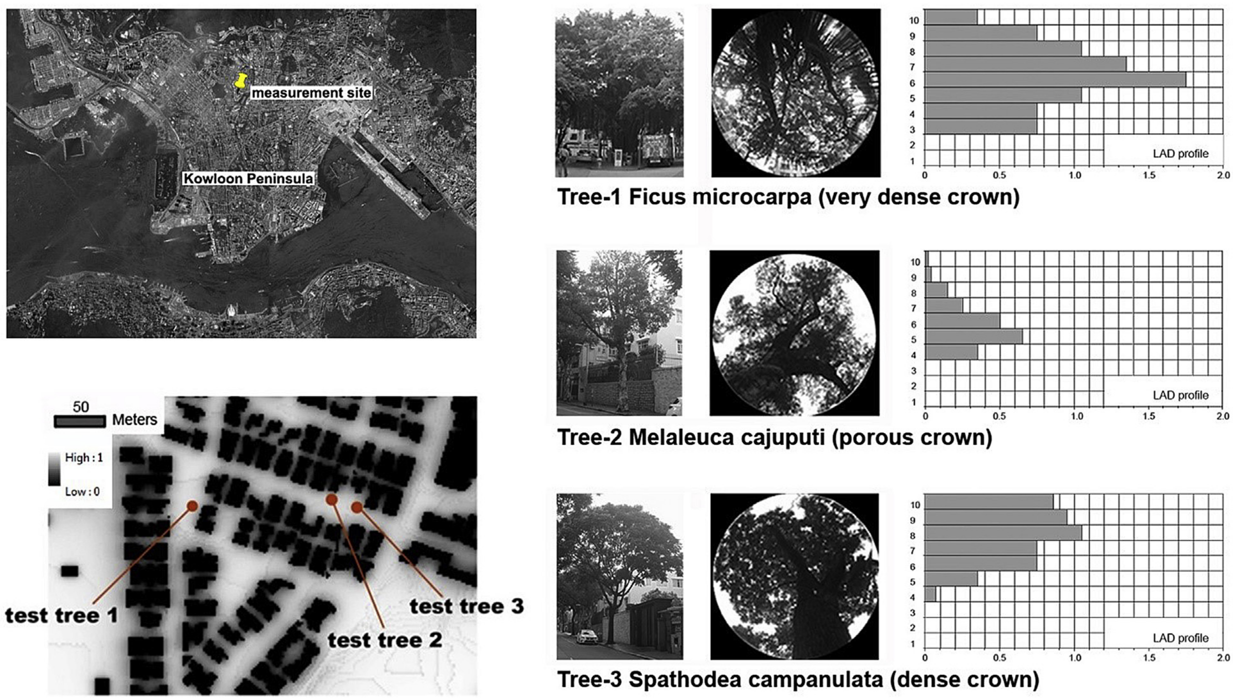


Fig. 4. Site of the small-scale survey and the LAD profiles of the studied trees.

albedo values, 0.5 and 0.1, representing upper and lower bounds in surface albedo in urban environments [61], were adopted in the sensitivity tests.

3.2.2. Testing variables and model initialization

The objective of the parametric study was to evaluate the influence of SVF and background weather on the thermal performance of roadside trees. The typical building block array geometry on the Kowloon Peninsula was adopted in the simulations. A statistical summary of the SVF values in various districts showed that the highest and lowest values, in terms of district-averaged SVFs, were 0.2 and 0.5, respectively (Fig. 5). Therefore, in the parametric studies, the building heights were set at 18 m and 75 m to simulate low-SVF (0.2) and high-SVF (0.5) scenarios. Conditions of few clouds and abundant clouds were set up in the simulations to assess the thermal performance of urban trees under different background weather conditions. 2 oktas (of a maximum of 8) of high clouds represented the few cloud conditions in the simulations, and 2 oktas of medium clouds and 4 oktas of low clouds represented the cloudy conditions.

A 250 × 250 × 30 grid was selected for the model domain, with grid sizes of 3 m used for high resolution. Denser vertical telescoping grids (three layers) were set within the first 2 m to achieve more accurate results at the pedestrian level. In the vegetated scheme, trees were arranged on the exposed sides of the streets in the simulations. The tree model was profiled with an existing tree species in the study area (LAI = 4.5, average LAD = 0.45 $m^2\ m^{-3}$). The model inputs for the parametric study are listed in Table 1. The input initial temperature and relative humidity were based on 2014 summer records from the weather station in the study areas (the SSP station). The input wind data were extrapolated downward from 500-m height records for each district using a wind profile power law expression. The roughness length α was set to 0.1, considering the relatively low density in the upwind areas [62]. The shortwave adjustment factor was set to 1.2 to simulate high radiation levels in summer [50].

Four scenarios were run in ENVI-met, for simulation periods from 6:00 to 14:00. The results for the 13:00 and 14:00 period were analyzed. In addition to the air temperature (T_a), the surface temperature of the road surface (T_s) and T_{mrt} were calculated to assess the outdoor radiation environment [54,63]. PET values were also estimated using the ENVI-met package BioMet to evaluate the effects of roadside trees in improving pedestrian comfort. For the human parameter setting in BioMet, the clothing index was adjusted to 0.4, the average level of clothing in summer in Hong Kong [64,65]. Metabolic activity was set to 90 W/m^2 for the purpose of the PET calculation [66].

3.2.3. Demonstration cases

Based on the measured data and survey results, tree planting in highly developed areas with low SVF values and profound UHI effects was investigated further. Two densely built districts on the Kowloon Peninsula were selected for use as demonstration cases (Fig. 6). Mong Kok (MK) is a highly developed urban district with an extremely high population density of 130,000/km^2 [67]. The area has mixed land use, with a combination of tall commercial towers and residential buildings the form a geometry that can be characterized as LCZ-1, i.e., compact high-rise, in the local climate zone classification system [68]. The MK area has an average SVF value of 0.14, with a standard deviation of 0.15. It has been reported that MK has the strongest UHI effect of any district in Hong Kong, because of the compact building morphology, and that urban greenery offers a practical solution for the area [69]. The second studied site was Sham Shui Po (SSP), a heavily built-up residential district with a population density of 39,905/km^2. The mean SVF value in the SSP area is 0.23, with a standard deviation of 0.24. The geometry of the SSP site can be characterized as a mixture of LCZ-1 (compact high-rise) and LCZ-2 (compact mid-rise). The two studied districts are both located in waterfront areas, and the streets have different solar orientations. Local guidelines [70] recommended 33% green coverage. In both of the studied districts, areas with SVF values in the lowest 33% were identified using ArcMap10, and trees were

DISTRICT	MEAN of SVF	STDEV. of SVF
1 Sham Shui Po (a)	0.23	0.25
2 Sham Shui Po (b)	0.27	0.26
3 Prince Edward	0.22	0.22
4 Mong Kok	0.18	0.20
5 Yau Ma Tei	0.29	0.26
6 Jordan	0.19	0.21
7 Tsim Sha Tsui (west)	0.21	0.27
8 Tsim Sha Tsui (middle)	0.19	0.24
9 Tsim Sha Tsui (East)	0.36	0.31
10 Hung Hom	0.26	0.27
11 Tai Wan	0.30	0.33
12 To Kwa Wan	0.28	0.30
13 Kowloon City	0.27	0.28
14 Kowloon Tsai	0.48	0.35
15 Kowloon Tong	0.54	0.36
16 Yau Yat Chuen	0.47	0.35
17 Mong Kok East	0.45	0.35
18 Ho Man Tin	0.40	0.32

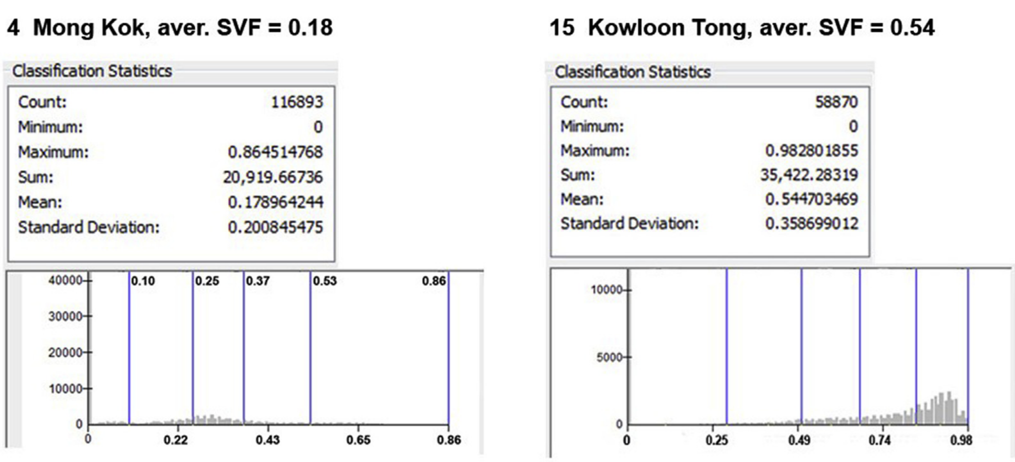


Fig. 5. Means and standard deviations of SVF distributions in specific neighborhoods on the Kowloon Peninsula. The highest and lowest average SVF values of the Kowloon Peninsula are 0.54 and 0.18, respectively.

Table 1
Summary of input and test variables for parametric study.

Meteorological input		Building setting		Variable	
Initial air temperature [K]	303	Heat transmission walls [W/m^{2}K]	2	Building height (m)	18
Relative humidity 2 m [%]	70	Albedo walls	0.2		75
Wind speed 10 m [m/s]	3	Heat transmission roof [W/m^{2}K]	2	Cloud cover	2/8 (sunny)
Factor of shortwave adjustment	1.2	Albedo roofs	0.3		6/8 (cloudy)

arranged in these low-SVF areas in the demonstration runs. Meteorological inputs for the demonstration cases were consistent with those for the parametric study. Based on the simulation results, SVF-based planning and site-specific climatic design strategies were examined.

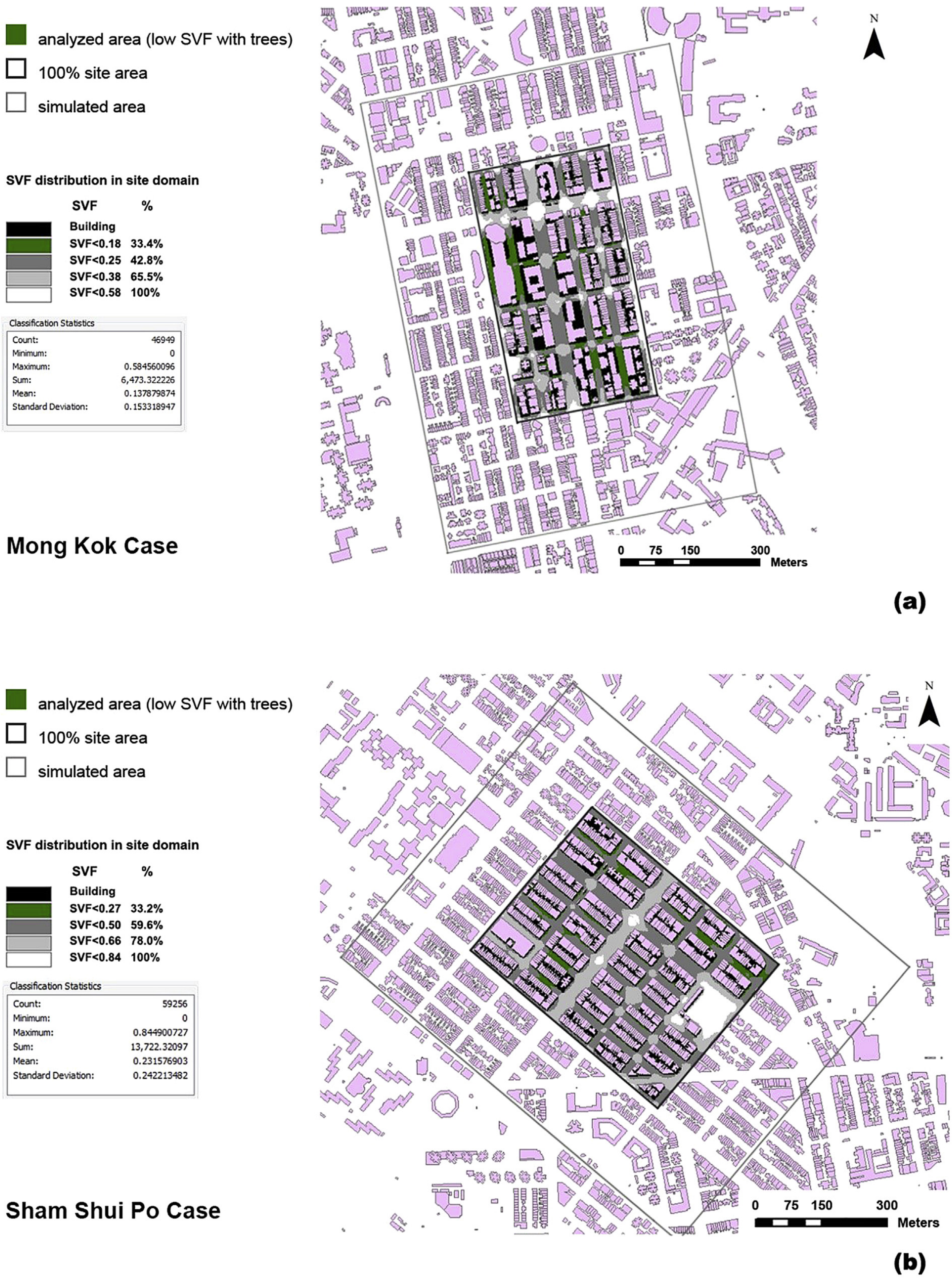


Fig. 6. Studied sites in Mong Kok (a) and Sham Shui Po (b).

4. Results

4.1. Measurement results

The results of the site surveys indicate that the net effects of trees are SVF-related. The measured data show that when trees with close solar transmission ratios are planted individually in urban sites with similar SVF values, equivalent cooling outcomes in T_{mrt} can be achieved under similar background radiation levels. T_{mrt} reductions achieved by trees at sites with SVF values of 0.52 and 0.50, were 21.7 °C and 21.6 °C, respectively. The difference was only 0.1 °C (given radiation levels at the exposed point ranging between 790 W/m^2 and 820 W/m^2 and tree crown solar transmission ratios of approximately 0.08). T_{mrt} reductions by trees with 0.06 solar transmission ratio at sites with SVFs of 0.73 and 0.70 were 17.5 °C and 17.0 °C, respectively, representing a difference of only 0.5 °C (for radiation levels at the exposed point ranging between 790 W/m^2 and 820 W/m^2 and tree crown solar transmission ratios of approximately 0.06).

Under both sunny and cloudy conditions, there are significant differences in the net environmental effects of trees planted under low SVF and high SVF conditions. In this study, the reductions in T_{mrt} under high SVF and low SVF conditions were approximately 30 °C and 23 °C, respectively, i.e., a difference of approximately 7 °C in sunny weather. For cloudy conditions, the magnitude of the reduction was 15 °C under high SVF and 3.0 °C under low SVF, a difference of 12 °C (Fig. 7). The results indicate that larger cooling magnitude in T_{mrt} were observed at high-SVF sites locations than at low-SVF locations. As to the influence of background weather, the cooling effects of urban trees were more significant during sunny days. On the other hand, the influence of building morphology, which was assessed by the difference in the magnitude of T_{mrt} reduction attributable to trees under low-SVF and high-SVF conditions was more evident on cloudy days. In cloudy conditions, diffuse radiation comes from different parts of the sky and is more uniform over the sky, compared to sunny conditions during the early afternoon [71]. Therefore, given the same range of background radiation and similar tree canopy transmissivities, the effects of trees in reducing T_{mrt} depend on the fraction of the sky obstructed by the tree crowns on cloudy days, which varies with the SVF of the site. As a large part of the subtropical region is dominated by cloudy weather during the summer and because increased occurrence of low-level clouds is expected in the subtropics as a result of climate change [48], it is important to study SVF-based planning strategies for the planning of roadside tree planting in subtropical cities.

4.2. Parametric study

4.2.1. Model validation and sensitivity test

Fig. 8 shows the regression analysis results for the measurement-based results and simulation results in terms of PET, T_{mrt}, and T_s. The coefficients of determination (R^2) obtained for PET and T_{mrt} were 0.73 and 0.82, respectively. These high coefficients of determination indicate that the ENVI-met model is a reliable tool for studying the thermal effects of trees on urban microclimates in a subtropical climate.

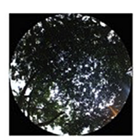
The sensitivity of the model to surface albedo values was evaluated. The results demonstrate the difference in T_{mrt} attributable to wall albedo alteration for high-SVF and low-SVF cases. Under cloudy conditions, the differences in T_{mrt} between high and low wall albedo values were approximately 3–4 °C in the high-SVF case and depended on the distance from the wall surface. The magnitude was larger under sunny conditions. The range was 5–8 °C in

Measurement results for the effects of trees on the radiant environment in sunny days

Banyan under SVF 0.8
solar transmission of crown:
0.05
radiation level at exposed
896 W/m2

Banyan under SVF 0.2
solar transmission of crown:
0.04
radiation level at exposed
813 W/m2

Location	Exposed point				Under tree canopy			
Variable	Globe temp		T_{mrt}		Globe temp		T_{mrt}	
SVF	high	low	high	low	high	low	high	low
Measured data	47.7	41.0	65.0	57.3	34.0	32.1	35.0	33.4
SVF-difference	6.7		7.7		1.9		1.6	
Net tree effect	/				-13.7	-8.9	-30.0	-23.9



Banyan under SVF 0.8
solar transmission of crown:
0.06
radiation level at exposed
791 W/m2

Banyan under SVF 0.2
solar transmission of crown:
0.04
radiation level at exposed
776 W/m2

Location	Exposed point				Under tree canopy			
Variable	Globe temp		T_{mrt}		Globe temp		T_{mrt}	
SVF	high	low	high	low	high	low	high	low
Measured data	44.5	42.1	66.1	56.0	34.2	33.9	36.5	35.4
SVF-difference	2.1		10.1		0.3		0.7	
Net tree effect	/				-10.3	-8.2	-29.6	-20.6

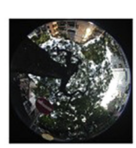
(Tmrt values are calculated with other measured variables with the method of Thorsson et al., 2007)

Measurement results for the effects of trees on the radiant environment in cloudy days

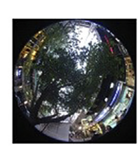
Flametree under SVF 0.8
solar transmission of crown:
0.20
radiation level at exposed
596 W/m2

Cassia under SVF 0.2
solar transmission of crown:
0.15
radiation level at exposed
628 W/m2

location	Exposed point				Under tree canopy			
variable	Globe temp		T_{mrt}		Globe temp		T_{mrt}	
SVF	high	low	high	low	high	low	high	low
Measured data	42.2	34.9	53.0	38.8	35.7	33.9	38.1	35.9
SVF-difference	7.3		14.2		1.8		2.2	
Net tree effect	/				-6.5	-1.0	-14.9	-2.9



Flametree under SVF 0.8
solar transmission of crown:
0.20
radiation level at exposed
596 W/m2



Cassia under SVF 0.2
solar transmission of crown:
0.16
radiation level at exposed
230W/m2

location	Exposed point				Under tree canopy			
variable	Globe temp		T_{mrt}		Globe temp		T_{mrt}	
SVF	high	low	high	low	high	low	high	low
Measured data	42.2	34.0	53.0	37.7	35.7	32.9	38.1	34.5
SVF-difference	8.2		15.3		2.8		3.6	
Net tree effect	/				-6.5	-1.1	-14.2	-3.2

(Tmrt values are calculated with other measured variables with the method of Thorsson et al., 2007)

Fig. 7. Comparison between reductions in globe temperature and T_{mrt} under different SVFs in sunny and cloudy conditions.

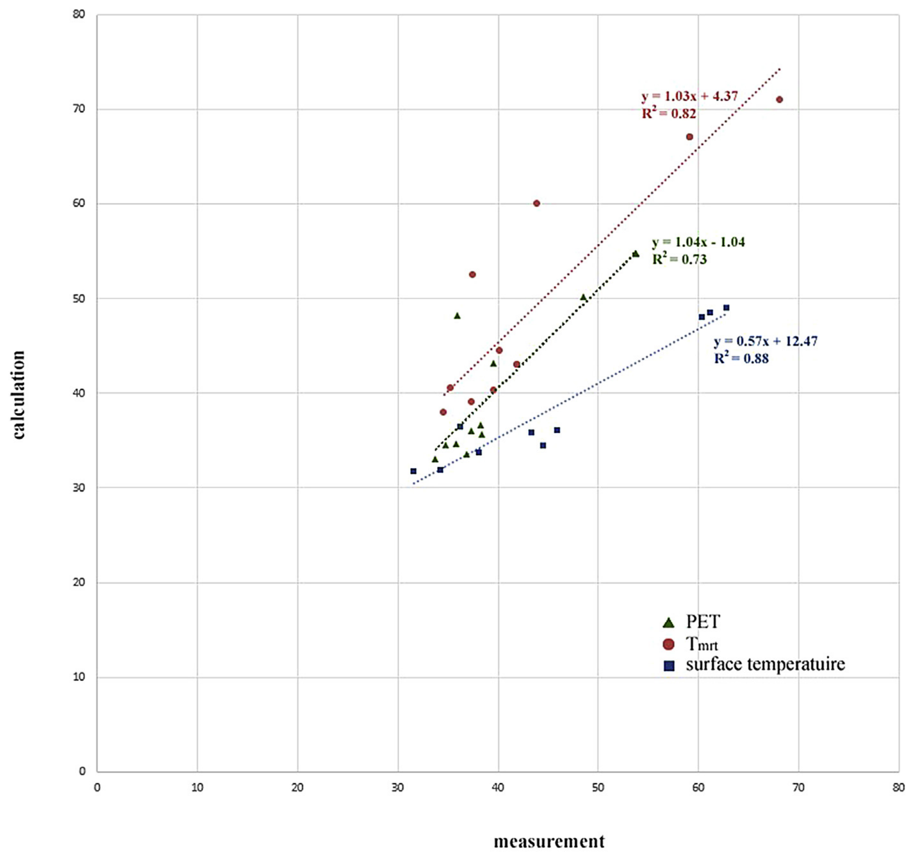


Fig. 8. Model validation.

the low-SVF case, because of the change in the incident radiation, indicating that the influence of surface characteristics is more remarkable in denser urban environments. Under sunny conditions, the difference in air temperature associated with wall albedo alteration was approximately 0.5 °C for the high-SVF case. For the low-SVF case, it was close to 0.8 °C next to the wall surface and 0.6–0.7 °C in the street. These results are consistent with those of Taha [72] and Sailor [73]. Sensitivity tests show that surface albedo significantly alters the microclimate variables in the model, affecting the simulated T_{mrt} values in particular. Most buildings in the studied areas are decades old, with dark-toned facades. Thus, in the parametric studies, the albedo of building surfaces was adjusted to low values: 0.2 for walls and 0.3 for roofs [74,75].

4.2.2. Parametric study results

In the parametric study, the environmental effects of roadside trees in the low-SVF spaces (SVF values of approximately 0.2) and high-SVF spaces (SVF values of approximately 0.5) of heavily built-up districts were investigated. Cooling effects expressed in terms of T_a, T_s, and T_{mrt} under sunny conditions are presented in Table 2. T_a is reduced by approximately 0.8 °C in the high-SVF case and 0.5 °C in the low-SVF case. Because of the subtropical summer sun angle in the early afternoon, shadows are cast along two sides of the building blocks. More space exists in the shade of buildings in the low-SVF case than in the high-SVF case. Reductions in T_{mrt} and T_s by trees were observed to be smaller in magnitude and to show more spatial variation (see Table 2).

Ali-Toudert and Mayer [39] noted that it is difficult to achieve a comfortable outdoor environment with passive design strategies during summer in the subtropics. The measurement results and parametric study indicate that the cooling effects of roadside trees would be different if the trees were planted in low-SVF versus high-SVF environments. With trees planted in areas with high SVF, T_{mrt} was substantially reduced beneath the tree canopies under both sunny and cloudy conditions. PET was close to 46.3 °C in the exposed areas but was reduced to 37.6 °C beneath the tree canopy under cloudy conditions. However, the outdoor comfort standard was not achieved in the high-SVF areas by tree planting. On the other hand, PET was lowered to 29 °C (from approximately 35–39 °C) by trees in low-SVF areas under cloudy conditions (Fig. 9-a). With trees, T_{mrt} was reduced from over 40 °C to 33–34 °C, below the upper limits of the outdoor comfort range in subtropical

Table 2
Cooling effects of roadside trees in high-SVF case and low-SVF case, sunny conditions.

	High SVF		Low SVF	
	crossroad area (SVF~0.54)	street canyon (SVF~0.48)	crossroad area (SVF~0.23)	street canyon (SVF~0.17)
$\triangle T_{a\ (\text{base case - tree})}$	0.7 °C	0.8 °C	0.4 °C	0.5 °C
$\triangle T_{s\ (\text{base case - tree})}$	13.8 °C	13.8 °C	8.4–13.2 °C	2.1–13.2 °C
$\triangle T_{mrt\ (\text{base case - tree})}$	28.2 °C	28.2 °C	4.9–24.3 °C	1.6–24.3 °C

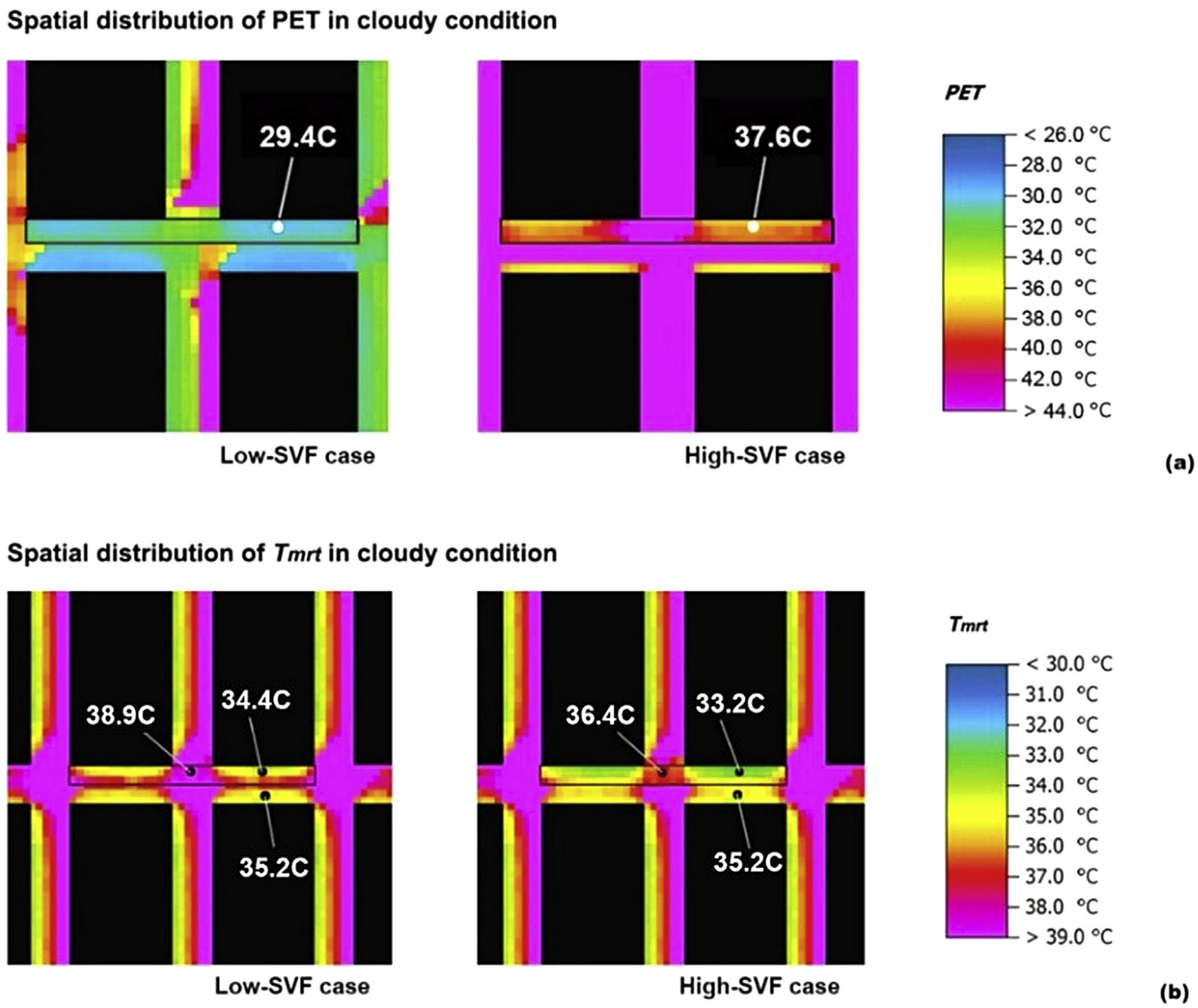


Fig. 9. Spatial distribution of PET (a) and T_{mrt} (b) in low-SVF and high-SVF cases in cloudy conditions (planting areas are indicated with black frame).

urban environments (Fig. 9-b). Therefore, the priority in tree planting should be given to areas of low SVFs to provide more comfortable outdoor spaces in the heavily built-up districts of subtropical cities.

4.3. Demonstration cases

4.3.1. The SVF-based planning method

The measurement results and the parametric study results indicate that planting trees in urban areas with low SVF values provides a comfortable microclimate for pedestrians. Based on the results, two demonstration cases were examined to assess the feasibility of SVF-based planning in existing heavily built-up districts. The planning method was applied in both the MK case and the SSP case, and roadside trees were arranged in 33% of the areas with the lowest SVF values (i.e., the analyzed areas) in each case.

For the Mong Kok case, with 33% green coverage, the set planting locations in the studied district were areas with SVF values of 0.18 or below. In the case without tree planting, the T_{mrt} values were between 35 and 40 °C in the shade of buildings and were close to 50 °C in exposed spots in the analyzed areas under cloudy conditions. For the sunny conditions, the T_{mrt} values were between 43 and 47 °C in the shade and above 60 °C in exposed spots in the analyzed areas. Similarly high values have been recorded in the urban areas of other subtropical cities in the summer [36,76]. In the greening scheme, the T_{mrt} values were lowered to 32–34 °C (with in the comfort threshold) in most of the green spaces under cloudy conditions (Fig. 10). For sunny conditions, the T_{mrt} values were 35.5–38.4 °C in the analyzed areas with trees. With the existing building geometry and no trees, the PET values in the analyzed areas were 31.9–38.7 °C under cloudy conditions, and 34.5–40 °C (in the shade of buildings) and above 50 °C (in exposed spots) under sunny conditions. Such high values are not unusual in subtropical cities with hot humid climates [77]. With trees arranged in areas with SVF values less than or equal to 0.18, PET values at a height of 1.5 m were below 32 °C in most of the analyzed areas under cloudy conditions, with minima at approximately 28.8 °C in several cool spots (Fig. 11). For green spaces with higher PET values, the values were mostly within the range of 32–33 °C, which is very close to the comfort range. The PET values were also substantially reduced to 33.2–37.8 °C under sunny conditions.

The building geometry in SSP is less compact than in MK. The set planting locations were areas with SVF values lower than 0.28 in the SSP study area. In the base case, the T_{mrt} values exceeded 50 °C in the hot spots in the analyzed areas under cloudy conditions. In green spaces with tree planting, low T_{mrt} values of 31.1–32.8 °C were obtained in areas with low SVF. In the analyzed areas with SVF values of approximately 0.3, the T_{mrt} values under tree canopy were between 34.3 and 36.4 °C, which is close to the comfortable range.

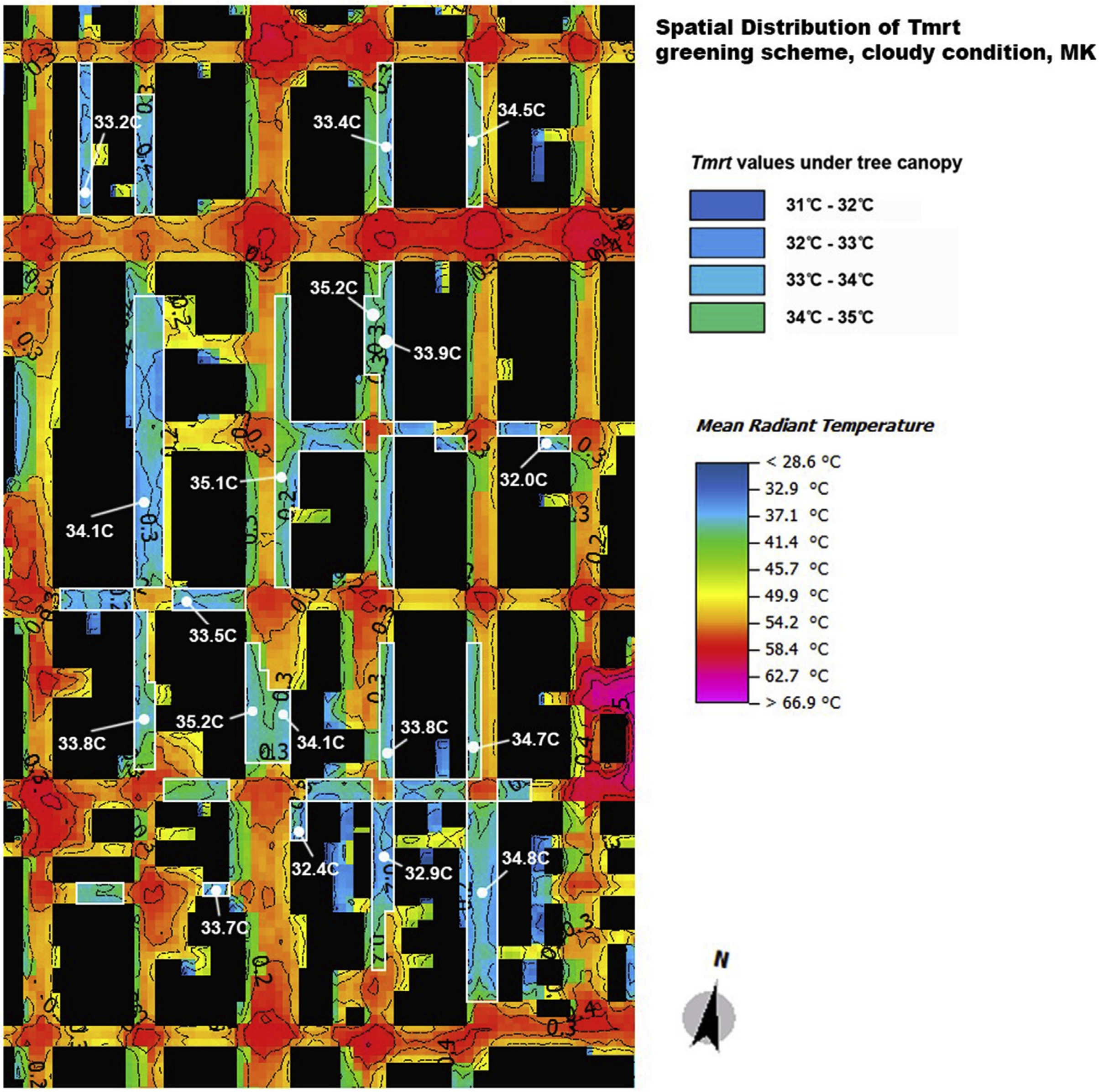


Fig. 10. Spatial distribution of T_{mrt} for the greening scheme in cloudy conditions for the MK case (SVF values are represented by contour lines with 0.1 intervals and the analyzed areas with trees are indicated with white frames).

4.3.2. Site-specific climatic design strategies

Recent studies [78,79] on urban greenery have indicated that the spatial extent of the cooling effects is influenced by urban morphology and wind direction. Simulation studies have shown that the effects of trees present considerable spatial diversity in low-SVF environments. For the demonstration cases, planning strategies for tree planting in areas with low SVFs were further reviewed with regard to the climatic characteristics of a particular site, including the solar orientation of the building blocks and areal prevailing wind, to develop site-specific climatic design strategies and identify optimal planting locations.

The shadow patterns in low-SVF environments in subtropical cities are determined by the sun angle in these regions [80]. Nichol et al. [81,82] suggested that the building geometry of the site and local sun angle and azimuth be considered when selecting planting locations. The studied site in MK offers examples of sites that are oriented primarily in N–S and E–W directions. The T_{mrt} values in the base case were compared with the greening case. At approximately 13:00, the roadside trees achieve their maximum benefit, when planted on the northern and southern sides of the buildings in the E–W orientated areas and when planted the western sides of the building blocks in N–S orientated areas. In green spaces with E–W orientation, reductions of T_{mrt} by trees reached 12.8–14.8 °C, and values under the tree canopy were maintained in the comfortable range under cloudy conditions. For trees planted on the western sides of the building blocks, T_{mrt} reductions exceeded 13 °C. In contrast, the magnitudes dropped to approximately 2 °C for trees planted on the eastern sides of building blocks in the N–S orientated green space. With the shifting sun position, the effects of roadside trees in lowering T_{mrt} gradually diminish in most of the N–S oriented green spaces, with T_{mrt} reductions of 0.5–2 °C at 14:00. The thermal effects of trees in E–W orientated areas are profound at 14:00, especially on the northern sides of the buildings. The magnitudes of T_{mrt} reduction by trees on the northern sides of

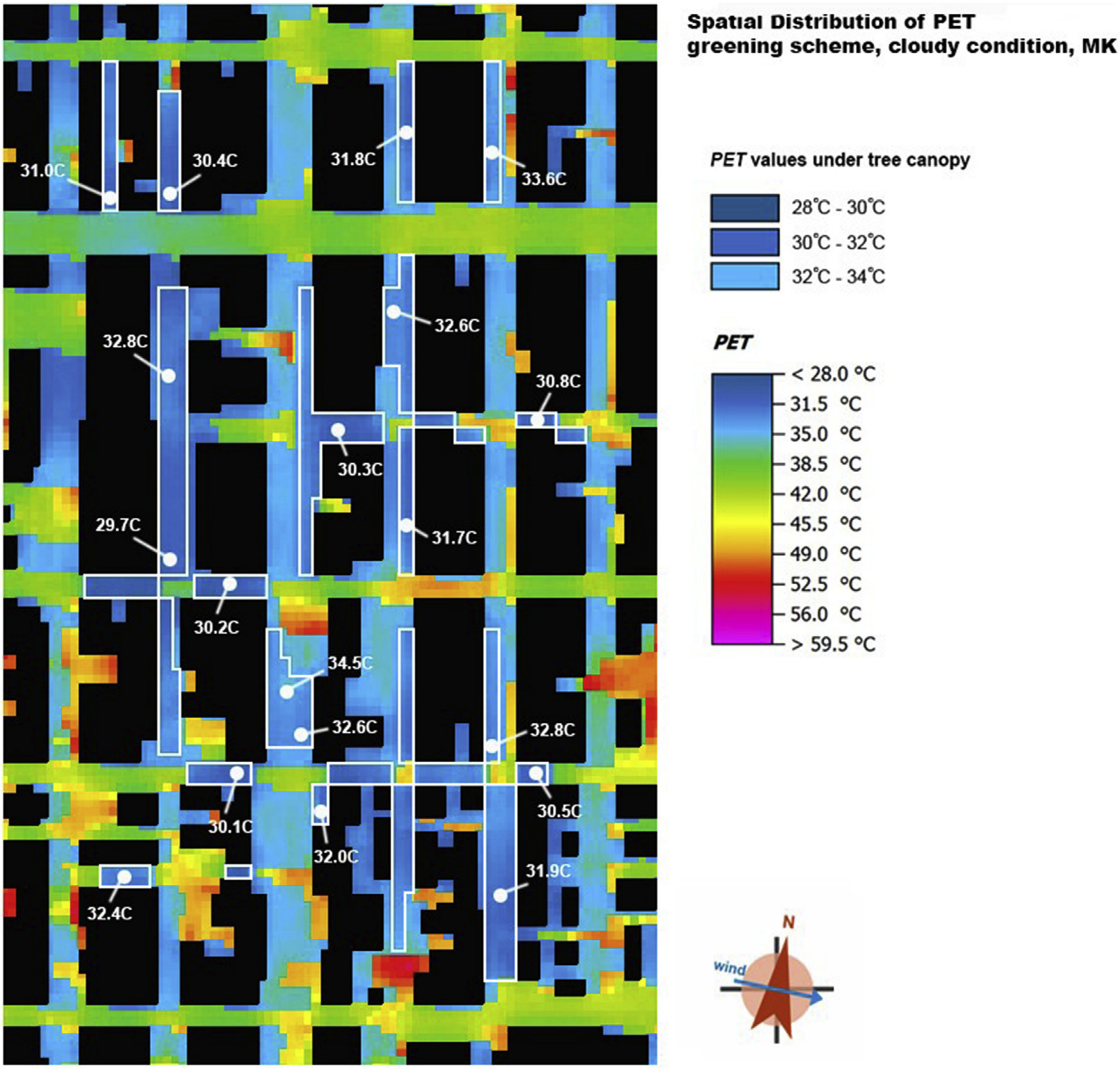


Fig. 11. Spatial distribution of PET for the greening scheme in cloudy conditions for the MK case (the analyzed areas with trees are indicated with white frames).

building blocks reached 11.6–16.7 °C under cloudy conditions.

The SSP study area is an example of sites with intermediate orientations. The building blocks are rotated 50° from the N–S orientation, and the green spaces are NW–SE and SW–NE orientated in the studied SSP area. Roadside trees arranged on the southwestern sides of building blocks in NW–SE orientated areas have profound thermal effects, and the T_{mrt} values at pedestrian level were reduced by 12–13 °C at 13:00 and 15–16 °C at 14:00 under cloudy conditions. Trees on the northeastern sides of building blocks do not have distinct effects in the early afternoon (1.5–2.6 °C reduction in T_{mrt}). For green spaces with SW–NE orientation, trees arranged on the northwestern sides of building blocks offer substantial reductions in T_{mrt} (approximately 11–12 °C at 13:00 and 14.9–15.7 °C at 14:00 under cloudy conditions), while the trees on the southeastern sides have less profound effects. From the two demonstration cases, one can see that in terms of designing for the most critical early afternoon period, the optimized planting orientations in subtropical regions are: 1). E–W oriented areas, and the western sides of buildings in the N–S oriented areas, for districts with N–S and E–W orientated outdoor areas; 2). Southwestern sides of buildings in NW–SE oriented areas, and northwestern sides of buildings in SW–NE oriented areas, in districts with intermediate orientated outdoor areas.

On the other hand, ventilation is crucial for thermal comfort in the subtropics [11,83], and the cooling effect of greenery is affected by wind [84]. When planned properly with regard to wind conditions, the thermal performance of trees planted around buildings is enhanced [85]. As PET is an index that takes into account all of the comfort-related environmental parameters, i.e., air temperature, radiation, humidity, and wind speed [86,87], the spatial relationship of the planting location and the areal wind direction has a remarkable impact on the PET values in the green areas. In the testing green case of SSP, some of the green spaces were in the wind paths (wind speeds of 1.0–3.0 m/s), while others were in leeward positions (wind speeds of 0.1–0.5 m/s). Trees planted in the wind paths reduce PETs to approximately 31.5–32.4 °C under cloudy conditions. PET values were substantially higher in the green spaces in leeward positions (Fig. 12). For locations that combine the optimized planting orientations with good ventilation, the PET values under the tree canopy were reduced to 32.0 °C or below

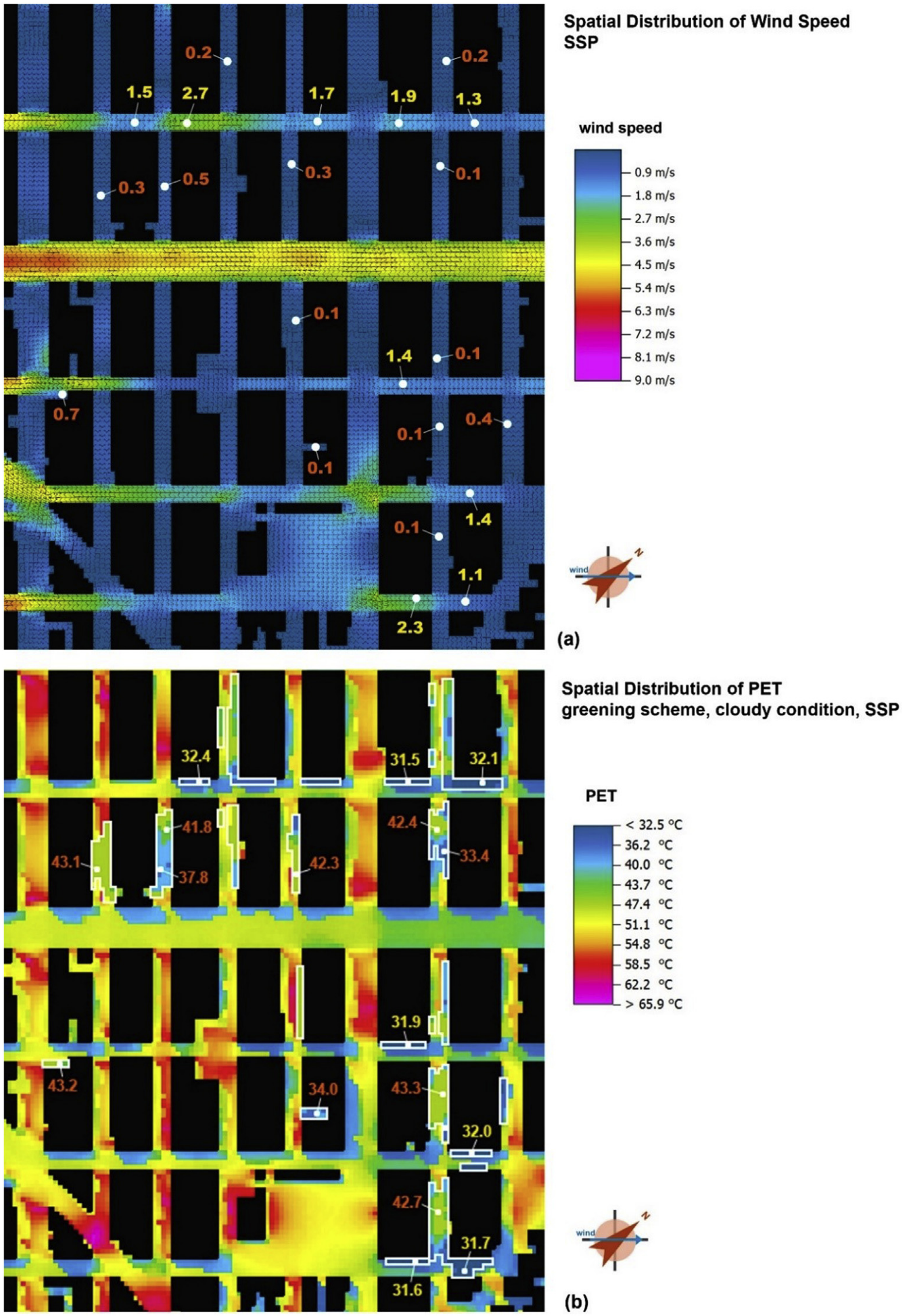


Fig. 12. Cooling effects of trees on PET reduction and spatial relation with areal wind: (a) wind speeds in wind paths and leeward areas in base case and (b) spatial distribution of PET in the greening scheme under cloudy conditions.

under cloudy conditions (Fig. 13-c). The results indicate that tree planting in areas with low SVFs should be integrated with optimized planting orientations and areal wind paths to provide more comfortable green spaces in high-density districts.

5. Discussion

Since 2004, the Civil Engineering and Development Department of Hong Kong has launched the Green Master Plans (GMPs) programs to create a "greener, lusher environment" for Hong Kong. The program has increased the amount of vegetation in the city and has succeeded in obtaining the necessary project endorsements and approvals. However, in some of the projects, GMPs have failed to fulfil their mission of "[maximizing] the greenery of the built-up areas." Trees were planted under overpasses or arranged along highways at the edge of the planned areas, while in substantially sized core urban areas that are heavily built, the greenery coverage remained low. If these trees were moved to popular core urban

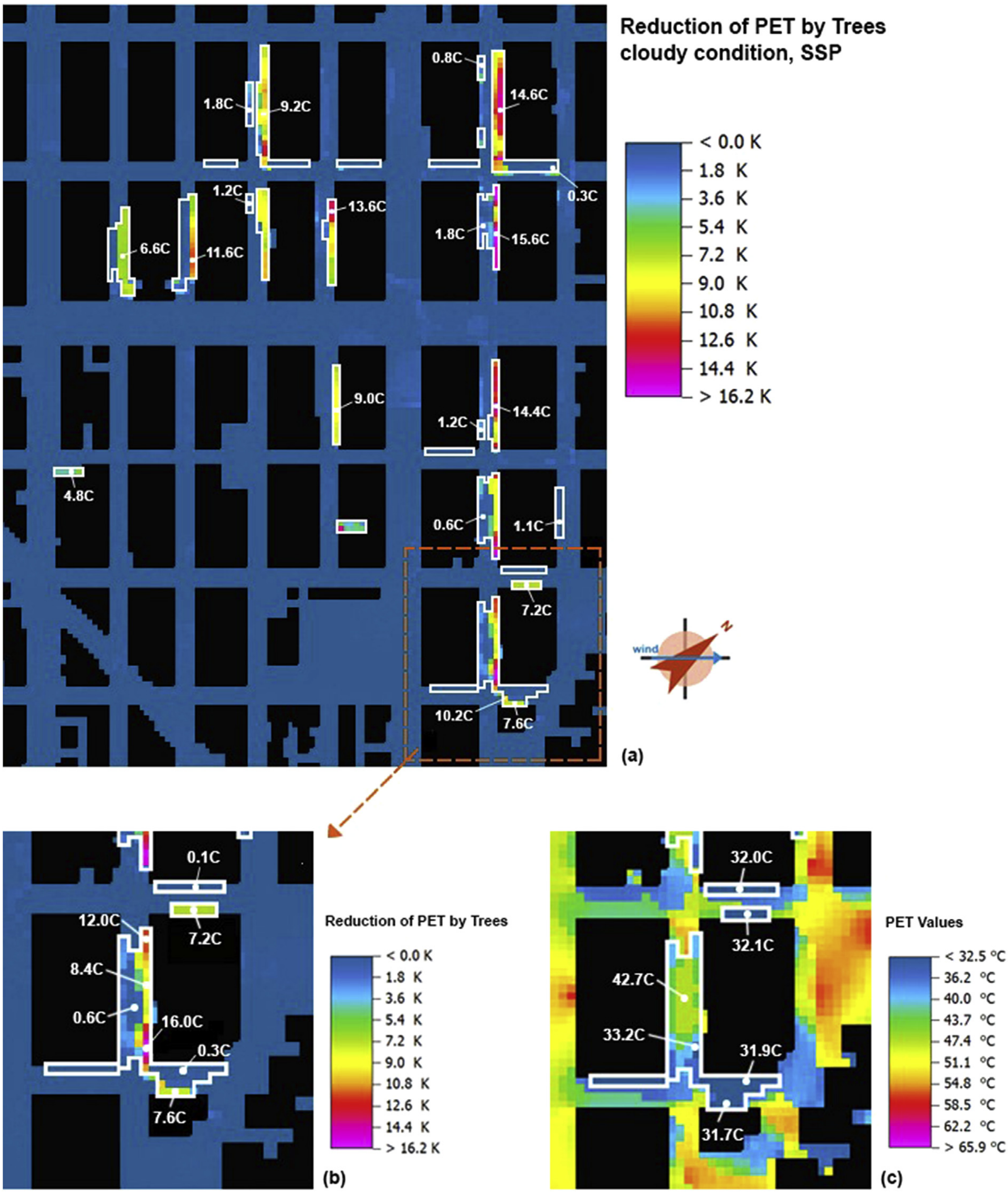


Fig. 13. (a) and (b) spatial distribution of PET reduction for the greening scheme under cloudy conditions for the SSP case (white frames indicate the analyzed areas), and (c) PET values at pedestrian level in the green areas presented in (b). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

areas, more significant benefits would be achieved for pedestrian comfort. On the other hand, the aim of the GMPs is to identify potential planting locations "through a careful study of the physical conditions and land use characteristics of the areas." However, the factors or aspects that were taken into account are not fully explained. As the UHI effects in highly developed districts greatly influence outdoor comfort and the well-being of residents [88–90], the cooling effect of greenery is critical in these areas [91–94]. The GMPs overlooked the thermal benefits of urban vegetation and did not adequately plan for outdoor comfort improvement.

The results of this study provide insights to the refinement of the GMPs design method. Tree planting is important, and it has long been believed that "the more we plant, the better" [18,95,96]. Sailor et al. [97] stated that instead of the scope of implementation, improving thermal comfort and well-being of urban inhabitants should be the real driving force for urban heat mitigation efforts.

This study showed that in subtropical high-density cities, where high green coverage ratios are difficult to achieve, "where to plant" is crucial in terms of providing comfort to pedestrians. In a recent study, de Dear [98] proposed the concept of thermal alliesthesia. Instead of avoiding thermal stress and providing uniform neutral sensation in urban space, he suggested designing for thermal pleasantness that would be stimulated by a dynamic an isothermal environment and spatial diversity. Moreover, thermal diversity in the urban environment helps to build resilience and to increase adaptive capacity to climate change in a region [99,100]. The current study has demonstrated that planting trees in urban areas with low SVFs will create a more diverse thermal environment with several comfortable green spots here and there, allowing people to restore the thermal comfort level in such intermittent green spaces. Given a background of increasing urban density and climate change, the findings of the study offer a solution to enhance pedestrian comfort with tree planting in highly developed districts in the subtropics. Planners are also advised to combine the morphology-based planning method with site-specific design strategies to offer more comfortable green spaces in the city.

6. Conclusions

The SVF-oriented planning method offers a new perspective for designing for outdoor comfort and climate resilience in subtropical high-density cities. Both measured data and simulation results indicate that a comfortable microclimate can be provided by roadside trees planted in low-SVF urban areas, and the results for demonstration cases indicate that the T_{mrt} and PET values can be maintained in a comfortable range in the planted spaces with SVF values lower than 0.2 under prevailing conditions of cloudy weather. For planting areas with SVF values lower than 0.3, climatic design strategies combining the optimized planting orientations and areal wind paths (with wind speeds of 1.0–2.0 m/s) can reduce the PET values to 32 °C or below. It is recommended that areas with the lowest SVF values be designed as green spaces in planned sites, to create more comfortable outdoor areas in high-density districts and to offer the potential for thermal pleasure in a stimulating urban environment.

Urban greenery has multiple ecological functions in the urban environment. Apart from microclimate regulation and outdoor comfort enhancement, urban trees provide ecological networks and buffer areas in the built environment, offer support to ecosystems in the city, and create aesthetic and psychological benefits to different cultural groups. In future research efforts, all of the various functions of urban trees should be taken into account and linked judiciously to develop a comprehensive greening master plan at the city scale.

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