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Assessment on seasonal variations of outdoor thermal comfort with on-site monitoring in a precinct

Jianlin Liu[a,b,]*, Jianlei Niu[a]

[a]*Department of Building Services Engineering, The Hong Kong Polytechnic University, Hung Hom, Hong Kong and 999077, China*
[b]*State key laboratory of subtropical building science of South China University of Technology, Guangzhou and 510640, China*

Abstract

City residents desire to enjoy more outdoor recreational activities, such as walking, cycling and picnicking. The authors' earlier study reported that thermally comfortable environment could be generated in a local space at hot summer in a subtropical city. The present study aims to further assess the variations of the thermal perceptions for the temperate autumn and cool winter in the two same outdoor sites on an campus via on-site monitoring at the pedestrian level winds and thermal parameters at two sample days (sunny and cloudy) in a precinct. The daytime wind directions were also recorded from a nearby urban weather station and used for the analysis on the differences of wind and thermal comfort between the two surveying sites. The instantaneous thermal perceptions were assessed using PET (Physiological Equivalent Temperature) and the PET based index, normalized environmental parameter differences. Results indicate that the wind speed differences become smaller between the two sites due to their different building designs and the changes of wind directions in summer and winter. Not as the hot summer, the PET results note that the space without shading, directly subject to solar radiation, which can provide a thermally comfortable area at a sunny day in the cool seasons. Specifically in winter, wind speed difference is not contributed significantly to improve the thermal comfort while adaptive sunshine can obtain better thermal perception. The results reconfirm the possibility that a local outdoor thermal comfort zone can be built at selected urban spots even in cool seasons and provide a reminder for planners to consider the seasonal impacts in precinct planning within high dense city.

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Keywords: Outdoor thermal comfort, Microclimate, Wind direction, PET (Physiological Equivalent Temperature);

* Corresponding author. Tel.: +852-276-678-01.
E-mail address: jian-lin.liu@connect.polyu.hk

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1. Introduction

City residents are willing to have more outdoor recreational activities in a livable urban environment. Making the city more favorable becomes a significant issue for the urban planning and built environment design in a high dense city, with severe urban heat island (UHI). Hong Kong is such a typical example with the long and hot summer, short transitional seasons and cool winter, so that, the building energy consumptions are large and most of them are costed for the air conditioning systems. The exhausted indoor heat to the outside environment would enhance the UHI effect, which lower the averaged pedestrian wind speed. The Hong Kong government conducted the Air Ventilation Assessment (AVA) scheme (also called microclimate design) [1] and recommended in urban projects to establish the wind amplification/ attenuation environment in some local built sites.

Nomenclature

T_a	air temperature
T_g	globe temperature
V_a	wind speed
RH	relative humidity
T_{mrt}	mean radiant temperature
I_{clo}	heat resistance of clothing
d	diameter of the black globe
ε	emissivity of the black globe
$\Delta V_{a,0.5}$	thermally perceivable wind speed differences
$\Delta T_{mrt,0.5}$	thermally perceivable mean radiant temperature differences
$\Delta T_{a,0.5}$	thermally perceivable air temperature differences
$\Delta\theta_{Va,2\text{-}1}$	normalized wind speed differences
$\Delta\theta_{Tmrt,2\text{-}1}$	normalized mean radiant temperature differences
$\Delta\theta_{Ta,2\text{-}1}$	normalized air temperature differences

The outdoor thermal comfort is such a key part in microclimate study, and field measurement and questionnaire survey are the two frequently using methods in the outdoor thermal comfort area, especially for the hot and humid climate regions. Some developments and findings [2, 3] were reported on the recent outdoor thermal comfort measurements and the use of outdoor spaces. Lin et al. [4] presented the shading effect should be well considered for the long term outdoor thermal perceptions in subtropical Taiwan. Hwang and Lin [5] investigated the thermal environments of some semi-outdoor spaces via field survey and indicated that considering the requirements of occupants were essential in the hot and humid regions. The urban scale human thermal comfort was surveyed by Ng and Cheng [6] and revealed the neutral PET (Physiological Equivalent Temperature) in summer Hong Kong was around 28 ℃. The authors' earlier study [7] also conducted on-site measurement and proofed that thermally comfortable condition could be generated in a local space at hot summer in a subtropical city. Moreover, a combined method for outdoor thermal comfort prediction was published recently, which was based on the measured environmental parameters [8]. In addition, Yang et al. [9] carried outdoor thermal study and explored the effect of thermal adaptation on human thermal sensation in outdoor spaces of tropical Singapore. Trindade da Silva and Engel de Alvarez [10] evaluated the ventilation's effects on the outdoor thermal comfort in a given location and indicated that the wind direction had the relationship with the local thermal perceptions though it was not clear enough. Some researchers in Yangtze river delta with hot summer were also active, such as Yang and Chen [11] presented a thermal atlas system to assess the thermal environment at the urban district and illustrated the Lujiazui CBD in Shanghai for an example.

Our previous results only revealed the possibility in summer that the local thermally comfortable space beneath an elevated building block could be built in a precinct of a city, while the thermal perceptions in other seasons as autumn and winter were not clear enough. Meanwhile, the impact of wind directions was not well considered in the thermal comfort assessment for the authors' knowledge. In the present study, the hypothesis is that one space feels thermal comfortable in hot season may not be comfortable for the cool seasons, while we could still build a local comfort zone via built design at cool seasons as winter in a precinct around 2 km diameter for a subtropical city. The aim of this paper is to assess the variations of the thermal perceptions for the hot summer, temperate autumn and cool winter in the two same outdoor locations on an campus via on-site monitoring at the pedestrian level winds and thermal parameters at two sample days (sunny and cloudy). The daytime wind directions were recorded as well from a nearby urban weather station and used for the analysis of the impacts on the differences of wind and thermal comfort between the two survey sites in different seasons.

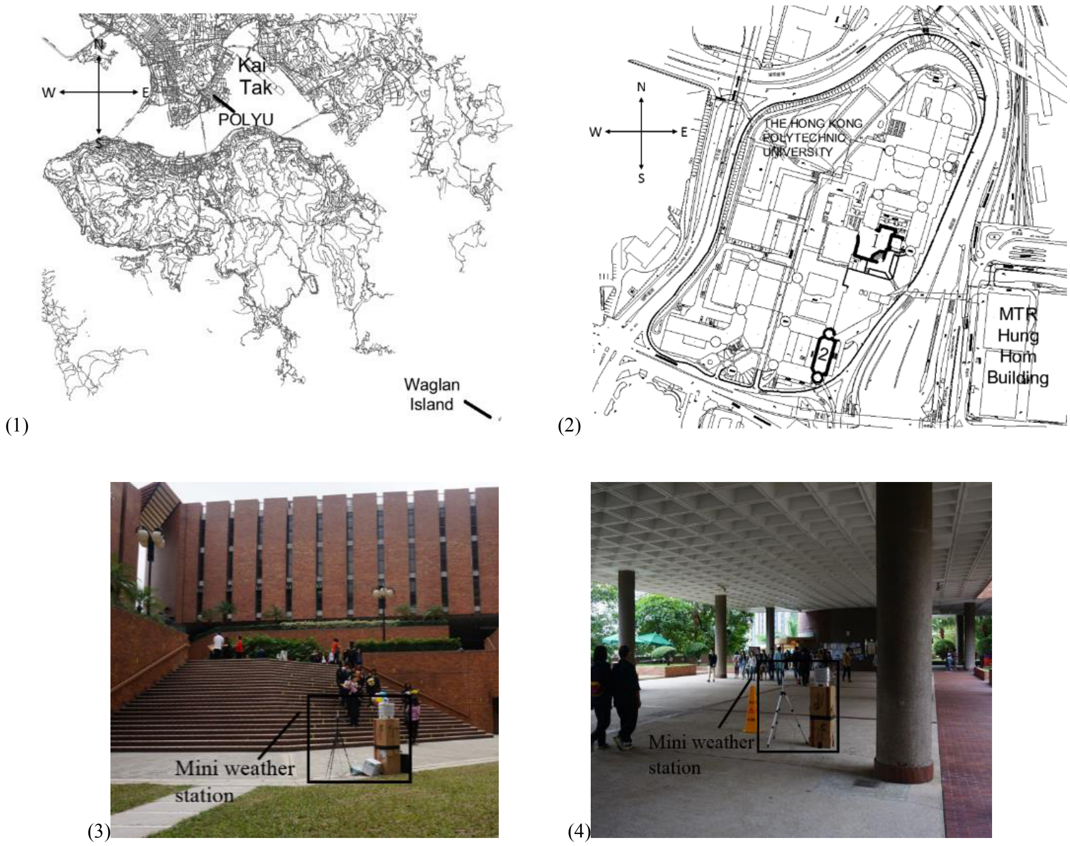


Fig. 1. The university campus layout and monitoring sites: (1) location of the campus in Hong Kong; (2) architectural layout, (3) site 1 and (4) site 2.

2. Methodology

2.1. Field measurement

The earlier study conducted the on-site monitoring on the summer environmental parameters at a university campus (POLYU) in Hong Kong. The same sites to the present field measurement. Fig.1 shows the location and architectural layout of the campus and two monitoring sites as the measured samples. The microclimatic parameters affect the pedestrians' thermal perceptions were continuously measured for two survey days (a sunny day and a cloudy day) for each season, including June (summer), November (fall) in 2014 and January and February (2015) for winter conditions. The two measured sites are presented as: 1) an below ground level open space surrounded by buildings (Fig.1.(3)) and 2) an open space at ground level beneath an elevated block. To be specific, the first site is an open lawn in the campus, using the lowered area below the campus podium. It is blocked by buildings except the northwestern side. Anecdotal evidence present that this site receives direct and multiple reflections of solar radiation for most of the time in a year. Site 2 is shaded and preferred by people, it is frequently used for staff and student communal activities such as open forums and Taichi [7].

Two mini weather stations (Fig.1) were placed at the monitoring sites, each site with one, and simultaneously used to measure the instantaneous thermal environmental parameters, included air temperature (T_a, ℃), globe temperature (T_g, ℃), wind speed (V_a, ms^{-1}) and relative humidity (RH, %). Fig.2 shows the whole image of the used mini weather station, which was constructed by the above parameters' testing sensors and the HOBO data loggers. All the sensors and data loggers were calibrated and pre-measured before the on-site monitoring. These equipment were all conformed to the ISO standard 7726 [12]. The on-site measurement were started at 9:00 am and ended at 18:00 pm because most of pedestrians (mainly the students and staffs) had outdoor activities during this period. The mini weather stations were located at 1.5 m height of the pedestrian level above the ground and collected data at 5 min intervals. Table 1 describes the measured range and accuracy of all the used instruments. Note that the self-made weather shelter was fabricated by aluminum foil and cardboard so as to decrease the effects of solar radiation on the air temperature investigation.

(1) (2)

Fig. 2. Mini weather station with solar radiation shield design: (1) the whole image and (2) the inside view of the mini weather station.

Table 1. Descriptions of the instruments used in the microclimatic monitoring

Environmental parameter	Description	Accuracy	Range
V_a	Anemometer and DANTEC velocity analyser	±0.25ms^{-1}	0.25~5(ms^{-1})
T_a	Shaded air temperature measuring device	±0.5℃	-30~50(℃)
T_g	Black globe temperature measuring device with table tennis ball painted in black (emissivity = 0.95)	±0.5℃	-30~50(℃)
RH	Hygrometer	±1%	0~100(%)
	Adjustable tripod	-	-
	weather shelter: fabricated by aluminium foil and cardboard	-	-

2.2. Differences in thermal comfort

The thermal comfort index PET, is frequently used to assess the outdoor thermal perceptions and described by degree unit as the air temperature does. It presented the thermal comfort conditions of the human body in a physiologically relevant way which was based upon the Munich Energy-balance Model for Individuals (MEMI) [13]. The following meteorological and thermos-physiological parameters were as the input for the PET calculations, including air temperature, wind speed, relative humidity and mean radiant temperature (T_{mrt}, ℃), heat resistance of clothing (I_{clo}) and the activity of humans [14]. It can be calculated by the available software, RayMan [15]. The mean radiant temperature is calculated by the formula as follow:

$$T_{mrt} = \left[(T_g + 273)^4 + \frac{1.10 \times 10^8 \times V_a^{0.6}}{\varepsilon d^{0.4}} (T_g - T_a) \right]^{1/4} - 273 \quad (1)$$

where d (38 mm) and ε are the diameter and the emissivity of the black globe.

The grades of thermal perception for PET in general are different for different climatic regions (Table 2), such as Lin and Matzarakis (2008) reported that the different neutral PET values and the thermal perception differences of two adjacent PET levels between Taiwan (subtropical region) and the western/middle Europe [16]. Moreover, a PET based index, the normalized environmental parameter differences, was presented by Niu et al. [7]. It utilized the thermally perceivable environmental differences ($\Delta V_{a,0.5}$, $\Delta T_{mrt,0.5}$ and $\Delta T_{a,0.5}$ for wind speed, mean radiant temperature and air temperature, respectively), and used to assess the thermal comfort differences between two sites. The basic assumption of them was: the environmental parameter change that would cause PET change of 2 ℃ (when the subtropical PET range was chose) or 3 ℃ (when PET was above 23 ℃ for Europe)/2.5 ℃ (when PET was below 23 ℃ for Europe) difference from the comfortable condition $T_a = T_{mrt}$ = 30 ℃ (or 23 ℃), which corresponded to a PMV difference of 0.5 in Table 2. More descriptions of the indices were in [7]. Between any two monitoring sites, the defined index for wind speed is normalized ($\Delta\theta_{Va,2\text{-}1}$) as follow:

$$\Delta\theta_{V_{a,2-1}} = \Delta V_{a,2-1} / \left|\Delta V_{a,0.5}\right| \quad (2)$$

where the $\Delta V_{a,2\text{-}1}$ is the wind speed difference between the investigated sites 2 and 1. A positive value would mean that the wind speed is making site 2 cooler than site 1. The greater magnitude of this value, the more impact of the environmental parameter. Meanwhile, an absolute value greater than one would indicate that wind speed has a significant effect on the thermal perception between these two sites [7]. Similarly, the normalized differences for mean radiant temperature ($\Delta\theta_{Tmrt,2\text{-}1}$) and air temperature ($\Delta\theta_{Ta,2\text{-}1}$) between site 2 and site 1 can be calculated via:

$$\Delta\theta_{T_{mrt,2-1}} = -\Delta T_{mrt,2-1} / \left|\Delta T_{mrt,0.5}\right| \quad (3)$$

$$\Delta\theta_{T_{a,2-1}} = -\Delta T_{a,2-1} / \left|\Delta T_{a,0.5}\right| \quad (4)$$

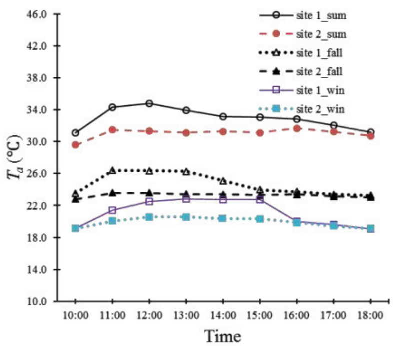
Table 2. PMV and PET grades of thermal perception on humans in Taiwan and Western/Middle European [7, 16].

PMV	PET range for subtropical region (°C)	PET range for European (°C)	Thermal perception
			Very cold
-3.5	14	4	
			Cold
-2.5	18	8	
			Cool
-1.5	22	13	
			Slightly cool
-0.5	26	18	
			Comfortable(Neutral)
0.5	30	23	
			Slightly warm
1.5	34	29	
			Warm
2.5	38	35	
			Hot
3.5	42	41	
			Very hot

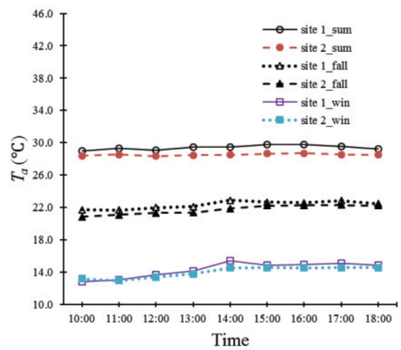
3. Results and discussions

3.1. Microclimatic parameter measured

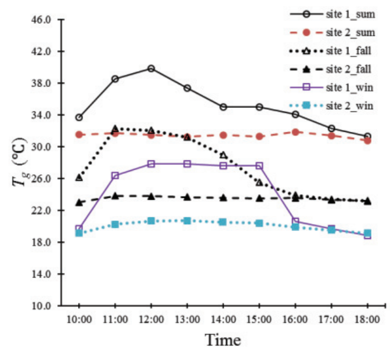
The thermally environmental parameters were simultaneous measured and recorded, included T_a, T_g, V_a and RH for summer, fall and winter of two survey days, respectively. Fig.3 shows the variations of the monitoring environmental parameters. All the instantaneous results are hourly averaged and named for each site at different seasons in the sunny day and cloudy day, respectively, such as site 1_sum is the measured data in summer at site 1. Similarly, the fall is represented for autumn and winter is shorten as win. Obviously the air temperature at sunny day is higher 2~6 ℃ than the results at the cloudy day. It should be noted that the air temperature shows difference of 1~3 ℃ between sites 1 and 2, even if the weather shelter is used to reduce the solar radiation effect. The difference of globe temperature is more evidently than the variation of T_a between the two measured sites, especially at the sunny day. All the T_g curves of site 1 show first sharply increasing trend till 12:00 am, and become shortly and slightly unchanging then decreasing slowly afternoon at sunny day (Fig.3.(3)). On the other hand, the T_g values of each season at site 2 (Fig. 3.(4)) present no significant changes and lower than site 1 all day long. It indicates that the shading effect is obvious of the elevated building and this makes site 2 subject to less solar radiation in the whole year round.



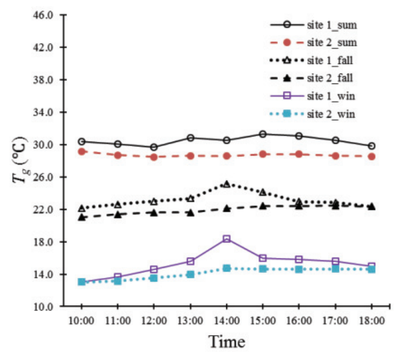
(1) T_a -Sunny



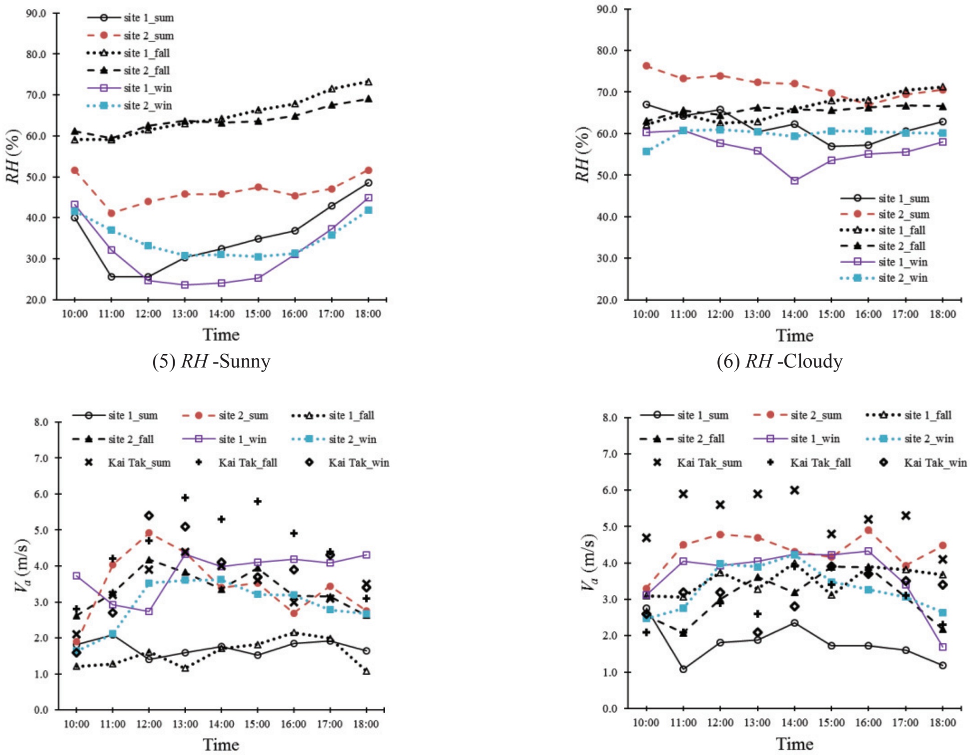
(2) T_a -Cloudy



(3) T_g -Sunny



(4) T_g -Cloudy



(5) RH -Sunny (6) RH -Cloudy

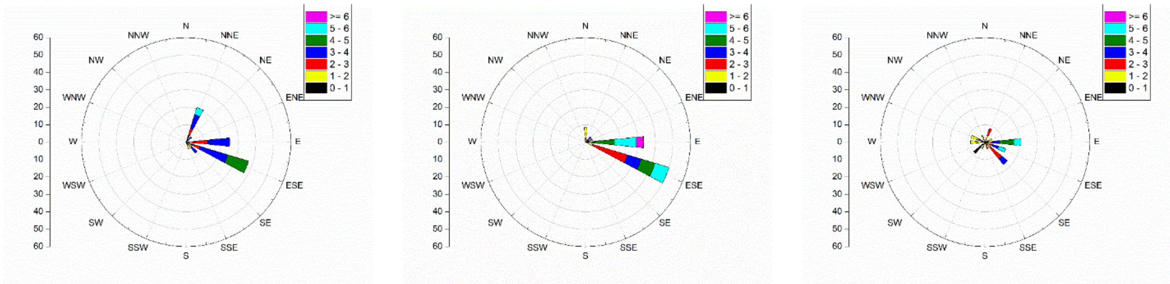
(7) V_a -Sunny (8) V_a -Cloudy

Fig. 3. Hourly averaged environmental parameter variations of summer, fall and winter obtained from the simultaneous measurement: (1) and (2) air temperature on the sunny and cloudy days; (3) globe temperature on the sunny day, and (4) on the cloudy day; (5) and (6) relative humidity; (7) and (8) wind speed during the sunny and cloudy days.

The relative humidity results at site 2 are mainly higher than site 1 in the sunny day, while there are no significant differences between the two sites for the cloudy day of the three seasons. The wind speeds has been compared between the monitoring sites and the annual mean wind speeds recorded in a urban weather station (King's Park) of recent years in our earlier study, which should be cautioned that the comparison was subject to probability questioning [7]. To appreciate this question, we conduct the direct comparisons between the sites' measured V_a and the hourly mean recorded data at the survey days from a near weather station, Kai Tak (obtained by Hong Kong Observatory, HKO) [17] in the present study, where is the ex-airport of Hong Kong. It is close to the monitoring campus (POLYU in Fig. 1), while directly faced to the seaside and surrounded without any buildings, so that the wind speed here is used to compare and obtain the wind differences of the two urban investigation sites. The wind speed of site 2 is 3~5 m/s as similar as Kai Tak while site 1 (fluctuated between 1~2 m/s) is lower than them at sunny day in summer. Specifically, the wind speed V_a at site 2 is higher than site 1 at both of the two survey days in summer which is in accordance with the proved local wind amplification effect of the building elevated design [7, 8]. However, note that the mean V_a of the two sites and the Kai Tak show approximately similar results at the cloudy day in fall. Moreover, most of the survey time in winter, site 1 provides similar or even slightly higher wind speed than site 2. This new phenomenon should be concerned that it may cause differences in the thermal comfort between the two sites at different seasons. The possible reasons are the change of the local predominant wind directions, especially between summer and winter, which will be discussed later with analysis of the daily wind direction at the survey days.

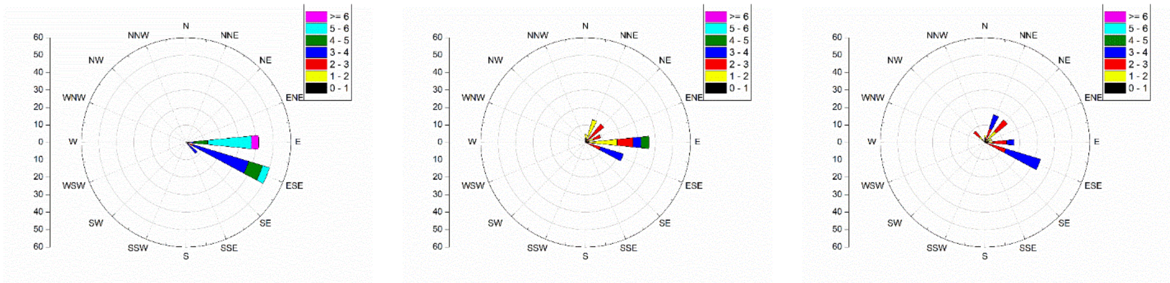
3.2. Effect of the wind directions in different seasons

Waglan Island, locates approximately 5 km southeast of Hong Kong Island (Fig.1.(1)), has been used by HKO, formerly the Royal Observatory, Hong Kong, for the collection of long-term wind data since December 1952. That data is considered to be of the highest quality available for all wind engineering purposes in Hong Kong. Due to its location, relative lack of development over the past 50 years and its generally uninterrupted exposure to winds, data collected at Waglan Island is considered to be representative of winds approaching and departing the Hong Kong region. The nearby buildings, mostly high-rises, around many other stations in Hong Kong, make these data to be least useful for general wind engineering applications. On the other hand, since the Kai Tak station is located only about 3 km away from the northeast of the proposed test sites and surrounded without any buildings, its wind data are obtained in parallel with the Waglan Island data at the survey days. For the Waglan Island, data obtained from HKO shows that the predominant wind direction is between southeast and east with highest wind speed of 10~12 m/s in summer, while becomes northeast with maximum V_a of 6~8 m/s at winter [18]. Note that this results represent as the predominant wind direction of Hong Kong in the survey days without considering the effects of the nearby buildings in urban environment.



June 13th November 15th January 22nd

(1) Sunny



June 11th November 14th February 6th

(2) Cloudy

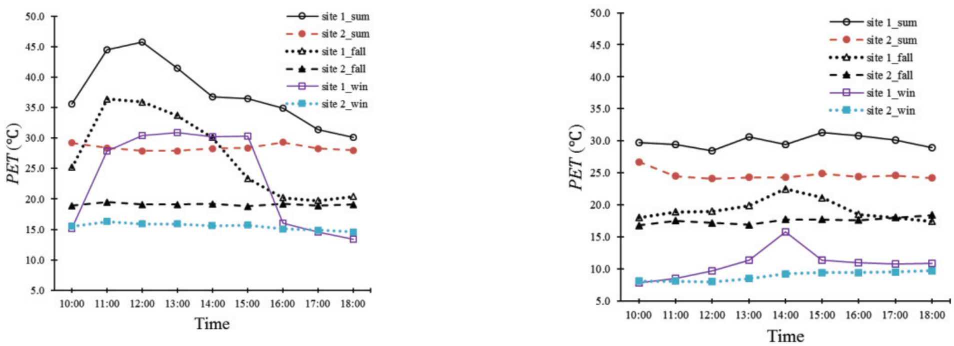
Fig.4. The wind rose of Kai Tak urban weather station at (1) sunny day and (2) cloudy day of three seasons.

Fig.4 presents the wind rose at the Kai Tak station of the six monitoring days [19]. In June, the predominant wind direction is between southeast and east as Waglan Island while the maximum wind speed is around 6 m/s of sunny and cloudy day. The similar wind direction also shows in the sunny day of November. However, the predominant wind direction changes to east and the maximum wind speed lowers to 4~5 m/s for the cloudy day. In the two winter survey days, no obvious predominant wind direction shows in the sunny day besides the max V_a occurs at northeast direction. The instantaneous wind directions may have probabilities for directions of northeast or southeast with max 4 m/s at the cloudy day. We mentioned that the wind speed differences changed at the two monitoring sites for the three seasons, especially between summer and winter. The possible factors cause this phenomenon are the different building design of the two sites and the changes of wind direction. Specifically, from the horizontal layout of campus map (Fig. 1.(2)), site 1 is surrounded by buildings except the northwest direction. Site 2 shows angles of around 30° to the north direction and the wind can blow through the southeastern or northwestern direction easily. For the summer condition, the predominant wind direction is southeast and east which causes the wind blow through site 2 easier than site 1, so that the hourly mean wind speed at site 2 is higher. For the autumn at the cloudy day, the wind direction changes to mainly east which makes less wind directly blown at site 2 through the southeastern direction and site 1 may obtain more winds than the summer. This indicates that the differences of the hourly mean wind speed are less between the two sites than the summer condition. Moreover, as in autumn, the wind direction in winter becomes more different from summer, especially the higher probability for the wind from the northeastern direction in the cloudy day. This means that more wind can blow into site 1 but less wind directly moves through the southeastern side of site 2, which further explains that the less wind speed differences between the two sites in winter (Fig.3.(8)).

3.3. Thermal perceptions differences

The environmental parameters were simultaneous monitored and collected from the two sites at the pedestrian level. Fig. 5 shows the PET values calculated from the hourly averaged results on both sunny and cloudy days. In the calculations, the assumption of the pedestrian is a 25 years old male with 1.75 m and 70 kg. The clothing level is 0.5 clo, 0.7clo and 1.0 clo for summer, autumn and winter, respectively, and 80 W/m^2 for the internal heat production which is based upon the authors' observations and suggested values of ASHRAE Standard 55 [20]. It is noted that the lower PET values are observed at site 2 in both days for the three seasons. This indicates that site 2 with an elevated design may build a relative cool area, especially in summer, and the summer average PET is around 29 ℃ means the comfortable condition at site 2 while site 1 presents hot condition for the subtropical PET range as Taiwan. The mean PET value shows cool condition at site 2 in autumn for the two days, whereas the thermal perception becomes comfortable or slightly warm at site 1 in the sunny day from 10:00 am to 14:00 pm. Moreover, the thermal perceptions between the two sites are changed at sunny day in winter. Note that the mean PET value of site 1 presents 30 ℃ (comfortable) which is higher than the 15 ℃ of site 2 from 11:00 am to 15:00 pm. This should be concerned that the space as site 1, directly subjects to solar radiation, can provide a thermally comfortable area at a sunny day in winter.

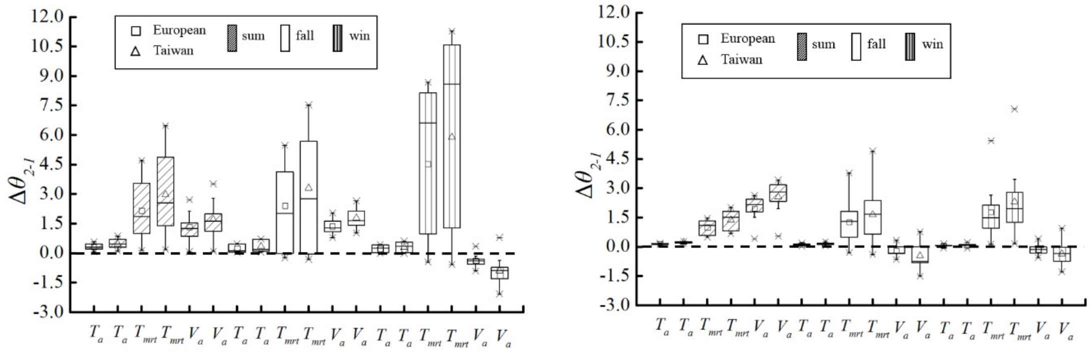
The PET values present only the whole image of the thermal perception at one site, whereas the real question is that the impact of environmental parameters' differences can cause the changes of thermal comfort between two investigated sites in different seasons. To evaluate the differences, the instantaneous environmental parameter differences between sites 1 and 2 were calculated with using equations (2)-(4). Then they were daily averaged and normalized for the two days with two sets of data were provided in Fig. 6, calculated using the thermal parameters' changes that would cause a PET change of 3 ℃/2.5 ℃ (for European) and 2 ℃ in Table 2, respectively.



(1) Sunny (2) Cloudy

Fig.5. PET distributions at (1) sunny day and (2) cloudy day

The normalized air temperature differences between the two sites of the three seasons (sum, fall and win) are apparently close to 0. It indicates that air temperature is not a causal factor of PET changes not only in summer as Niu et al. (2015) [7] reported but also in autumn and winter. Between the two sites, the wind and mean radiant temperature have the similar effects on the PET differences in summer, although the radiant temperature cause slightly larger effect on the sunny day while the cloudy day wind speed take more weight on PET [7], the similar results show at the sunny day in autumn. For the present study, the effects of wind speed and radiant temperature are changed in late autumn and winter. The radiant temperature presents higher effects on PET differences than wind speed at the cloudy day in autumn, with mean $\Delta\theta_{Tmrt}$ = 1.4 for European set and 1.6 for subtropical region set, and $\Delta\theta_{Va}$ = -0.2 for European and -0.4 for subtropical regions respectively. Similarly, for the winter conditions, the day-average of normalized radiant temperature ranges from 4.5 to 5.8, and the wind differences ranges from -0.4 to -0.8, which indicate the radiant temperature presents larger differences than wind speed at a sunny day in winter. This means the mean radiant temperature makes site 1 warmer or more comfortable than site 2, but lower wind makes site 2 slightly warmer than site 1. On the both days of summer, wind amplification and shading effects are useful in improving the thermal comfort at the open space underneath the elevated building. However, on the cool seasons, such as the cloudy day of autumn and both days of winter, wind speed difference is not contributed significantly in improving the thermal comfort due to the changes of the predominant wind directions so that lowers wind speed differences between both sites. Higher radiant temperature difference cause larger PET changes, indicating that the adaptive sunshine requirements would improve the outdoor thermal comfort in winter.



(1) Sunny (2) Cloudy

Fig.6. Normalized environmental parameter differences $\Delta\theta_{Ta}$, $\Delta\theta_{Tmrt}$ and $\Delta\theta_{Va}$ (two sets of data estimated respectively using European and subtropical studies) between site 2 and site 1 at pedestrian level on (1) sunny day and (2) cloudy day.

4. Conclusions

This paper presents some findings of seasonal (summer, autumn and winter) variations of outdoor thermal comfort at two different locations in a precinct at a subtropical city. The important conclusions of this study are as follows: 1) Between the hot summer and cool winter, the changes of wind directions and the different building design of the two sites, which cause changes of the wind speed differences at the two monitoring sites. Different from summer, the less wind speed difference between the two sites in winter. This further give rise to differences in the thermal comfort of the two sites at different seasons. 2) The thermal perceptions between the two sites are also different at sunny day in winter. Not as summer, the open space as site 1 without shading, directly subjects to solar radiation, can provide a thermally comfortable area at a sunny day in winter. 3) Wind amplification and shading effects are useful in summer for improving the thermal comfort. However, in the cool seasons as winter, wind speed difference is not contributed significantly in improving the thermal comfort due to the changes of the predominant wind directions. Higher radiant temperature difference cause larger PET changes, indicating the adaptive sunshine requirements would improve the outdoor thermal comfort in winter, even in a subtropical city as Hong Kong with high building density.

The above findings note that different outdoor thermal perceptions can generate in different locations at a precinct around 2 km diameter distance, while different seasons as winter and summer may cause different thermal comfort in the same space. This is a reminder for the urban planners who require to consider the seasonal impacts in precinct planning. Moreover, at the planning stage, an accurate predication method is desirable for the outdoor wind and thermal simulation and CFD technique may be useful, while the wind turbulence and direction should be considered. The further works on the outdoor thermal comfort will be evaluated in correlating with the spotted wind directions and added questionnaires for further accurate analysis.

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References

[1] E. Ng, Policies and technical guidelines for urban planning of high-density cities - air ventilation assessment (AVA) of Hong Kong, Build. Environ. 44 (2009) 1478-1488.
[2] L. Chen, E. Ng, Outdoor thermal comfort and outdoor activities: A review of research in the past decade, Cities. 29 (2012) 118-125.
[3] R.F. Rupp, N.G. Vásquez, R. Lamberts, A review of human thermal comfort in the built environment, Energy Build. 105 (2015) 178-205.
[4] T.P. Lin, A. Matzarakis, R.L. Hwang, Shading effect on long-term outdoor thermal comfort, Build. Environ. 45 (2010) 213-221.
[5] R.L. Hwang, T.P. Lin, Thermal comfort requirements for occupants of semi-outdoor and outdoor environments in hot-humid regions, Archit. Sci. Rev. 2007;50:357-364.
[6] Ng E, Cheng V. Urban human thermal comfort in hot and humid Hong Kong, Energy Build. 2012;55:51-65.
[7] J. Niu, J. Liu, T. Lee, Z. Lin, C. Mak, K. Tse, et al, A new method to assess spatial variations of outdoor thermal comfort: Onsite monitoring results and implications for precinct planning, Build. Environ. 91 (2015) 263-270.
[8] J. Liu, J. Niu, Q. Xia, Combining measured thermal parameters and simulated wind velocity to predict outdoor thermal comfort, Build. Environ. 105 (2016) 185-197.
[9] W. Yang, N.H. Wong, S.K. Jusuf, Thermal comfort in outdoor urban spaces in Singapore, Build. Environ. 59 (2013) 426-435.
[10] F. Trindade da Silva, C. Engel de Alvarez, An integrated approach for ventilation's assessment on outdoor thermal comfort, Build. Environ. 87 (2015) 59-71.
[11] F. Yang, L. Chen, Developing a thermal atlas for climate-responsive urban design based on empirical modeling and urban morphological analysis, Energy Build. 111 (2016) 120-130.
[12] I. S. O., International Standard 7726. Ergonomics of the thermal environment -Instruments for measuring physical quantities, International Standard Organization, Geneva, 1998.
[13] P. Höppe, The physiological equivalent temperature–a universal index for the biometeorological assessment of the thermal environment, Int. J. Biometeorology. (43) 1999 71-75.
[14] A. Matzarakis, F. Rutz, H. Mayer, Modelling radiation fluxes in simple and complex environments: basics of the RayMan model, Int. J. Biometeorology. 54 (2010) 131-139.
[15] A. Matzarakis, F. Rutz, H. Mayer, Modelling radiation fluxes in simple and complex environments—application of the RayMan model, Int. J. Biometeorology. 51 (2007) 323-334.
[16] T.P. Lin, A. Matzarakis, Tourism climate and thermal comfort in Sun Moon Lake, Taiwan, Int. J. Biometeorology. 52 (2008) 281-90.
[17] Hong Kong Observatory, http://www.hko.gov.hk/cis/awsDailyElement_e.htm?stn=SE&ele=MEAN_WIND&y=2014. Accessed in July 2016.
[18] Hong Kong Observatory, http://www.weather.gov.hk/cis/awsDailyExtract_e.htm?stn=WGL&y=2014&m=6. Accessed in July 2016.
[19] Hong Kong Observatory. http://www.hko.gov.hk/cis/awsDailyElement_e.htm?stn=SE&ele=PREV_DIR&y=2014. Accessed in July 2016.
[20] A.S.H.R.A.E., ASHRAE Standard 55-2013. Thermal Environmental Conditions for Human Occupancy. Am. Soc. Heat. Refrig. Air-cond. Eng. Atlanta, 2013.