Wind and Heat Environment in Densely Built Urban Areas in Hong Kong

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Abstract

Global environmental changes, especially global warming, are becoming an issue for urban designers. Coupled with that are the issues of life in mega- and high-density cities and the urban heat island effect. Hong Kong is one of the world's highest-density cities, with over sixty thousand persons per square kilometre in its urban areas. High-rise, bulky and closely packed buildings are the norm; and this increases the urban heat island intensity and reduces urban air ventilation. Given Hong Kong's hot, humid tropical summers, high heat stress can be expected in the urban environment. Since 2003, the Hong Kong Government has commissioned studies on this issue. An air ventilation assessment (AVA) study was carried out. In addition, an urban climatic map was drafted based on an evaluation of human thermal comfort. A study of intra-urban temperature variations is underway and their possible implications to localised hot days and hot spells is being investigated. The criticality of rising intra-urban temperature and decreased wind speed can be established. This has provided objective input for planning actions in the form of urban climatic recommendation maps. This work is on-going in Hong Kong. The present paper summarises some of these projects and documents the study process and rationale.

Key words: urban ventilation, city planning, human thermal comfort, wind tunnel tests, high density living

1. Introduction

Global environmental changes and global warming have been an issue lately. In general, cities in tropical regions will experience increased summer temperatures, higher urban heat stress and higher frequencies and longer durations of hot spells. In Hong Kong, based on observed temperatures since 1885, the Hong Kong Observatory has calculated an increase of 0.12°C per decade (Leung *et. al.*, 2004). More importantly, the data indicate that the rate of increase has accelerated. The average temperature rise from 1947 to 2002 was 0.17°C per decade, but the rate of warming increased toward the end of that period, to 0.61°C per decade from 1989 to 2002. While the maximum temperature (56 years since the 2nd World War) has seen little change, the minimum temperature has undergone a rising trend of 0.24°C per decade. The observed temperature increase can also be attributed to the rapid urbanisation of Hong Kong since the 2nd World War. In a comparison of the temperature time series at the Hong Kong Observatory Headquarters with the global time series, scientists at the HKO have noted that:

The global mean temperature dataset sourced from the Climate Research Unit (CRU), University of East Anglia, and the temperature at the Hong Kong Observatory Headquarters both follow more or less the same trend as the global temperature during the pre-World War II period. In the post-war years, there were two periods with notable temperature rises at the Hong Kong Observatory Headquarters. The first was from the mid-1950s to mid-1960s. The second period of temperature rises began in the early 1980s, which was in line with the global trend of significant warming in the past two decades. A faster rate of warming at the Hong Kong Observatory Headquarters compared to the global trend since the early 1980s can be attributed to the effects of high-density urban development.

Leung has concluded that there is an additional rise of 0.4°C per decade due to urbanisation. (Leung *et. al.*, 2004)

2. Designing High Density Cities for Thermal Comfort

More than 20 cities in the world are what are called "mega," i.e., they have more than 10 million inhabitants. High density city design is a topical issue. There is a need to deal with land scarcity, to design a viable public transport system and to re-build the communities of our inner cities. The high-density city is iconic (Wolf, 2006). High density living is increasing the number of issues planners have to confront. Hong Kong is a high-density city with a population of 8 million living on a piece of land 1,000 square kilometres in area. The urban density of Hong Kong is close to 60,000 persons per square kilometre. Site development density can reach 3000 persons per hectare.

In 2003, the Hong Kong Government's Team Clean Report suggested that gradation of development height profiles, provision of breezeways, layout planning and disposition of building blocks to allow for more open spaces, greater building setbacks to facilitate air movement, reduced development intensity, increased open space provisions especially in older districts and more greenery are necessary to mitigate the ill effects of the urban heat island effect and weak urban ventilation.

The key concern of higher urban temperatures has been the problem of urban thermal heat stress. Based on comfort survey data (Givoni & Noguchi, 2004), researchers in Hong Kong drew up the Hong Kong Outdoor Comfort Temperature Chart (Cheng & Ng, 2006). The Hong Kong chart incorporates the average minimum, mean and average maximum summer temperatures of Hong Kong, at 26.4°C, 28.3°C and 31.3°C, respectively (Fig. 1). It can be noted that in the shade (solar radiation of less than 100 W/m2), given an air temperature of 28°C, there is a need for a wind speed of approximately 0.8 m/s for a person to remain comfortable thermally. Table 1 compares wind speed criteria suggested by various studies at the same environmental settings. Climatic adaptation exists; the Hong Kong chart generally agrees with the recommendations of Macfarlane for a warm-humid climate, and is in a reasonable range from the predictions of Nikolopoulou (Penwarden, 1973) and Nikolopoulou (Nikolopoulou & Steemers, 2003; Nikolopoulou *et al.* 2003).

The important point to note is that at an outdoor temperature of 30°C, the wind speed needs to exceed 2.5 m/s to provide thermal comfort. This is not feasible. Hence, on the one hand, there is a need to allow wind into the city; but on the other hand, there is a need not to allow the urban air temperature to rise too much beyond the ambient air temperature. Hence, for high-density city design, there is a need for allowing wind permeability with optimised urban morphological design, and urban heat island countermeasures with greenery, water elements and cool materials.

Table 1 Comparison of wind speed criteria for pedestrian comfort in the shade at a mean air temperature of 28°C.

Researcher	Place Studied	Wind Speed (m/s)	Relative Humidity (%)	Comments
Macfarlane	Warm-humid region	0.6	75	comfortable
Nikolopoulou	Greece	1.5	75	neutral
Ahmed	Dhaka, Bangladesh	0.0	75	comfortable
Givoni	Japan	1.0	-	neutral
The HK Chart	-	0.8	-	neutral

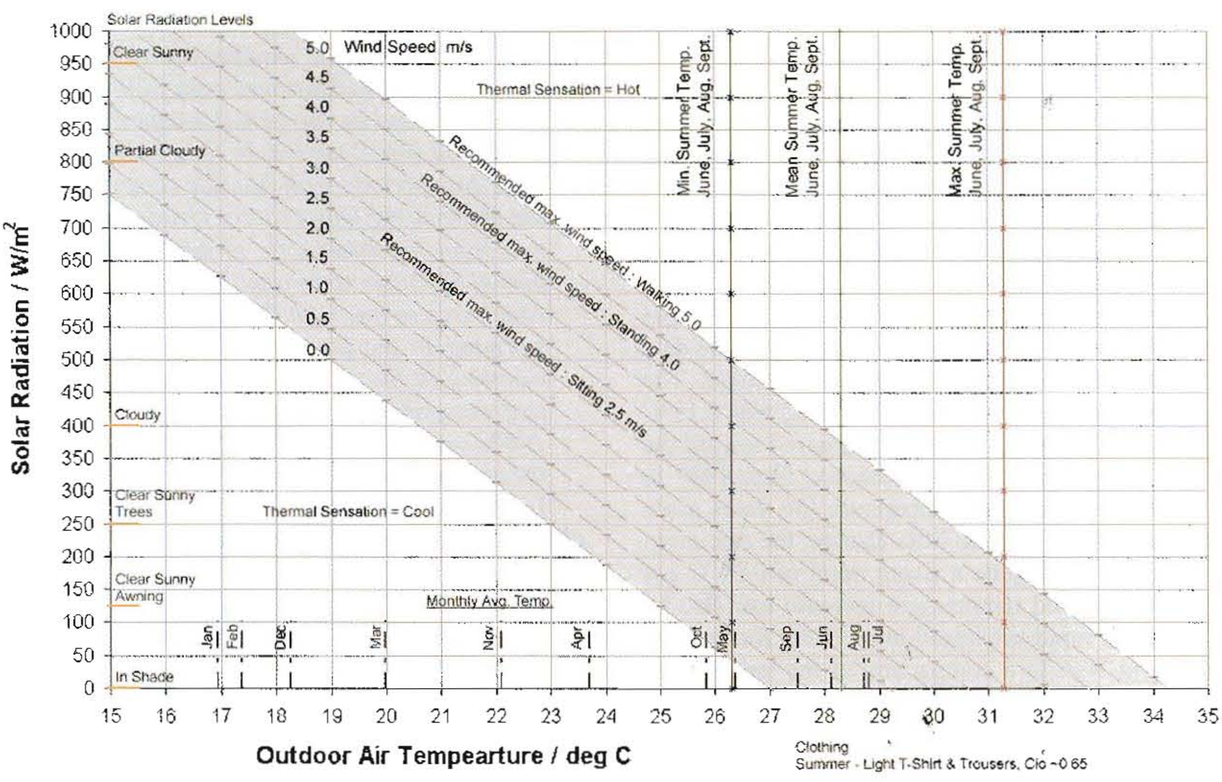

Fig. 1 The Outdoor Comfort Temperature Chart of Hong Kong

3. A Review of Existing Conditions

Since 2003, the Hong Kong Government has commissioned studies on Hong Kong's urban air ventilation, implemented some policies to mitigate the problem, and established guidelines to improve design and planning. An air ventilation assessment (AVA) study was carried out that led to the introduction of technical and planning guidelines (Ng, 2006). In addition, since 2006, an urban climatic map has been drafted. Planning recommendations to optimise urban ventilation and to mitigate urban heat island problems have been proposed.

A few studies on the urban heat island intensity of Hong Kong have been conducted (Ren *et. al.*, 2008; Fung and Lam, 2009; Nichol, 2005; Wu *et. al.* 2008). The existing city conditions in Hong Kong were further evaluated based on an expert qualitative evaluation by Professors Baruch Givoni, Lutz Katzschner, Shuzo Murakami and Mat Santamouris, and Dr. Wong Nyuk Hien (Ng, 2009). With minor differences in their opinions, they made the following key comments.

Breezeways/air paths: As a general rule, the more air ventilation to the streets the better for these dense urban areas. The overall permeability of the district has to be increased at the ground level. This is to ensure that the prevailing winds travelling along breezeways and major roads can penetrate deep into the district. This can be achieved by properly linking open spaces, creating open plazas at road junctions, maintaining low-rise structures along prevailing wind direction routes, and widening the minor roads connected to major roads. It is also important to avoid obstructing sea breezes. Any localised wind problem along the waterfront should be dealt with locally and not affect the overall air ventilation of the city.

Podiums/Site Coverage: The effect of building layout (especially in terms of building site coverage) has a greater impact than that of building height on the pedestrian wind environment (Fig. 2). Stepping building heights in rows would create better wind at higher levels if the differences in building heights between rows are significant. The "podium" structures commonly found in Hong Kong are not desirable from the viewpoint of maximizing wind availability to pedestrians. Podiums with large site coverage not only block most of the wind to pedestrians (affecting comfort and air quality), but also minimize the "air volume" near the pedestrian level (affecting air quality).

Building Disposition: Proper orientation and layout of buildings with adequate gaps between them are needed. Stagger the arrangement of the blocks such that the blocks behind are able to receive the wind penetrating through the gaps between the blocks in the front row. In the case of new development, to avoid obstruction of the sea breeze, the axes of the buildings should be parallel to the prevailing wind. In order to maximize wind availability to pedestrians, towers should preferably abut the podium edge that faces the main pedestrian area/street so as to enable most of the downwash wind to reach the street level.

Building Heights: Vary the heights of the blocks with decreasing heights towards the direction from which the prevailing winds come. If that is not possible, it is better to have varying heights rather than similar or uniform height. Given the extremely high density of the urban fabric and narrow streets, a probable strategy for improving air ventilation is to vary building heights in order to divert winds to the lower levels. Nonetheless, assessment will be required to further quantify the actual performance of such potential in view of the deep urban canyon profiles common in Hong Kong.

Building permeability: The provision of permeability or gaps nearer to the pedestrian level is far more important than that at high levels. Create permeability in housing blocks. Try to create voids at ground level to improve ventilation for pedestrians. This will improve

Fig. 2 A typical building morphology in Hong Kong: tower blocks sitting on a podium that occupies the entire site. When such podiums are very close together, they significantly reduce the air space at pedestrian levels.

not only the air movement at the ground level (thus improving pedestrian comfort), but also help to remove the pollutants and heat generated at the ground level. The channelling effect created by the void also helps to improve the ventilation performance for those residential units at lower floors. Creation of openings in the building blocks to increase their permeability may be combined with appropriate wing walls that contribute to pressure differences across building facades and thus facilitate airflow through the openings of the buildings. The wing walls have to be designed according to the known standards. For very deep canyons or very tall building blocks, mid-level permeability may be required to improve the ventilation performance for those occupants situated at mid-floors.

The more the better: It was the general opinion that unlike most cities in the world, Hong Kong may find wind gusts not to be a problem in most areas. On the contrary, wind stagnation and blockage is the main problem. For the tropical climatic conditions of Hong Kong, where winds in the summer are a welcoming quantity, the five experts opined unanimously that "the more the better" should be the guiding spirit. That is to say, designs and development should focus on facilitating the incoming wind, as well as minimising stagnant zones at the pedestrian levels.

In a nutshell, the evaluation indicates two very important urban morphological parameters that need to be optimised for the design of high density cities. On the one hand, it points to the issue of building volume, and hence the density of the city. On the other hand, it also points to the issue of how the buildings occupy the ground and their permeability from an urban design point of view, especially at the near ground, or pedestrian, level.

4. Field Case Studies of Intra-Urban Temperatures

Given the high-density environment of Hong Kong, a number of case-based field studies have been conducted during the summer months in Hong Kong. One of the studies focused on a commercial city area call Tsim Sha Tsui, relying on handheld mobile measurement equipment for assessing temperature, humidity, globe temperature and wind speed. Teams of researchers traversed the area starting from the waterfront, working their way into the city and returning. At each measurement point, the researchers stationed their equipment for three minutes. Simultaneously to the ground measurements, a wind mast at the top of a building tower monitored the upper urban canopy layer. Readings from nearby meteorological stations were also downloaded. The case study was conducted in the afternoon (1-3 pm) in the summer months under calm-wind conditions. One example of intra-urban temperature (Tiu) elevation is expressed by the contour lines in Fig. 3. A difference of 3°C to 4°C can be noted from the seafront to the high-density inner core of the city.

To further understand the basis of the intra-urban temperature gain, area average sky view factors (SVF) were calculated using urban morphological data of Hong Kong (Fig. 4). A linear relationship between SVF and temperature variation has been adopted, as shown in

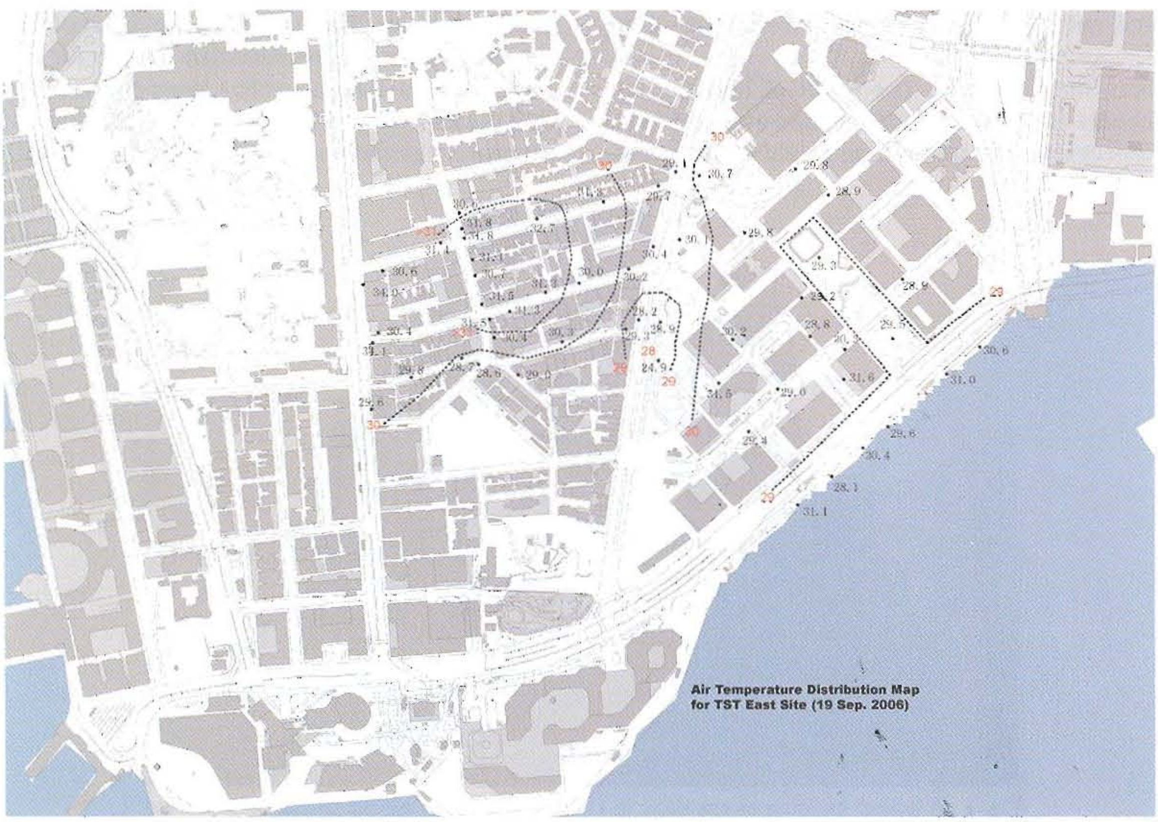

Fig. 3 Intra-urban temperature variations as shown with contour lines. The legend denotes an urban climatic classification based on building heights and volumes, and the resulting sky view factor. The two match well.

Equation 1 (Oke, 1981; Svensson, 2004; Yamashita *et al.*, 1986; Grimmond, 2001; Eliasson, 1990). It reveals a logarithmic relationship between building volume and temperature.

$$\Delta T = c * BV^{\alpha} \tag{1}$$

When the two sets of data (Figs. 3 and 4) are superimposed, a close correlation is found (Table 2). That is to say, areas with higher building volume, and hence higher density, are warmer than open areas or areas with high SVF. The relationship is logarithmic. As such, it is possible to predict intra-urban temperature differentials based on urban morphological information for the entire city. Combining the building volume data with an assessment of altitude and greenery, a thermal load map of Hong Kong can be evaluated (Fig. 5). The legend indicates the predicted temperature attenuation, from minus 2°C to plus 3°C. Data from the mobile traverse further validate the thermal load layer of the Hong Kong urban climatic map (Chen & Ng, 2008). Given Hong Kong's average air temperature of 28°C, an intra-urban temperature increase would bring this to 30°C or 31°C.

Table 2 T-SVF-Building Volume relationship for selected points in the field measurement.

T (°C)	SVF	Building Volume (%)
28.2	0.59	2.0
29.2	0.33	6.0
30.7	0.22	12.8
31.8	0.07	21.6

T_{ref} = 28 °C

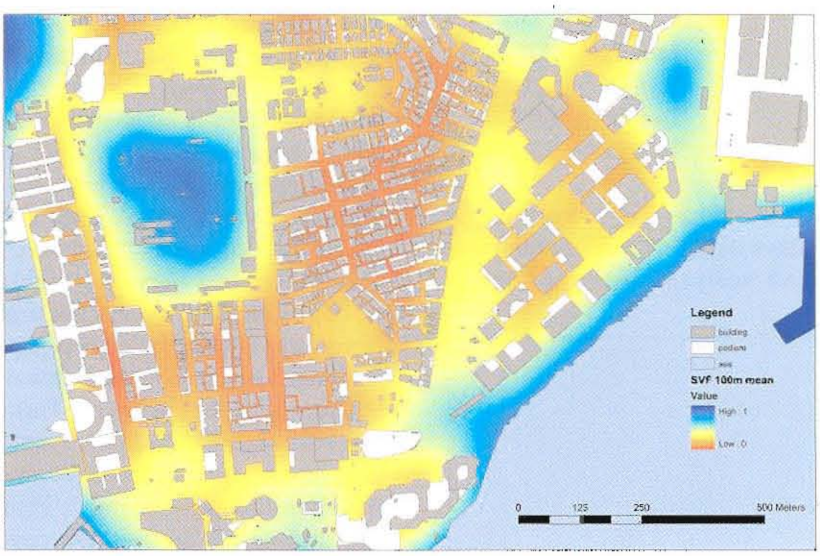

Fig. 4 Areal Sky View Factor map of the study areas.

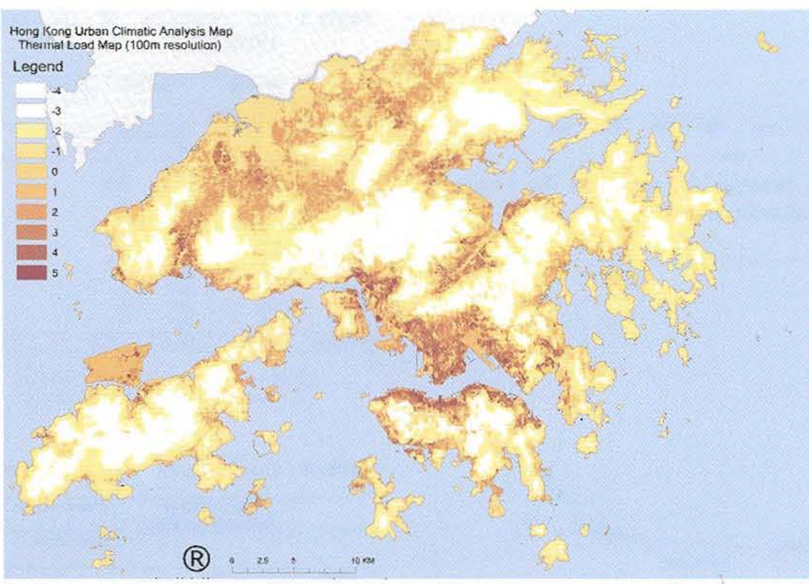

Fig. 5 The Thermal Load layer of Hong Kong's Urban Climatic Map. Six classes of intra-urban temperature differentials are indicated. Class 0 indicates neutral ambient air temperature at sea level, each positive class (say +1) indicates approximately 0.5°C rise above the ambient temperature. Likewise, each negative class (say –1) indicates approximately 0.5°C rise below the ambient temperature. The map predicts an intra-urban temperature rise of 2°C to 3°C from the ambient air temperature. Areas of higher altitude (200m+ above sea level) can experience a negative intra-urban temperature differential of 1°C to 2°C. It is not without reason that these cooler areas are also the more expensive and sought after residential areas of the city.

5. Implications of Intra-Urban Temperature – Hot Days and Hot Spells

Bio-meteorological indicators like "hot days," "hot nights," "very hot days" and "very hot nights" have been used (Hajat *et. al.*, 2002; Masumoto, 2008; Diaz *et al.*, 1986; Leung *et. al.*, 2008). They are known to correlate to health impacts on city dwellers. Various definitions of these terms exist, for example, the Japan Meteorology Agency defines "very hot days" as days on which the maximum air temperature (Ta max) exceeds or equals 30°C; whereas the Hong Kong Observatory defines them as days on which Ta max >= 33°C. This has to do with the differences between the climatic conditions of the two cities. For this study, the following definitions will be adopted.

Very hot day	Ta max >= 33°C
Hot day	Ta max >= 30°C
Very hot night	Ta min >= 28°C
Hot night	Ta min >= 25°C

The Hong Kong Observatory has observed the occurrence of very hot days and very hot nights since 1885. The data was trend analyzed (11-year running average) and the results as shown in Figs. 6 and 7; to which regression equations (2, 3 and 4) have been fitted, are given by:

For very hot days $y = 0.097(x - 1890) + 0.997$

$$r = 0.844 \quad (2)$$

For very hot nights

step 1: 1890-1980

$$y = 0.059(x - 1890) + 0.201 \quad r = 0.733 \quad (3)$$

step 2: 1970-2003

$$y = 0.502(x - 1970) + 5.231 \quad r = 0.970 \quad (4)$$

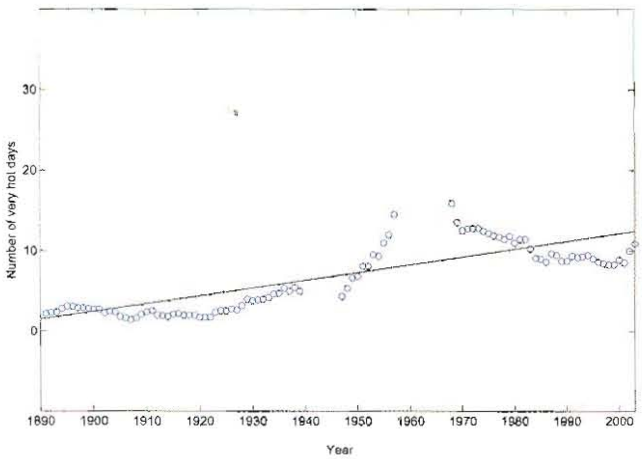

Fig. 6 Linear relationship between the year and the 11-year running average of number of very hor days.

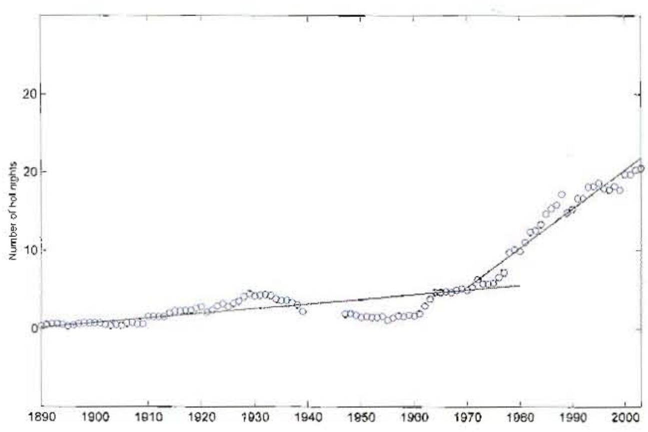

Fig. 7 Linear relationship between the year and the 11-year running average of number of hot nights, in two steps: 1890-1980 and 1970-2003.

To promote further understanding, the Hong Kong Observatory (HKO) publishes a summary of meteorological observations in Hong Kong annually. It contains tables of Daily Mean Temperature (°C), Daily Maximum Temperature (°C), and Daily Minimum Temperature (°C) at the HKO. For this study, published data of the nine year from 1998 to 2007 have been used. The data tabulation is as shown in Table 3. For example, in 2007, there were 25 very hot days and 117 hot days. More importantly, there were six very hot days that were preceded by at least six other consecutive very hot days (Table 4) – known as "long very hot days" in this paper. Likewise, when very hot nights were preceded by at least six consecutive very hot nights they were known as "long very hot nights" in this paper (Table 5).

Based on the tabulated data of Tables 4 and 5, given an intra-urban temperature (Tiu) rise of 1°C, 2°C or 3°C, it can be seen that both the number of long hot days and the number of long hot nights increase exponentially, as shown in Equations 6 and 7. That is to say, the impact of any intra-urban temperature rise duc to the urban heat island effect can be serious.

Table 3 An overview of the hot days and nights of 1998-2007.

	Very hot days (Tmax>=33)	(Tmax>=32)	Hot days (Tmax>=30)	Hot nights (Tmin>=25)	(Tmin>=27)	**Very hot nights (Tmin>=28)**
		Intra-urban +1	Intra-urban +3	Intra-urban +3	Intra-urban +1	
2008	**15**	42	74	115	48	**15**
2007	**25**	61	117	121	52	**23**
2006	**3**	25	82	117	53	**15**
2005	**12**	33	93	135	51	**26**
2004	**6**	26	94	123	47	**19**
2003	**14**	40	91	139	62	**20**
2002	**10**	32	93	133	45	**17**
2001	**9**	38	90	121	41	**16**
2000	**10**	40	99	124	51	**22**
1999	**6**	49	113	133	55	**17**
average	**10.6**	38.2	96 9	127 3	50 8	**19.5**

(no. of very hot days) = 29 6*(Tmax) - c R2 = 0 99
(no. of very hot nights) = 36 0*(Tmin) - c R2 = 0 99

Table 4 Occurrences of long very hot days in 1998-2007.

	(Tmax>=33) or long very hot days	(Tmax>=32+1)	(Tmax>=31+2)	(Tmax>=30+3) or long hot days
		Intra-urban +1	Intra-urban +2	Intra-urban +3
2008	**0**	0	0	39
2007	**6**	27	35	52
2007	**0**	0	10	23
2006	**1**	6	9	22
2005	**0**	0	10	31
2004	**0**	15	22	42
2003	**0**	7	21	58
2002	**0**	3	5	30
2001	**0**	8	30	39
2000	**0**	5	13	50
average	**0.8**	7.9	17.2	38.6

Based on the tabulated data of Tables 4 and 5, given an intra-urban temperature rise of 1, 2 or 3°C, it can be seen that both the number of long hot days and the number of long hot nights increase exponentially, as shown in Equations 6 and 7. That is to say, the impact of any intra-urban temperature rise due to the urban heat island effect can be serious.

$$\text{Episodes of long very hot days} = 1.2516e^{1.2407(\text{Tiu})} \quad R2 = 0.920 \qquad (6)$$

$$\text{Episodes of long very hot nights} = 1.274e^{1.4617(\text{Tiu})} \quad R2 = 0.935 \qquad (7)$$

Table 5 Occurrences of long very hot nights in 1998-2007.

	(Tmin>=28) or long very hot nights	(Tmin>=27+1)	(Tmin>=26+2)	(Tmin>=25+3) or long hot nights
		Intra-urban +1	Intra-urban +2	Intra-urban +3
2008	0	12	29	44
2007	0	26	30	74
2007	0	9	29	50
2006	2	4	21	69
2005	1	7	23	75
2004	0	12	39	82
2003	0	3	29	71
2002	0	6	20	60
2001	1	10	47	73
2000	3	11	33	93
average	0.8	9.8	30.1	71.9

Table 6 NET and PET under various climatic conditions in the hot summer months of Hong Kong.

Ta (°C)	Intra-urban Ta gain (°C)	RH (%)	V (m/s)	NET	PET
28	0	80	0 5	27 5	29 6
29	+1	80	0 5	26 9	28.6
30	+2	80	0 5	27 9	29.9
31	+3	80	0 5	28.9	30.1
32		80	0 5	29.9	32 3
33		80	0 5	30.9	33.4
28	0	80	1	25.9	27 4
29	+1	80	1	26.3	27.7
30	+2	80	1	27 3	29.1
31	+3	80	1	28.4	30.4
32		80	1	29.5	31 8
33		80	1	30.6	33 1

The seriousness of this increase in number of episodes can be seen against the predicted mortality rate due to heat stress. Leung, using Kong Kong's meteorological and health data found that the mean mortality associated with heat strokes would double per unit rise in the NET (Net Effective Temperature, which takes into account air temperature, relative humidity and wind speed) beyond 26 (Table 6).

Under the average summer air temperature in the summer months of 28°C, even given good urban ventilation with a mean wind speed of 1 m/s, the NET is 25.9°C. However, when taking into account an intra-urhan temperature rise of 3°C, the NET will be 28.4°C. This means a four-fold increase in the mean mortality. Based on Leung's study, the normalised mortality increases from 0.000 when the NET is 26 to, alarmingly, 0.015 when the NET is 29. The catch of this evaluation is that for Hong Kong a temperature increase of three degrees, due to global warming and intra-urban temperature elevation, means episodes of hot spells can increase from once a year to 38 times a year; and when this happens, one would expect the morality rate to increase very rapidly.

6. Field Case Studies of Intra-Urban Wind Fields

At the same time air temperature case studies were conducted, as mentioned above, in which urban ventilation was also measured, using a hot ball anemometer. The normalised wind velocity ratio is presented in Fig. 8. Zoning contours were also added. The air circulation pattern under moderate easterly incoming winds (the prevailing wind direction of the study area) was evaluated. In Fig. 8, zones of low wind velocity ratios are noted in areas where the ground coverage of buildings is

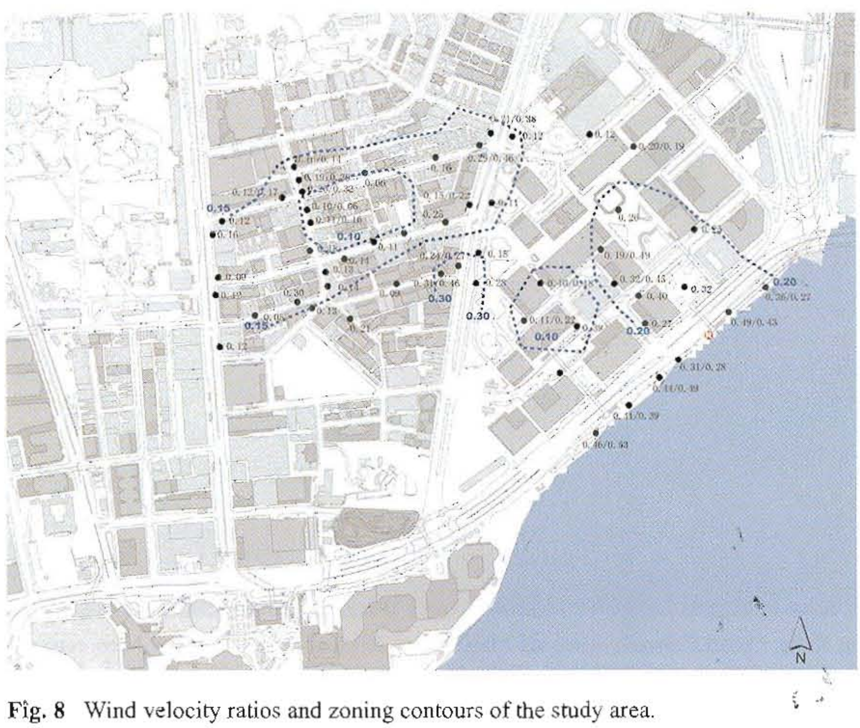

Fig. 8 Wind velocity ratios and zoning contours of the study area.

high. This coincides with recent wind tunnel test findings (Yoshie *et. al.*, 2008). Hence, based on the urban morphological understanding of ground cover, a dynamic potential map of Hong Kong can be generated (Fig. 9). This is further calibrated using wind tunnel tests.

7. Physiological Equivalent Temperature (PET) & Urban Climatic Maps

Bio-climatically based on Table 6, both NET and PET serve as indicators of human thermal comfort based on a combined consideration of air temperature and wind speed. Using a PET formulation for urban thermal

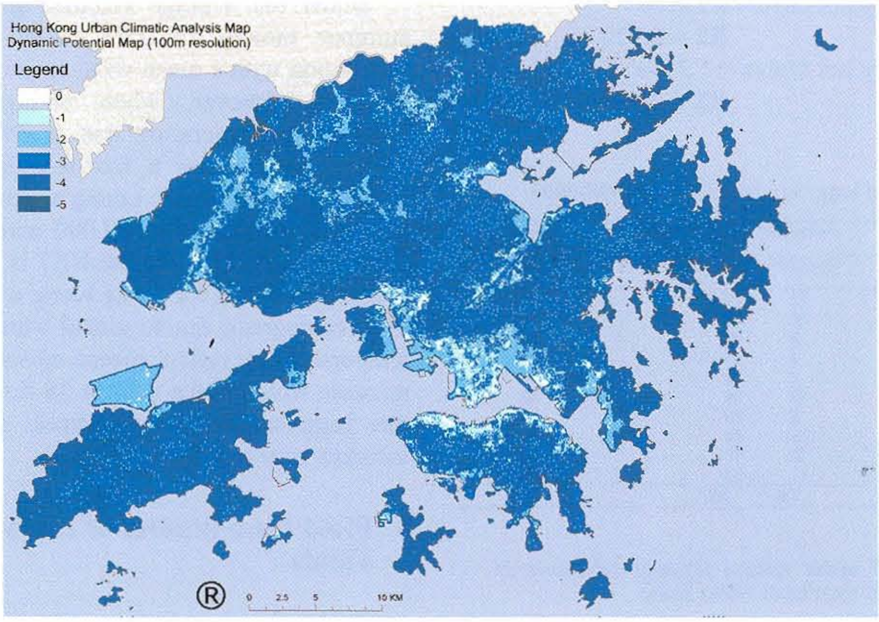

Fig. 9 A dynamic potential map of Hong Kong indicating areas of high roughness and weak urban ventilation performance. Legend 0 and -1 indicates urban areas of baseline dynamic potentials. A difference of minus one class is roughly equal to an increase in dynamic potential of about 0.5 m/s above the baseline.

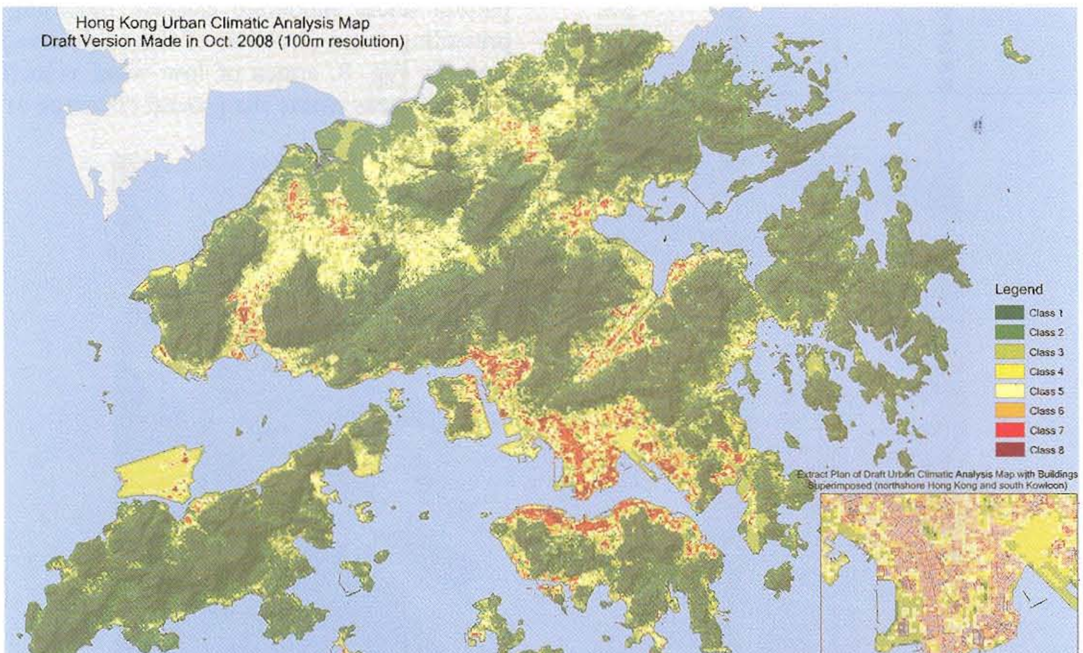

Fig. 10 Hong Kong Urban Climatic Analysis Map. An eight-class differential has been categorised. A one class differential is approximately equal to a one-degree difference in PET. Class 4 has been calibrated to represent the baseline ambient PET condition. Hence, areas of Class 7 and 8 is predicted to have an intra-urban PET increase of 3°C to 4°C.

comfort, it can be calculated that at low wind speeds of 0.5 to 2 m/s, every 1 m/s increase in air wind can mitigate a two-degree rise in air temperature. Hence it is possible to combine understanding of thermal load with that of dynamic potential, which was illustrated earlier. This helped in producing the Hong Kong Urban Climatic Analysis Map (Ng *et al.*, 2008) (Fig. 10). The urban climatic map thus created was further validated by field measurements based on figures obtained in studies of another area in Hong Kong and by wind tunnel tests.

The Urban Climatic Analysis Map provides a spatial understanding of the PET distribution in the urban areas. For example, in the metro core areas of the inner city of Hong Kong on both sides of Victoria Habour, it can be expected that the intra-urban temperature difference between the waterfront and inland areas on a typical summer afternoon in Hong Kong can be on the order of 3°C to 4°C. That is to say, given the average summer temperature of 28°C, the inner urban areas can experience air temperatures of 31°C to 33°C. Coupling that with a decrease in the available wind, the PET can increase by 4°C to 7°C. This creates spatially localised "hot days" and "hot spells" not conducive to healthy human living in built-up urban areas.

Based on the Urban Climatic Analysis Map and the possible implications to human thermal comfort, it is possible to draft up an Urban Climatic Recommendation Map with planners so that strategic planning actions can be developed. This work is currently underway in Hong Kong.

8. Conclusions

For cities located in the tropics and sub-tropics with hot, humid summers, the risk of global warming and the urban heat island effect due to buildings contributing to the already hot, humid thermal comfort conditions has been delineated. Field and data studies have established its criticality. An exponential increase in the numbers of hot days and hot spells can be expected for each degree rise in urban temperature. This is not conducive to urban living and can be dangerous to human health. It is possible to summarise the urban effects of an increase in intra-urban air temperature and decrease in wind and urban air ventilation using Geographic Information Mapping techniques. Urban climatic maps can be drafted for spatial understanding of the issue. With the information, strategic planning actions can be developed in the form of an urban climatic recommendation map. This can provide planners and designers an objective evaluation tool for mitigation actions. Measures can be implemented such as greenery, open spaces, shading with trees, well spaced buildings carefully positioned, reduction of ground coverage and building density and so on.

It is not possible to eliminate the ill environmental effects of cities and high-density cities completely. However, it is possible to design a city with well distributed pockets and routes of quality spaces and urban streets and roads so that pedestrians can have a diversified urban landscape to engage in and explore (Steane & Steemers, 2004). The task for planners is to utilise the available urban climatic information to make good decisions.

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