Urban Climatic Mapping in Hong Kong

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ABSTRACT

Over 50% of the world's population lives in cities. If a city can provide a conducive environment for the building and its occupant to begin with, designing for an energy efficient building is very much easier. One of the tasks is to establish an urban climatic study for the city taking into account the thermal environmental needs of its inhabitants. For cities located in the tropical and sub-tropical zones, the need for providing well-ventilated and thermally satisfactory outdoor spaces is very important. The study focuses on Hong Kong. The study firstly conducted a territory-wide user survey to establish the threshold of the thermal environment for the local inhabitants. Using GIS, the study maps the urban fabric, topography, land use, greenery, and other parameters spatially. The parameters' contributions to thermal comfort were then classified, either positively or negatively. Physiological Equivalent Temperature (PET) has been used as the basis of the classification. Wind dynamics based on observatory station data, as well as meso-scale modelled data has been used to provide the dynamics data to the map.

Background

High density living is increasing an issue that planners around the world have to deal with. A compact and high density city allows the practical design and implementation of an efficient public transport system. In addition, it allows mixed use, closer amenities and a more convenient pedestrian movement-based living pattern.

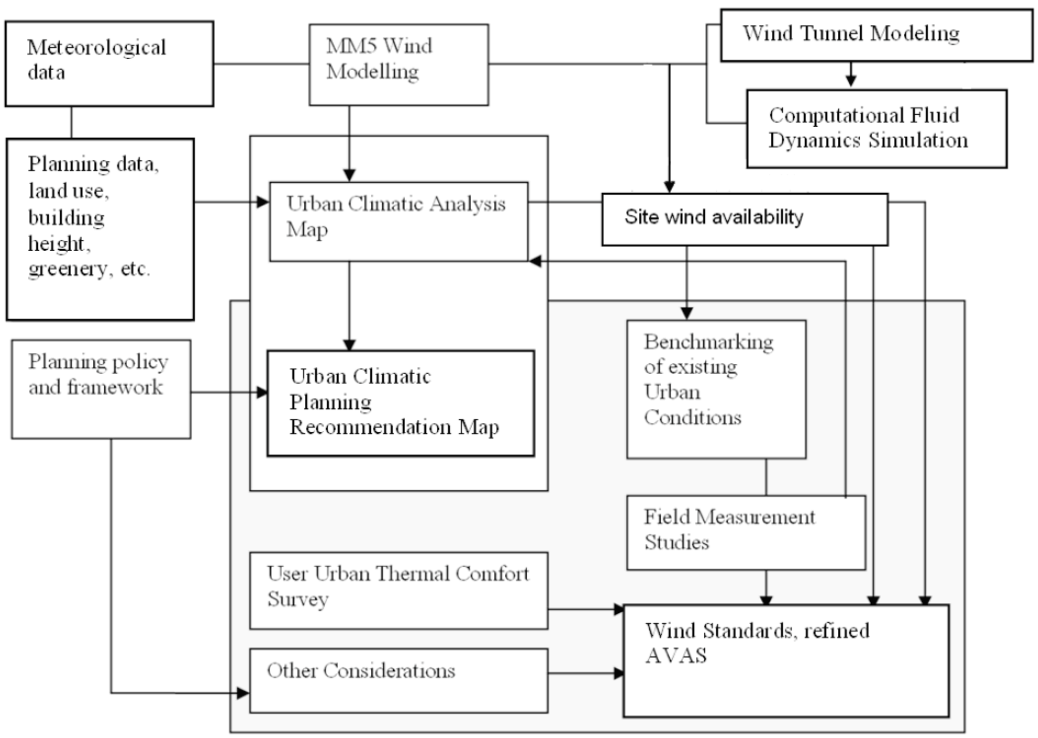
Hong Kong is a high-density city with a population of 8 million living on a piece of land of around 1,000 square kilometres. The urban (city) density of Hong Kong is around 60,000 to 100,000 persons per square kilometre. For residential developments, the estate (site) development density of a piece of land in the city can be up to 3000 to 4000 persons per hectare. In a nutshell, it means that there are a lot of activities happening per square metre of land and its air space. Urban Hong Kong is multi-zoned; commercial, amenity, residential, and sometimes industrial buildings are mixed and co-exist in close proximity.

In 2003, Hong Kong was hit by Severe Acute Respiratory Syndrome (SARS) from which many people died. The Hong Kong Government subsequently set up a Team Clean Committee to investigate possible infectious disease prevention measures and policies. Team Clean charged the task to the Planning Department of the Hong Kong Government. The Planning Department initiated a study titled: "Feasibility Study for Establishment of Air Ventilation Assessment (AVA) System". The study led to the methodology of Air Ventilation Assessment (AVA).

Unlike many countries with guidelines for dealing with strong wind problems, the AVA is a set of guidelines for the weak wind conditions specifically designed to deal with the congested urban environment (Ng et al. 2004, Ng 2009). The AVA establishes a method for project developers to objectively assess the impact of their designs to the urban wind environment. In July 2006, the Government of Hong Kong adopted the system, and since Dec 2006 has required all major governmental projects to undertake the AVA.

The government of Hong Kong has since July 2006 commissioned studies towards producing an urban climatic map (UCMap). The study procedure is outlined in Figure 1.

Figure 1. Study procedure and methodology of Hong Kong Urban Climatic Map (UCMap).



Thermal Comfort Survey

Outdoor microclimatic conditions have profound influences on the comfort sensation of people and therefore are important factors to be considered in the design of urban outdoor spaces. The issue of outdoor thermal comfort has attracted wide attention in recent years. Researches have been done to understand the thermal sensation of people in different outdoor spaces; under different climatic conditions; and with different adaptive behaviours (Ahmed 2003; Spagnolo and Dear 2003).

The methodology we employed in the user's wind comfort survey has an international standing in the field of thermal comfort study; it has been widely adopted in outdoor thermal comfort researches all over the world (Nikolopoulou and Lykoudis, 2006, Ramos and Steemers, 2003). The methodology basically can be divided into two parts: i) micro-meteorological measurement and ii) user questionnaire survey. The former includes physical measurement of the microclimatic conditions at the immediate surrounding of the subjects (Figure 2). The latter consists of questionnaire survey addressing the subjective thermal comfort data including the subjects' thermal sensation, comfort vote, record of subjects' demographic background, and clothing and activities during the survey. Subject's thermal sensation and comfort vote were recorded by face-to-face interview while subject's demographic background, clothing and activities were recorded by observation. Eventually, the results of the questionnaire survey were correlated with the micro-meteorological data; the analysis provides an understanding of people's subjective feeling towards different outdoor climatic conditions (Table 1).

Figure 2. The micro-meteorological station used in the user survey.

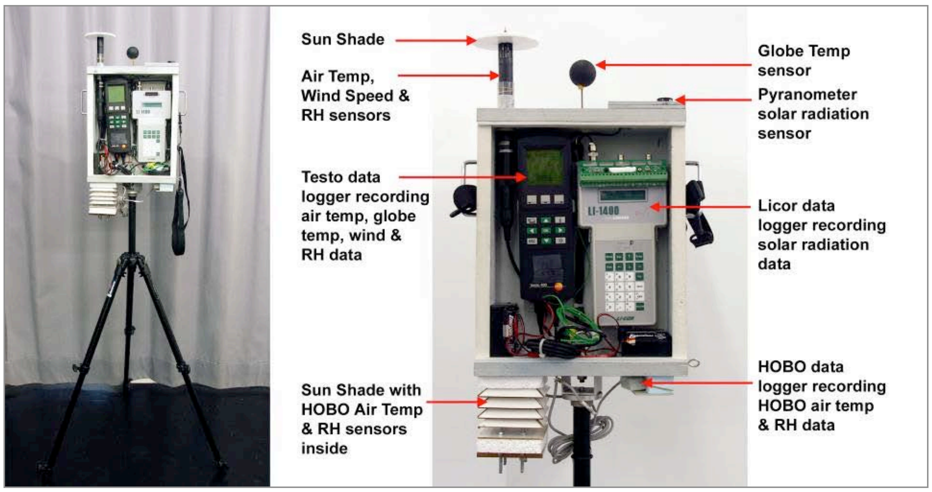


Table 1. A summary of survey sampling.

		Completed interview No.	Residents	Non-residents	Non-A/C (resident)	A/C (resident)
1	Summer 2006 (Pilot)	937	/	/	/	/
2	Winter data (including autumn +winter 2006)	1135	1077	58	503	574
3	Summer data (including spring +summer 2007)	1567	1525	42	686	839
	Total: 2702 (excluding pilot data)					

Physiological Equivalent Temperature (PET) is a thermal index derived from the heat-balance model of human body (Hoppe, 1999). It is defined as equivalent to the air temperature in a typical indoor setting at which, the heat balance of the human body is maintained, with core and skin temperature equal to those under the conditions being assessed. Thus, PET enables a lay-person to compare the integral effects of complex thermal conditions outdoors with his or her own experience indoors (Hoppe, 1999, Matzarakis et al., 1999). Some results of the survey are presented in Figure 3.

Figure 3. Some results of the survey (left) summer, (right) winter.

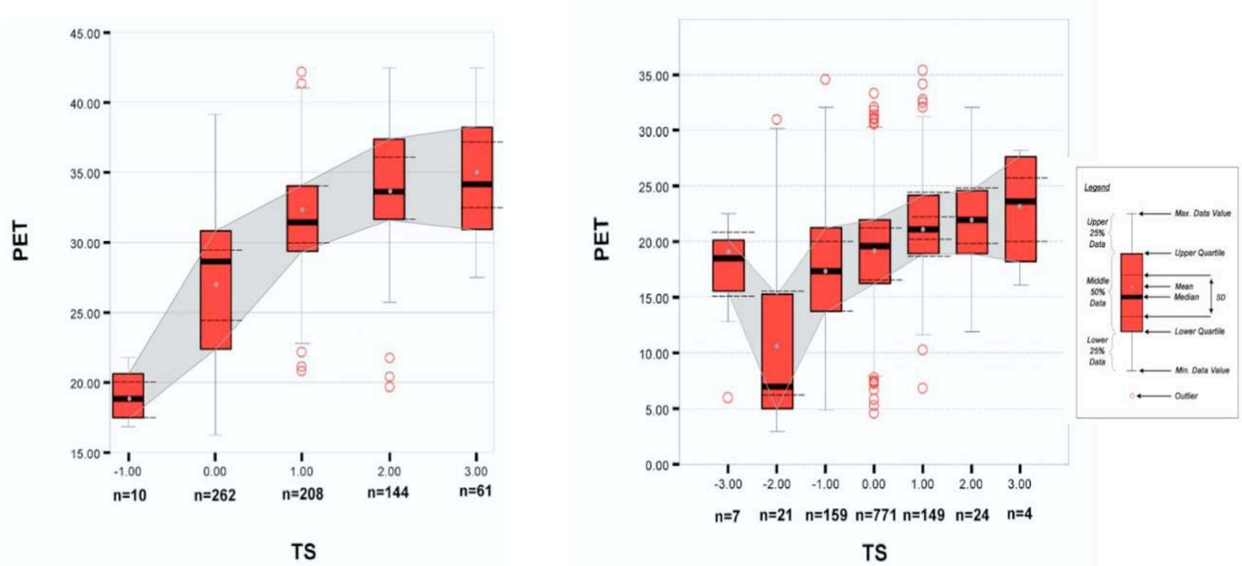


Figure summary (summer 2007, Non-AC)

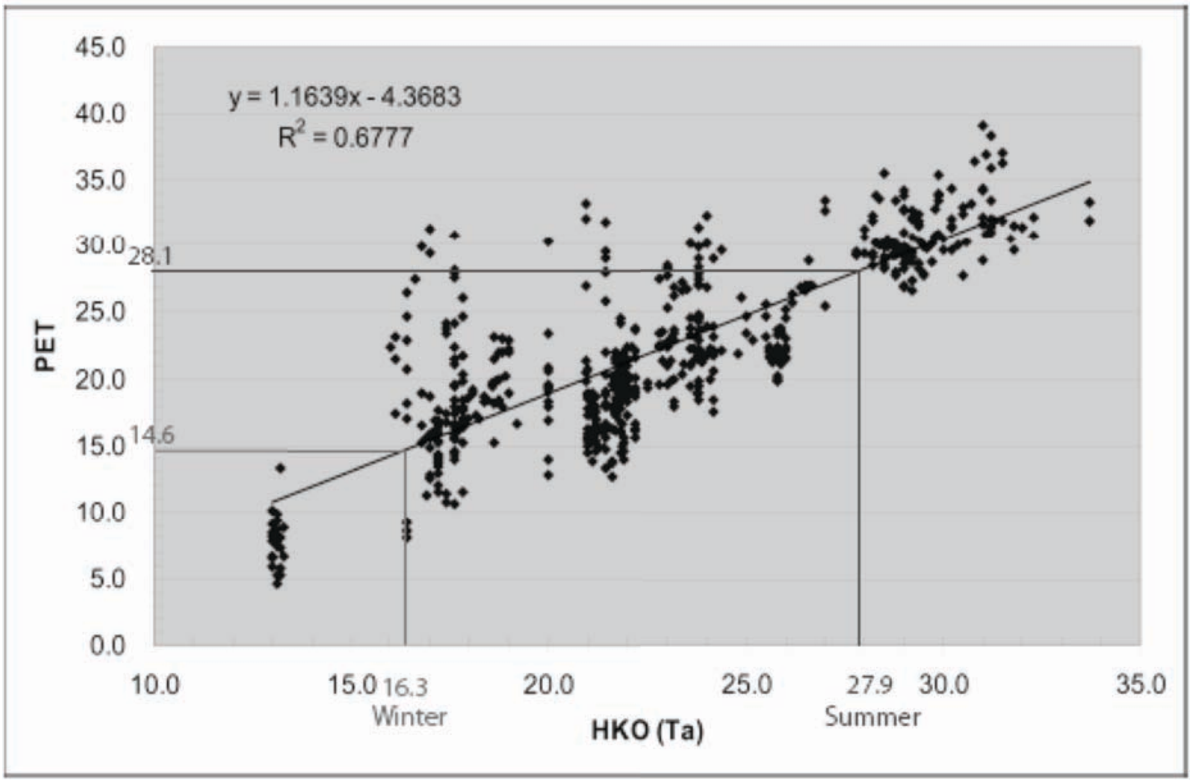
TS	-1	0	1	2	3
Frequency (n=685)	10	262	208	144	61
Mean	19	27	32	34	35
Median	19	29	31	34	34
SD	2	5	4	4	4
Upper quartile	20	31	34	37	38
Lower quartile	18	22	29	32	31

Figure summary (winter 2006, AC+Non-AC)

TS	-3	-2	-1	0	1	2	3
Frequency (n=1135)	7	21	159	771	149	24	4
Mean	17	11	17	19	21	22	23
Median	18	7	17	20	21	22	24
SD	6	9	6	5	5	5	6
Upper quartile	20	15	21	22	24	24	27
Lower quartile	16	5	14	16	19	19	19

The neutral PET is not static. It is highly dependent on the outdoor air temperature (Figure 4). For the purpose of the study, it is concluded that the neutral PET for typical summer conditions in Hong Kong is in the order of 28.1 degree C (or 27 to 29 degree C).

Figure 4. Adaptive PET.



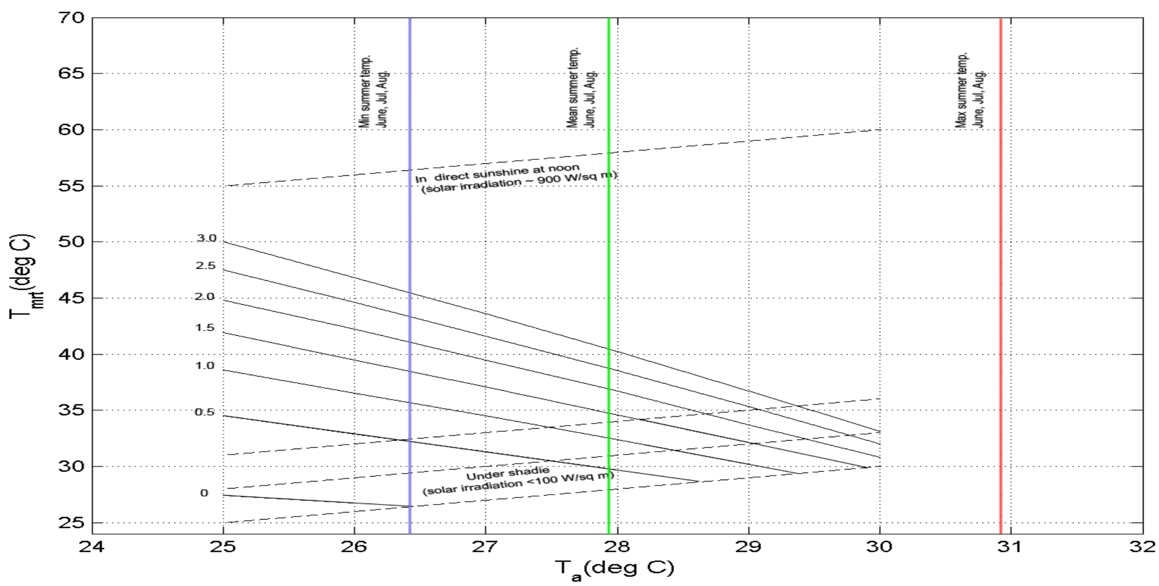
Based on this understanding, assuming in shade outdoor condition, the following look up chart and table are presented to city planners for their easy reference when a desirable urban ventilation condition needs to be specified (Table 2 and Figure 5).

Table 2. A look up table when neutral PET is 28.1 degree C.

RH=80%， Clo=0.3

PET=28.1 (° C)		
T_a (° C)	T_{mrt} (° C)	V(m/s)
27.9	28	0.20
	30	0.53
	32	0.87
	34	1.30
	36	1.76
	38	2.26
	40	2.83
	42	3.51
	44	4.08

Figure 5. A look up chart when neutral PET is 28.1 degree C.



Urban Climatic Map

The extraordinary urban morphology of Hong Kong and the complex wind environment makes the task a unique challenge. Using Geographic Information System (GIS), the study maps the urban fabric, topography, land use, greenery, and other parameters spatially. Overlaying it is the climatic data available from the Hong Kong Observatory. The combined parameters' contributions to thermal comfort were then calibrated and classified, either positively or negatively. Physiological Equivalent Temperature (PET) has been used as the basis of the classification. The GIS map establishes spatially the conditions of outdoor human comfort taking into account the urban morphologies of the location. Based on the map, the microclimatic conditions of a building in the city could be better understood. Studies of air paths, intra-urban climatic conditions and thermal comfort studies have also been conducted to scale the Urban Climatic Map's classifications. The methodology of the GIS based urban climatic map is summarised in Figure 6.

A key problem of urbanization is the urban heat island (UHI) it generates [Oke 1987]. For Hong Kong's hot and humid sub-tropical climatic conditions, urban heat island adds to human thermal stress in the summer months [Givoni 2003] [Cheng 2006a] [Cheng 2003b]. Field measurements indicate that at a typical mid-day in the summer of Hong Kong, UHI is about 2-4 degree C. Inhabitants of the city are less likely to be comfortable outdoor [Katzschner 2006a] [Katzschner 2004] [Katzschner 2006b] [Ali-Toudert 2006] [Matzarakis 1999] [Mayer 1998]. In addition, buildings' energy consumption also increases. The urban climate of the city could be characterized with a balanced consideration of "negative" urban heat island effects (e.g. building bulks and building layouts) and "positive" effects. For the positive effects, two aspects are considered: Mitigation potentials (e.g. green open spaces) and Dynamic potentials (e.g. air ventilation). Scientifically, for urban climatic understanding, the positive and negative could be illustrated in Table 3 and Figure 7.

Figure 6. The framework of Hong Kong's Urban Climatic Map showing processes from data to the Urban Climatic Analysis Map.

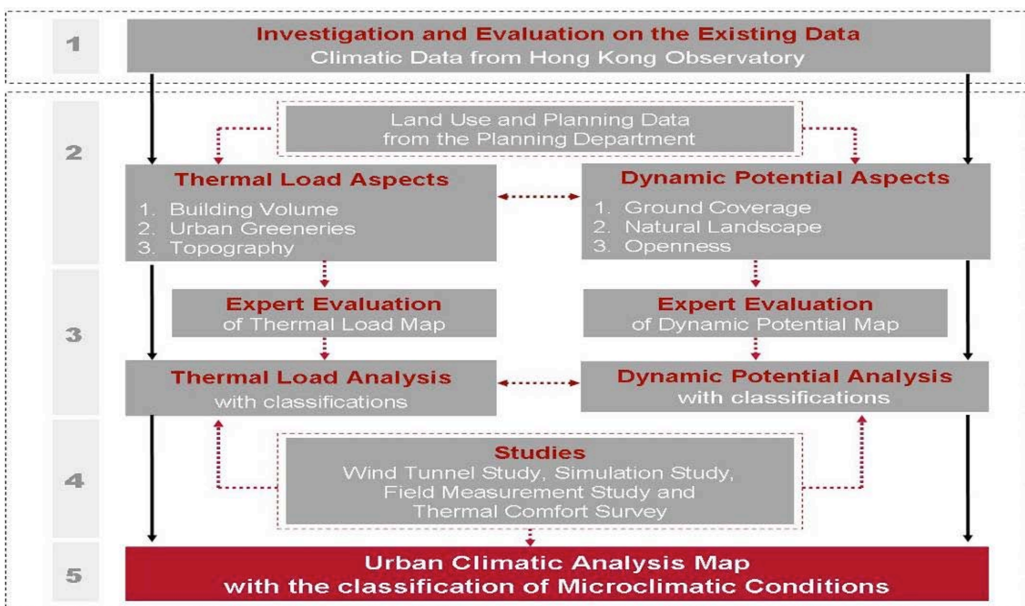


Figure 7. The layering structure of Hong Kong's Urban Climatic Map.

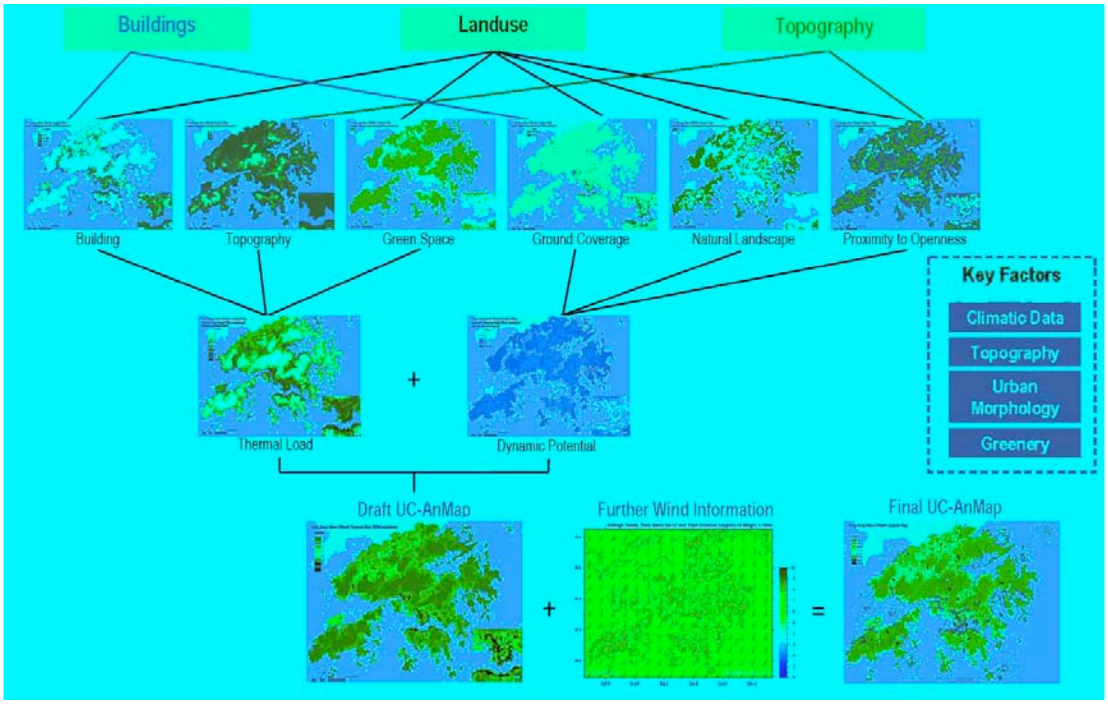


Table 3. Positive and negative effects and the layer structure of Hong Kong's urban Climatic Map.

	Physical criterion	Scientific basis	Input layer based on the criterion
Negative effects	(I) Urban Heat Island	Building bulk	Layer 1 – Building Volume Map
		Anthropogenic gains	Layer 2 – Land Use Map
		Altitude and Elevation	Layer 3 – Topographical Height Map
Positive effects	(II) Urban Heat Island Mitigation Potentials	Bioclimatic effects	Layer 4 – Urban Green Space Map
	(III)Dynamical Potentials	Urban permeability	Layer 5 – Ground Coverage Map
		Bioclimatic effects - Cool air movement	Layer 6 – Natural Landscape Map
		Downhill air movement	Layer 7 – Slope Map
		Reduced ventilation	Layer 8 – Ventilation (roughness length) Map
		Air mass exchange and Neighborhood effects	Layer 9 – Sea Breeze Map

Layer 1 and 2 – The building volume data are measured in cubic metres and converted to percentages of the highest building volumes in the Territory. High building volume traps solar radiation and reduces air flows. It does not just store more solar heat, but also reduces sky exposure slowing the release of solar heat at night. As a result, high building volume contributes to a significant increase in thermal load.

Layer 3 – The topography data are measured in metres above Principal Datum according to the Digital Elevation Model of the Planning Department. Air temperature is lower at higher altitude due to adiabatic cooling (cooling due to pressure changes). Thermal load effect is less severe in areas of higher topographical height. As Hong Kong is a hilly city, topographical condition is therefore an important factor when assessing thermal load.

Layer 4 – Greenery has a cooling and shading effect and can reduce the surrounding air temperature. Therefore, the extent and distribution of greenery are important in affecting the thermal load. Two different classification values are assigned to urban and rural areas with or without greenery.

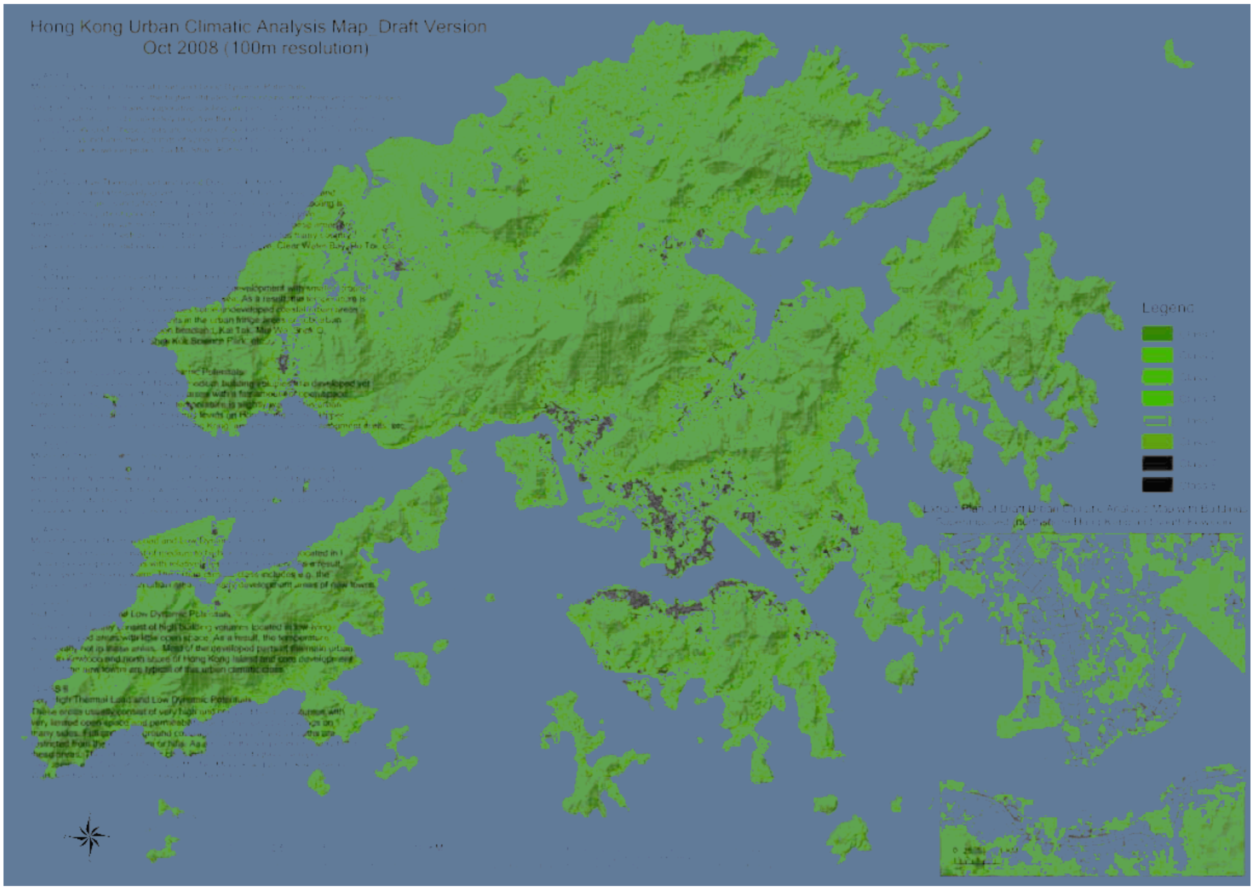
Layer 5 – Ground coverage measures the ground roughness in terms of percentages of ground occupied by buildings in a locality and indicates the urban permeability to wind. Larger ground coverage such as large podia will contribute to a reduction in pedestrian wind speed. Therefore, the extent of ground coverage is important in affecting the dynamic potential.

Layer 6 – Natural landscape, particularly grassland, has low roughness, which possesses higher dynamic potential than other landscape types, such as, woodland and urban landscape. Thus, grassland will contribute to dynamic potential to the city. 2 classification values are currently assigned, “Grassland” and "Woodland and Urban Landscape”.

Layer 7, 8 and 9 – This layer consists of 3 sub-layers of 3 different parameters: proximity to waterfront, proximity to open space and slope with vegetation. Waterfront, open areas and vegetated slopes are sources of air ventilation, and the locations of building developments in close proximity in relation to these features can benefit from them. For example, sea breezes decrease as the distances to sea shore increase. Distances in metres to waterfront, open space or slopes are given different classification values to estimate their dynamic potential.

When ther layers are collated based on their respective impacts to PET, the Urban Climatic Analysis Map of Hong Kong results (Figure 8)

Figure 8. The Urban Climatic Analysis Map of Hong Kong.



Planning Recommendations

Based on the user survey and the established neutral PET in the summer months of Hong Kong, the UCMap is interpreted based on an understanding of the urban impact on human thermal comfort (Table 4). The categorization and grouping of the 8 classes are by magnitudes of their positive dynamic potentials and negative thermal load effects. Urban climatically valuable areas should be preserved. Planning actions and mitigations should be directed to climatic zones that are critical and important, most particularly, the highly climatically sensitive areas.

Table 4. Thermal comfort impact and urban climatic classes of Hong Kong.

	Urban Climatic Class	Impact on Thermal Comfort	Urban Climatic Value / Sensitivity Zone	Possible action
1	Moderately negative Thermal Load and Good Dynamic Potentials	•• Moderate	(A) Urban climatically valuable area	Preserve
2	Slightly negative Thermal Load and Good Dynamic Potentials	• Slight		
3	Low Thermal Load and Good Dynamic Potentials	· Neutral	(B) Slightly urban climatically sensitive area	Preserve & enhance
4	Some Thermal Load and Some Dynamic Potentials	• Slight		
5	Moderate Thermal Load and Some Dynamic Potentials	•• Moderate	(C) Urban climatically sensitive area	Action desirable
6	Moderately High Thermal Load and Low Dynamic Potentials	••• Moderately strong		
7	High Thermal Load and Low Dynamic Potentials	•••• Strong	(D) Highly urban climatically sensitive area	Action necessary
8	Very High Thermal Load and Low Dynamic Potentials	••••• Very strong		

Moderately Negative Thermal Load and Good Dynamic Potentials (Class 1) These areas are situated on the higher altitudes of mountains and steep vegetated slopes. Adiabatic cooling and trans-evaporative cooling are prevalent to bring about good dynamic potentials and moderately negative thermal load. As a result, the temperature is usually very cool. These areas are sources of cool and downhill wind. This urban climatic class includes the summits of various mountains and peaks.

Slightly Negative Thermal Load and Good Dynamic Potentials (Class 2) These areas are extensively covered by natural vegetation, greenery, and natural coastal areas including the hilly slopes. Trans-evaporative cooling is prevalent to bring about good dynamic potentials and slightly negative thermal load. As a result, the temperature is generally cooler. These areas are sources of cool and fresh air. This urban climatic class includes many country park areas, beaches and outlying islands.

Low Thermal Load and Good Dynamic Potentials (Class 3) These areas usually consist of more spaced out developments with smaller ground coverage and more open space very near the sea. As a result, the temperature is mild. This urban climatic class includes some undeveloped coastal urban areas and many low-density developments in the urban fringe areas or sub-urban outskirts.

Some Thermal Load and Some Dynamic Potentials (Class 4) These areas usually consist of low to medium building volumes in a developed yet more open setting, e.g. in the sloping areas with a fair amount of open space between buildings. As a result, the temperature is slightly warm.

Moderate Thermal Load and Some Dynamic Potentials (Class 5) These areas usually consist of medium building volumes situated in low-lying areas further inland from the sea or in areas fairly sheltered by natural topography. As a result, the temperature is warm. This urban climatic class includes many medium density developed urban areas with urban greenery.

Moderately High Thermal Load and Low Dynamic Potentials (Class 6) These areas usually consist of medium to high building volumes located in low-lying development areas with relatively less urban greenery. As a result, the temperature is very warm.

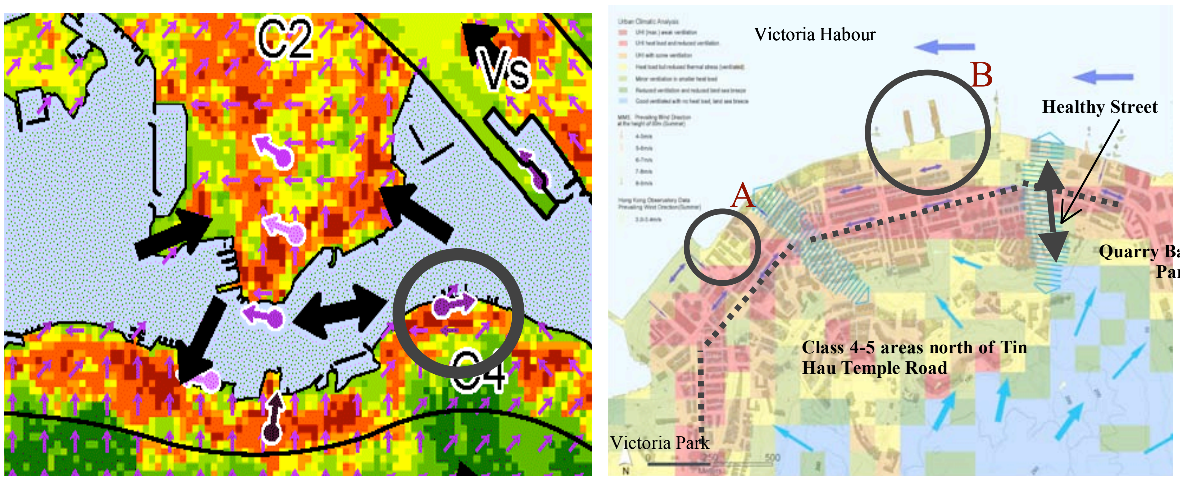
High Thermal Load and Low Dynamic Potentials (Class 7) These areas usually consist of high building volumes located in low-lying well-developed areas with little open space. As a result, the temperature is generally hot in these areas.

Very High Thermal Load and Low Dynamic Potentials (Class 8) These areas usually consist of very high and compact building volumes with very limited open space and permeability due to shielding by buildings on many sides. Full and large ground coverage is prevalent and air paths are restricted from the nearby sea or hills. As a result, the temperature is very hot in these areas.

Planning Interpretations

An example of how the Urban Climatic Map could be used at the district level is demonstrated in Figure 9.

Figure 9. From UC Analysis Map (left) to UC Planning Recommendation Map (right).



Referring to Figure 9 left, one can see the combined effects of buildings, open spaces, the natural landscape and topography. The urban climatic map illustrates a strategic and holistic approach towards understanding the urban climate of Hong Kong. When the urban climate Map is further examined at the 100x100m grid resolution, the wall-like effects of buildings along the coastline is apparent. There are small gaps, and those might need some protection (Figure 9 right). The downhill katabatic wind from the south over the ridges of the hill on the Hong Kong Island can be detected. This, perhaps more important than the already diminished coastline sea breezes, contributes positively to the urban climate of the district.

The district of North Point could be characterized with a Class 7-8 belt (areas colour coded RED in Figure 9 left and highlighted with the dotted line; also refer to Table 4 for description of Class 7-8) between Electric Road-Java Road and King's Road. This belt extends from Victoria Park to Quarry Bay Park Phrase II with a small gap near Healthy Street (blue arrow, Figure 9 right). This Class 7-8 belt is "effective" blocking a lot of the air ventilation coming down from the hills. The main reason of this belt is the high ground coverage and high building volume in the areas. This Class 7-8 belt is not too "thick"; penetrating it with strategic intervention may be possible. On the other hand, it is important not to "thicken" it by building another high density layer north or south of it.

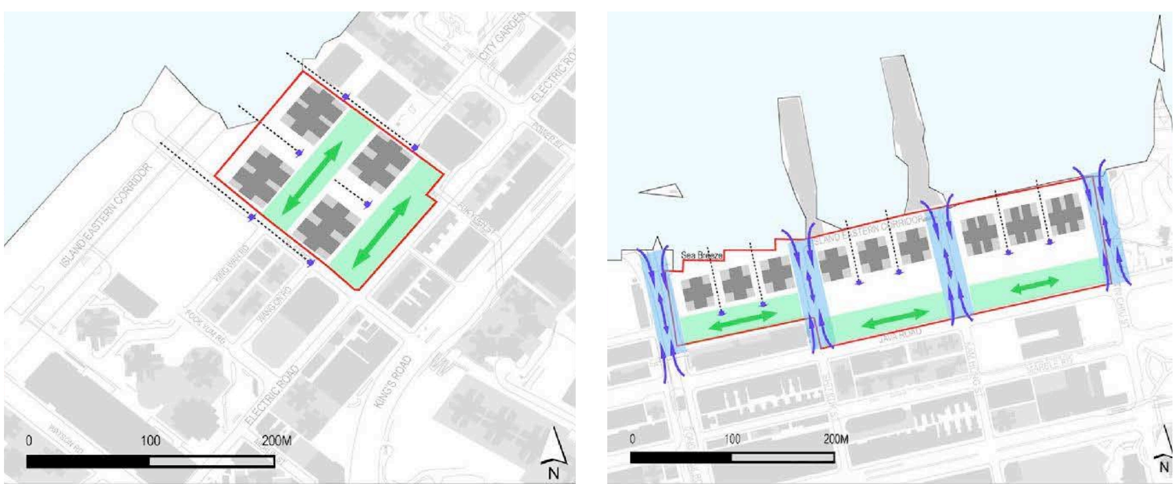
The Class 7-8 belt along the coastline is between the Victoria Harbor and Class 2-3 green areas (colour coded BLUE and GREEN in Figure 9 right) of the hills. A Class 4-5 area (colour coded YELLOW and ORANGE in Figure 9 right) can be seen north of Tin Hau Temple Road.

In the summer months, North Point benefits from two kinds of winds. On the one hand there is a southerly wind from over the hills; on the other hand, there is an easterly-westerly wind along the harbor front. North Point's slight protrusion into the harbor helps the easterly-westerly wind ventilating the area. East-west oriented streets are useful air paths. Strategically widening these air paths will help the area. Wind from the hills down slope to North Point also provides useful air ventilation. To capitalize on it, the Class 7-8 belt mentioned above must be perforated. There are two such existing perforations (near Healthy Street and near Power Street). They must be respected. More north-south air paths should be created to help the area. Strategically vary the building heights perpendicular to the Class 7-8 belt could create useful semi-air paths (air paths over lower buildings). Widening streets perpendicular to the belt would also help. It is useful that some of the smaller north-south orientated streets are to be pedestrianised. Relieving these streets from traffic pollution as well as greening them will greatly enhance the air ventilation quality of the area. Ideally, spacing these green air paths at roughly 100-200m intervals along the belt could be considered. The paths allow air ventilation to penetrate, as well as lowering the air temperature near the ground (Givoni 1998, Dimoudi et al. 2003) – around 1 to 3 degree C.

Buildings along the waterfront and south of King's Road must be carefully designed and spaced so as not to block both the easterly-westerly habour wind, and the downhill winds from the south. They could be set back from the boundary creating a wider east-west air path. They could also be spaced out adequately for the southerly winds from the hills.

Given that the belt areas described earlier is already Class 7-8, Thermal Load is high and air ventilation alone may not be enough to mitigate entirely. Greening is therefore recommended.

Figure 10. Planning Recommendations of Site A (left) and Site B (right).



In addition to the district-wide urban climate understanding, planning recommendations are illustrated in terms of building mass and depositions, breezeway, air paths and setbacks of two sites in the district, site A and B (Figure 10). As such, the urban climatic issues related to the micro-climatic conditions of the site have been dealt with from the planning perspective. In addition, the boundary conditions of the buildings are now better understood.

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