Chapter 8
Urban Climatic Map: Thermal Comfort as the Synergising Indicator

Abstract The distinctive features of urban climate have been widely studied for decades. However, the consideration of urban climate in urban planning and design framework is rather limited. One of the possible reasons is due to the difference in working languages between scientists and urban planners such that the urban climatic knowledge cannot be readily utilised in the planning and design practices. The concept of urban climatic map provides an information platform for the presentation of urban climatic phenomena on a two-dimensional spatial map in a format that can be readily interpreted by urban planners. Areas with environmental problems or sensitive to urban climate can therefore be easily identified for mitigation measures. In this paper, the methodology and results of the urban climatic analysis map, as the first part of the urban climatic map study of Hong Kong, are presented and the implications on urban planning and design practices are discussed.

Keywords Urban climate · Urban planning · Urban climatic map · High-density cities · Subtropical

8.1 Introduction

Rapid urbanisation results in the transformation of surface characteristics of the landscape and human activities in urban areas cause dramatic changes in climatic conditions in urban areas (Oke 1987; Mills 1997). A wide range of urban climatic studies were conducted in the last few decades (Arnfield 2003). However, the incorporation of urban climatic knowledge into urban planning and design frameworks is still limited. This leads to inefficient city planning and building design with regard to urban climate and hence impacts the energy consumption of the city (Bitan 1988).

Urban planners are generally found to have difficulties in understanding scientific findings of urban climatic studies and how these studies are usually constructed on the basis of meteorology, climatology, and atmospheric physics (Eliasson 2000; Mills 2006; Ren et al. 2013). It is therefore necessary to bridge the gap between scientific understandings of urban climatology and urban planning and design practices in order to translate climatic knowledge into planning language (de Schiller and Evans

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1990–1991; Alcoforado et al. 2009; Ren et al. 2011). A platform for information exchange is required to assemble climatic information and present the useful and necessary information to different stakeholders (Mills et al. 2010).

An urban climatic map (UCMap) is an information and evaluation tool which integrates urban climatic factors and town planning considerations by presenting urban climatic phenomena on a two-dimensional spatial map in a format that can be readily interpreted by urban planners (Ren et al. 2011, 2013). It is produced by collating various meteorological, topographical, planning, and land use information and "their interrelationship and effects on urban climate are analysed and evaluated spatially and quantitatively" (Ren et al. 2013, p. 2). Various "climatopes" are then defined as the spatial units of a UCMap in order to present areas with similar urban climatic conditions and features (Scherer et al. 1999; Alcoforado et al. 2009). They can also show the spatial variations of urban climatic characteristics and their significance. Urban planners can therefore easily identify areas with environmental problems or sensitive to urban climate and planning recommendations in corresponding areas can assist them to take appropriate actions.

The concept of UCMap was developed in Germany in the 1970s (Matzarakis 2005), and it has been applied in Europe, Asia, and South America (Scherer et al. 1999; Alcoforado et al. 2009). Most of the UCMap studies in the world focus on low-density urban planning and design except for the Thermal Environment Map for Tokyo (Tokyo Metropolitan Government 2005). However, it focuses on the thermal aspect of urban climate only and prevailing wind information and localised air movements are critical to outdoor thermal comfort of a coastal city. For high-density subtropical cities like Hong Kong, an improved methodology is required to accurately delineate the climatopes of the city.

This paper presents the methodology of the development of UCMap of Hong Kong. The UCMap system consists of two major components: the urban climatic analysis map (UC-AnMap) and the urban climatic recommendation map (UC-ReMap). The UC-AnMap, which collates meteorological, topographic, planning, and land use information and analyse their interrelationships and effects on the wind and thermal environment, is documented in this chapter. In this chapter, human thermal comfort in the outdoor environment, as represented by physiological equivalent temperature, is employed as the synergising factor to collate the layers of the UCMap. User survey of outdoor thermal comfort provides necessary information to determine the neutral conditions for typical summer in Hong Kong.

8.2 Methodology

8.2.1 Study Area

Hong Kong is situated at the south-eastern coast of China, and its downtown areas are located on both sides of the Victoria Harbour. A number of high-density residential districts are also found in different parts of the city. Although a large proportion of the territory is covered by natural landscape, greenery is somewhat limited in dense urban areas. The highly urbanised downtown areas result in severe urban heat island (UHI) phenomenon with about 4 °C (Wu et al. 2008). At the beginning of the twentieth century, Hong Kong was dominated by agriculture and fisheries with limited trade activities. Urban development was at a steady rate until the outbreak of the Second World War which caused enormous impacts on the economic activities in Hong Kong. After the Second World War, entrepot trade contributed to the prosperity of Hong Kong economy in the 1960s and the city was subsequently transformed into an industrial city in the following decades. With the intensification of urban development in the last few decades, Hong Kong has transformed into a megacity characterised by high-rise buildings and compacted urban form.

8.2.2 *Meteorological Data*

Hourly T_a and wind data were acquired from the meteorological stations operated by the Hong Kong Observatory (HKO; Fig. 8.1). The data period of all meteorological stations ends at the end of 2004 but varies from station to station due to the difference in establishment date. The HKO Headquarter has the longest meteorological record of 120 years while most of the stations have a record of only about 10 years. The highest T_a is observed from June to August and thermal heat load due to buildings and anthropogenic activities further increase T_a. Therefore, the summer months are

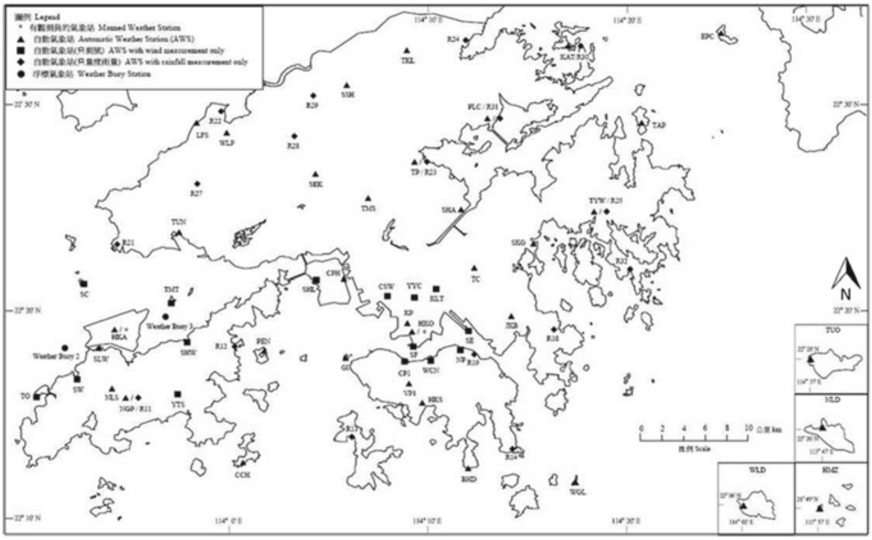

Fig. 8.1 Location of the ground-level meteorological stations operated by HKO

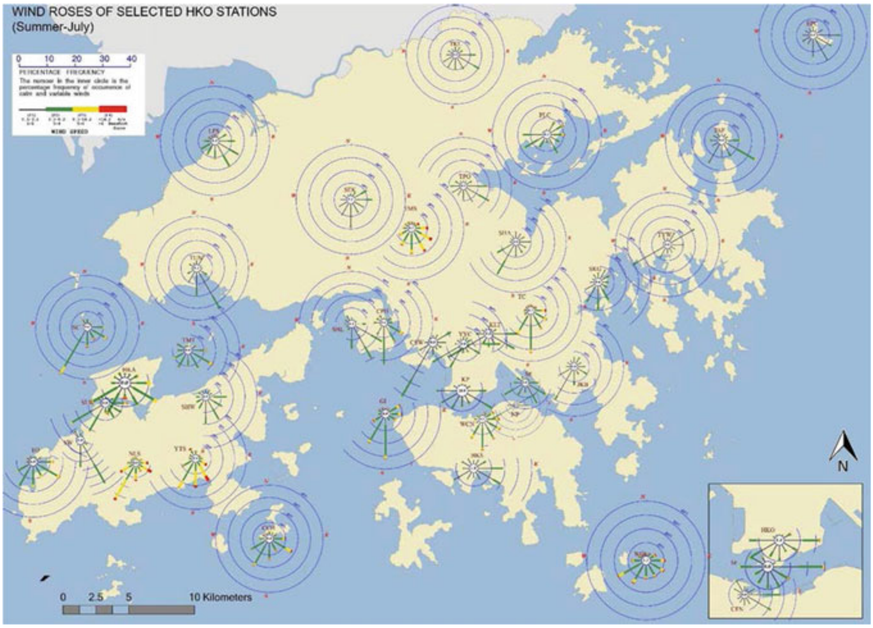

Fig. 8.2 Wind roses of ground-level meteorological stations

generally considered more critical to outdoor thermal comfort in Hong Kong (Ng and Cheng 2012) and the UC-AnMap is developed based on the summer conditions.

Wind data were expertly evaluated in order to provide information on prevailing wind directions under both annual and summer conditions. It helps to gain insights into land and sea breezes, thermal air mass movements, downhill air movements, and topographical effects (Fig. 8.2). The evaluation identifies wind flow patterns such as air paths and air mass exchange, and how they are influenced by prevailing wind was also assessed. In addition, the local conditions of the meteorological were characterised so that background wind, thermally induced circulation systems, and channelling effects were identified. For a more comprehensive understanding of prevailing winds in Hong Kong, the Fifth Generation Mesoscale Model (MM5) was employed to simulate wind speed and direction in Hong Kong for each month in 2004. The grid size is 100 × 100 m, and the lowest height is 60 m. The MM5 model was previously evaluated with reasonable accuracy (Yim et al. 2007). The 16-direction MM5 wind roses were compared with HKO wind roses for selected locations, and the prevailing wind directions were subsequently determined.

8.2.3 Land, Building, and Planning Data

Land, building, and planning data were acquired from the Planning Department in order to provide information about the topography, urban morphology, and greenery of Hong Kong. The topography of Hong Kong is represented by the digital elevation model (DEM) with a resolution of 2 m. Building and podium data describe the urban morphology in terms of building height and coverage as well as geometrical information. Land use data were used to determine the extent of greenery areas in Hong Kong. In addition, a Normalised Difference Vegetation Index (NDVI) image was also used to supplement the greenery data provided by Planning Department (Nichol and Lee 2005).

8.2.4 Structure of the UC-AnMap

The UC-AnMap adopts the GIS platform which allows urban planners to easily assess and utilise the data. The procedures of developing the UC-AnMap are outlined in Fig. 8.3. The acquired data were used to develop the six layers, namely building volume, topography, green space, ground coverage, natural landscape, and proximity

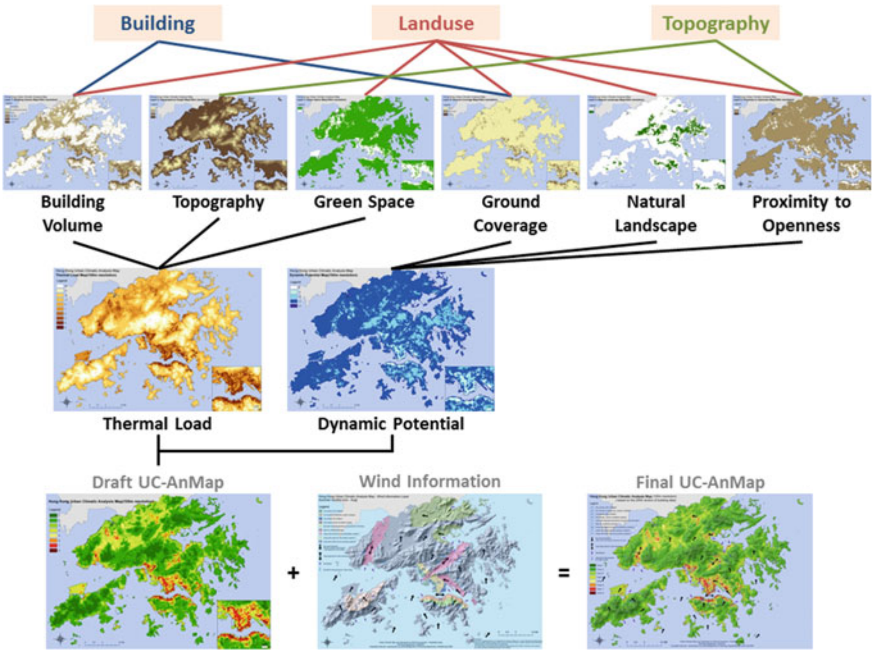

Fig. 8.3 Workflow of the UC-AnMap of Hong Kong

to openness. The layers were then classified into two categories so that the two major components of the draft UC-AnMap, thermal load, and dynamic potential, can be established. With the wind information layer incorporated into the draft UC-AnMap, the final version of the UC-AnMap was obtained.

8.3 User Questionnaire Survey for Outdoor Thermal Comfort

8.3.1 Synergising Indicator: Physiological Equivalent Temperature (PET)

The UCMap of Hong Kong employs physiological equivalent temperature (PET) as a synergising indicator to collate the UC-AnMap since it focuses on outdoor thermal comfort under typical summer conditions of Hong Kong. PET is widely used as a human thermal comfort indicator which is based on the Munich Energy-Balance Model for individuals (MEMI; Fig. 8.4). It is calculated from various climatic and physiological parameters including T_a, relative humidity, solar radiation, air movement, clothing, and metabolic rate in order to give a synergising indication of human thermal comfort in the present study.

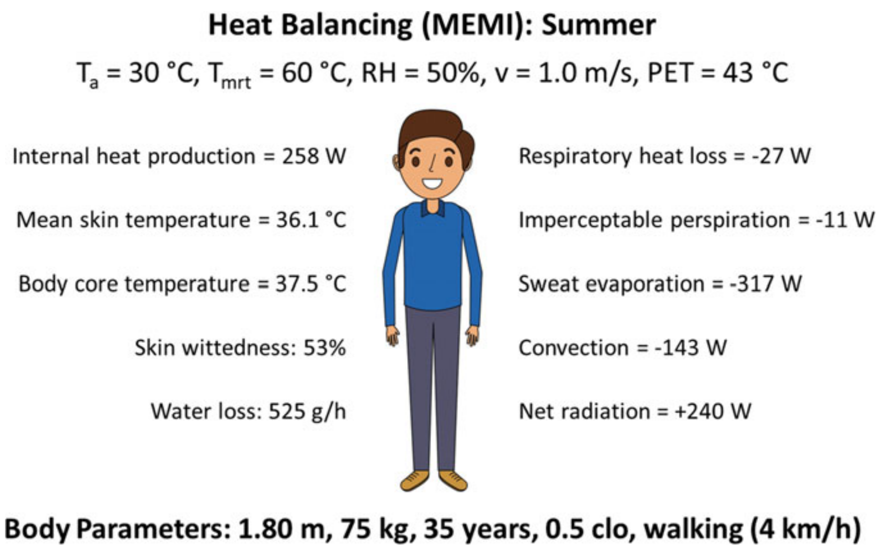

Fig. 8.4 Munich Energy-Balance Model for individuals (MEMI)

8.3.2 Survey Campaign

The objective of the user questionnaire survey is to obtain the subjective perception of outdoor thermal comfort of local citizens in urban areas of Hong Kong. The sites selected in the present study cover a wide range of microclimatic and environmental conditions, based on parameters related to the regional climatic conditions, topographic characteristics, and urban morphology. The parameters considered in the present study include wind environment, ground coverage, street pattern, building height, and building density. Different microclimatic conditions within a survey site were also considered so that the data obtained from the survey include a wide range of microclimatic conditions people encountered in the urban environment of Hong Kong. The selection criteria of survey sites also included different kinds of land uses and activities, including three types of sites, namely pedestrian streets, residential estates, urban parks. These categories take into account the differences in the nature of activities in the survey sites and the psychological expectation of the people within. A total of 2702 responses were collected from September 2006 to August 2007.

The survey campaign consisted of two parts, namely micrometeorological measurements and a questionnaire survey. Mobile meteorological stations were used to obtain the micrometeorological conditions in the surroundings of the respondents. Each mobile station consisted of sensors for the measurement of dry-bulb air temperature, globe temperature, wind speed, and relative humidity. Humidity ratio was derived by air temperature and relative humidity measurements in the analysis. These meteorological parameters were regarded as the main determinants of outdoor thermal comfort (Penwarden 1973; Gagge and Gonzalez 1974; Tacken 1989; Nagara 1996; Sasaki et al. 2000; Lindberg 2004). A TESTO three-function probe was used to measure air temperature, relative humidity, and wind speed. The temperature and humidity sensors were protected from direct sun exposure by a circular white disc made with polystyrene. Globe temperature was measured using a tailor-made globe thermometer consisting of a thermocouple wire (TESTO flexible Teflon Type K) held at the middle of a 38 mm diameter black table tennis ball (Humphreys 1977; Nikolopoulou et al. 1999). These sensors were connected to a TESTO 400 data logger with sampling and logging time of 5 s.

The questionnaire survey consisted of questions addressing the subjects' thermal comfort condition (e.g. thermal sensation and comfort vote) and also record of subjects' demographic background (gender and age), and clothing and activities during the survey. The subjects' thermal sensation and comfort vote were obtained by face-to-face interviews while the subjects' demographic background, clothing, and activities were observed and recorded by the interviewer conducting the surveys. The results of the questionnaire surveys were subsequently correlated with the micrometeorological data to analyse the general thermal comfort conditions in the outdoor spaces and the comfort requirement of the people in Hong Kong. Table 8.1 details the questions asked in the questionnaire survey. The clothing of the subject was recorded by the interviewer using the garment checklist provided in the questionnaire. The checklist was extracted from ASHRAE Standard 55-2010 and ISO Standard 7730

Table 8.1 Questions and responses of the questionnaire survey

	Questions and responses
1	Have you done this survey before? Yes/No (if the answer is "Yes", the survey will be terminated.) • This is to ensure the subject is not repeatedly sampled
2	Have you been staying in Hong Kong in the past 6 months? Yes/No • To understand the subject's mid- and long-term acclimatisation
3	In the past 15 min prior to the survey, have you been to (or stayed in) air-conditioned indoor spaces (cooled or heated spaces including bus, taxi, minibus, etc.)? Yes/No • To understand the subject's immediate past thermal experience
4	What were you doing in the past 15 min prior to the survey? Waiting for people or cars/resting/standing/sitting/working/grocery/shopping/shopping/doing exercises/others • To understand the subject's immediate past activity
5	Why do you choose to sit/stand at this particular place? (can choose more than one item) In shade/under tree cover/under sunshine/breezy/fresh air/views/have an appointment/no particular reason/going to school or work/close to home or office or school or station/others • The reason for the subject to be at the place of the survey may influence their thermal experience
6	How do you feel in terms of thermal perception?
	Very hot/hot/slightly warm/neutral/slightly cool/cold/very cold (7-point scale from + 3 to −3 in accordance with the ASHRAE thermal sensation scale) • To understand the subject's thermal sensation
7	Is the subject's head/body exposed to direct sunlight? (observation by interviewer) Yes/No • To understand if the subject is exposed to direct sun at the time of the survey
8	Overall, what would you say about this place? Reason to understand the subject's perception of the overall comfort Very comfortable/comfortable/uncomfortable/very uncomfortable (4-point scale from + 2 to −2) • To understand the subject's perception of the overall comfort

(Fig. 8.5). Clothing insulation, expressed in the unit clo, is defined as the resistance to sensible heat transfer provided by a clothing ensemble, as the sum of individual garment clothing value.

8.4 Outdoor Thermal Comfort Standard in Hong Kong

The purpose of the thermal comfort survey was to determine the requirements for air ventilation for pedestrians in Hong Kong. As PET is defined by a number of microclimatic variables, the data obtained from the thermal comfort survey were analysed to attain the understandings based on the microclimatic conditions when

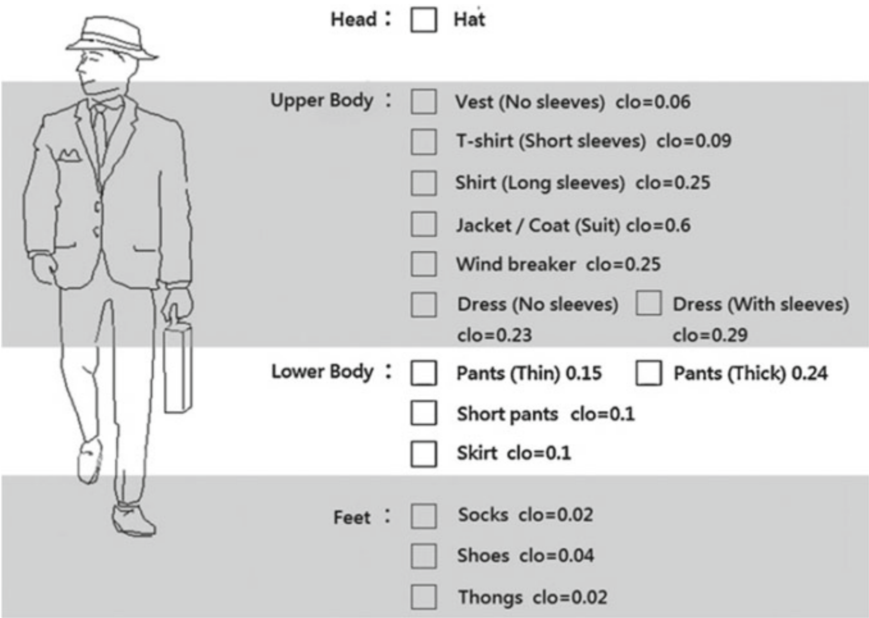

Fig. 8.5 Garment checklist was extracted from ASHRAE Standard 55-2010 and ISO Standard 7730

the survey was conducted. As suggested in Ng and Cheng (2012), the neutral PET for typical summer conditions in Hong Kong is 28.1 °C for outdoor temperature air temperature of 27.9 °C (mean summer temperature of Hong Kong, Fig. 8.6). Using the PET model, a set of possible microclimatic conditions were developed for this neutral temperature (Table 8.2), assuming that the outdoor air temperature of 27.9 °C and relative humidity of 80% (typical summer conditions in Hong Kong). Results show that higher wind speed is required to compensate for the radiant heat load in order to maintain the neutral PET in the outdoor environment. It indicates that for a person standing or walking under shade (mean radiant temperature of 32–34 °C) under typical summer conditions (air temperature of 27.9 °C), a light breeze of 0.9–1.3 m/s is required in order to achieve the neutral thermal sensation.

Findings of the survey also show that the chance of obtaining TS = 0 would be greater when lower air temperature and higher wind speed are combined. It shows that the percentage of the respondents getting TS = 0 increases gradually with an increasing wind speed (Fig. 8.7). As such, there are a number of possible strategies of improving the wind environment and thermal comfort in outdoor environments in the summer:

- To provide a conducive wind environment with wind speeds of 0.53–1.30 m/s in the city through better spatial planning and optimised potential urban development, through building coverage, layout, and disposition;

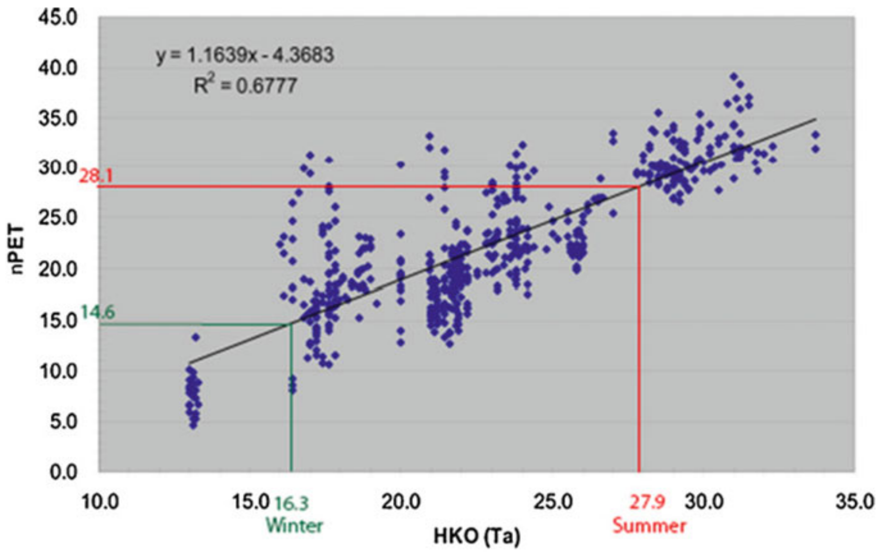

Fig. 8.6 Scatter plot of neutral PET and air temperature recorded at Hong Kong Observatory Headquarter station (Ng and Cheng 2012)

Table 8.2 Microclimatic conditions for neutral PET of 28.1 °C

Air temperature (°C)	Mean radiant temperature (°C)	Wind speed (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

Physiological equivalent temperature = 28.1 °C, Relative humidity = 80%, Clothing = 0.3

- To reduce radiative gains by pedestrians in streets or open spaces by providing sufficient shading opportunities, such as canopies covering building recesses and walkways, as well as colonnades. T_{mrt} under shades is slightly higher than air temperature. For example, a summer temperature of 27.9 °C corresponds to T_{mrt} in the shade of approximately 30–34 °C, whereas T_{mrt} can reach up to 50–60 °C under direct sun exposure; and
- To reduce the localised thermal load through the provision of greening, including trees and their canopies, shrubs, flower beds, and grass areas. The evapotranspiration of plants reduces sensible heat flux and hence air temperature. Urban green

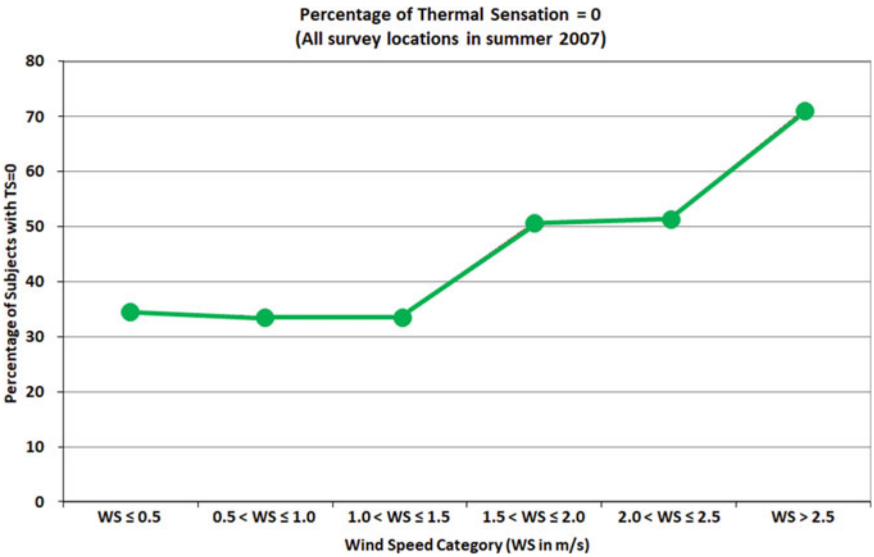

Fig. 8.7 Scatter plot of neutral PET and air temperature recorded at Hong Kong Observatory Headquarter station (Ng and Cheng 2012)

space with a size of approximately 100 × 100 m results in lower temperatures of 2–3 °C than in surrounding streets. Such urban oases enhance the thermal conditions of pedestrian environment for urban dwellers in Hong Kong.

8.5 Collating the Urban Climatic Map

Previous studies suggested that a 1 °C rise in T_a corresponds to an increase in PET by 1 °C. However, PET is also found to be inversely proportional to wind speed so that an increase of wind speed from 0.5 to 1.5 ms^{-1} decreases PET by at most 2 °C. According to Ng and Cheng (2012), the neutral PET value (i.e. human body feels neither cool nor warm) for summer conditions in Hong Kong is 28.1 °C. It provides the basis for the effect of the six parameters (layers) on outdoor thermal comfort and subsequently defines the classification values in the UC-AnMap. Increases or decreases in PET due to the magnitude of an urban morphological parameter allow for a balanced and synergetic consideration formulating the UC-AnMap when all the parameters are collated. It is assumed that a 1-class increase in the parameter would result in an increase in PET by at most 1 °C. Taking building volume as an example, the variation in thermal load due to different volumetric heat capacity of building can result in an increase of PET by up to 4 °C. Therefore, this parameter would have four positive categories from 1 to 4. The two important aspects, namely thermal load and dynamic potential, are collectively considered, by adopting PET as the synergistic element to collate the six layers of the UC-AnMap (Fig. 8.8).

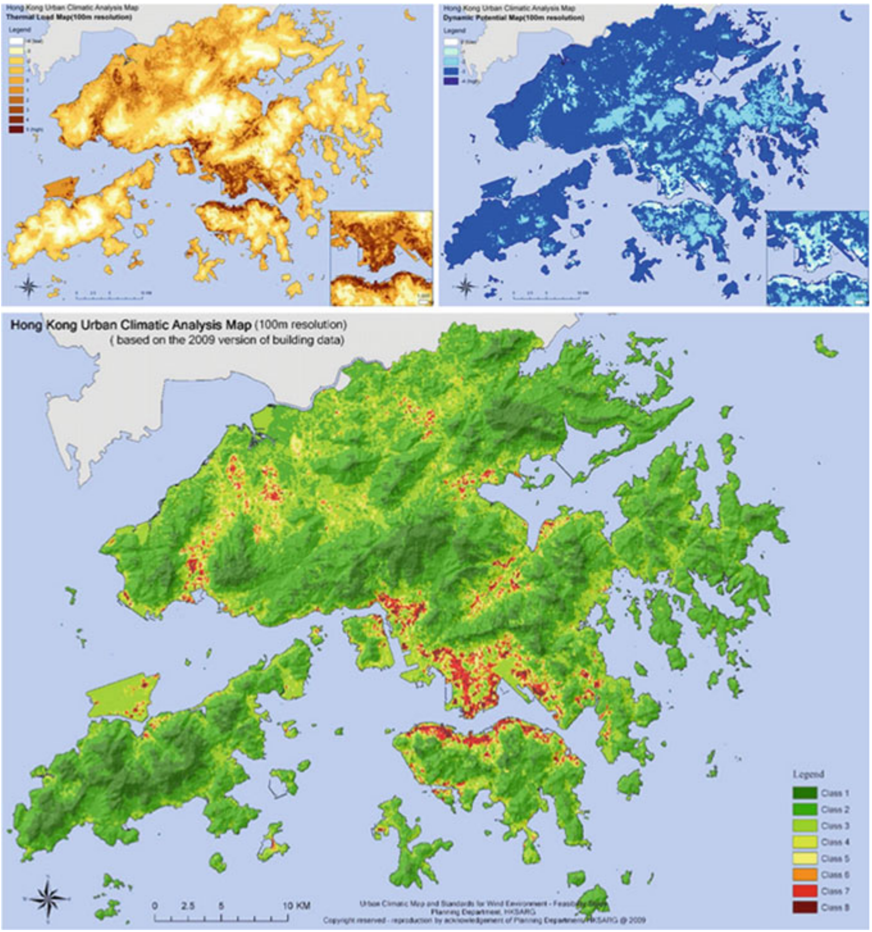

Fig. 8.8 Layers of thermal load (top left) and dynamic potential (top right) constituting the urban climatic analysis map (bottom)

The six basic layers represent three aspects which influence urban climate, including building, land use, and topography. Land use and cover information is generally used as the basic input of UCMap under low-density urban scenario (Mayer 1988; Ren et al. 2011). The mixed land use in high-density cities like Hong Kong requires additional information in order to more accurately define the climatopes (Ng 2009). In the UC-AnMap of Hong Kong, building volume and ground coverage are calculated from urban morphological such as building towers, podiums, street patterns, and open space in order to quantify urban density which affects surface roughness and heat capacity of urban areas (Ng et al. 2008). The fine resolution (100 m grid) can also capture the spatial heterogeneities of urban climatic conditions within a district so that problematic areas can be identified for urban planners and designers to take actions.

Two major components of the UC-AnMap, namely thermal load and dynamic potential, were evaluated for their corresponding implications on the urban climatic conditions of Hong Kong. The urban climatic classes were defined according to the effect of these two components (i.e. six basic layers) on outdoor thermal comfort under summer daytime conditions since it is the most critical situation in terms of thermal comfort and heat stress in Hong Kong (Ng and Cheng 2012). The wind information layer does not only provide information about the prevailing wind conditions but also identifies localised air movements such as land and sea breezes, katabatic wind, and channelling effects. Such information allows urban designers to make efficient use of localised air movements to mitigate the high thermal load in particular areas of the city.

8.6 Conclusions

The UC-AnMap of Hong Kong was developed based on six basic layers with an additional wind information layer. It describes the spatial variation of urban climatic conditions of the city in the context of outdoor thermal comfort under summer daytime conditions. It also summarises the scientific understandings of the effects of various urban morphological parameters on the urban climate which allows urban planners and designers as well as policymakers to better understand the urban climatic environment of the city. Therefore, mitigation measures and action plans can be developed in order to reduce anthropogenic heat release, improve air ventilation, reduce thermal load by shading and greenery, and creating or preserving air paths.

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