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Urban climatic map studies: a review

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ABSTRACT: Since their introduction 40 years ago, worldwide interest in urban climatic map (UCMap) studies has grown. Today, there are over 15 countries around the world processing their own climatic maps, developing urban climatic guidelines, and implementing mitigation measures for local planning practices. Facing the global issue of climate change, it is also necessary to include the changing climatic considerations holistically and strategically in the planning process, and to update city plans. This paper reviews progress in UCMap studies. The latest concepts, key methodologies, selected parameters, map structure, and the procedures of making UCMaps are described in the paper. The mitigation measures inspired by these studies and the associated urban climatic planning recommendations are also examined. More than 30 relevant studies around the world have been cited, and both significant developments and existing problems are discussed. The thermal environment and air ventilation condition within the urban canopy layer (UCL) of the city are important in the analytical processes of the climatic-environmental evaluation. Possible mitigation measures and planned actions include decreasing anthropogenic heat release, improving air ventilation at the pedestrian level, providing more shaded areas, increasing greenery, creating air paths, and controlling building morphologies. Further developments have and will continue to focus on the spatial analysis of human thermal comfort in urban outdoor environments and on the impacts and adaptations of climate change. Mapmakers must continue to share lessons and experiences with city planners and policy makers, especially in the rapidly expanding cities of developing countries and regions. Copyright © 2010 Royal Meteorological Society

KEY WORDS urban climate; climatopes; thermal environment; air ventilation; urban planning; urban climatic map

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1. Introduction

More than half of the world population now lives in urban areas (UNFPA, 2007). By 2030, nearly 60% of the humanity will be urban dwellers (UN, 2008). The rapid urbanization in the past half a century has not only brought new immigrants into the urban areas but has also gradually changed the physical urban environment. Both the landscape transformation and the associated activities of urban areas have modified the city's meteorology and urban climate (Esser, 1989; Lambin *et al*., 1999; Zhou *et al*., 2004; Lam, 2006; He *et al*., 2007), especially the climate below the rooftops of buildings or the urban canopy layer (UCL)(Oke, 1987; Mills, 1997; AMS, 2010). In this layer, the climate is dominated by micro-scale processes and exchanges, which are highly relevant to human comfort and the environmental health of the city (Leung *et al*., 2008; Jendritzky *et al*., 2009). There has been a worldwide vision to design cities that are sustainable, healthy, comfortable, and even enjoyable (UN, 2008). To achieve this goal, it is necessary to understand and apply urban climatic information in the urban planning and design process (Cleugh *et al*., 2009). However, urban climatic consideration has thus far had a low impact on planning (Schiller and Evans, 1990/1991; Eliasson, 2000). There is a need to bridge the gap between urban climatology and town planning and urban design, and to transfer the climatic knowledge into planning languages (Schiller and Evans, 1990/1991; Eliasson, 2000; Alcoforado *et al*., 2009). One important link is to create an information platform for interdisciplinary communication and collaboration.

The urban climatic map (UCMap) is an information and evaluation tool to integrate urban climatic factors and town planning considerations by presenting climatic phenomena and problems into two-dimensional spatial maps (Baumüller *et al*., 1992; VDI, 1997; Scherer *et al*., 1999). It has two major components: the urban climatic analysis map (or synthetic climate function map) (UC-AnMap) and the urban climatic planning recommendation map (UC-ReMap). This concept of UCMapping was first developed by German researchers in the late 1970s (Matzarakis, 2005). To date, there are over 15 countries around the world processing their own UCMap, applying climatic measures and guidelines to local planning practices.

In order to further develop our knowledge and to plan project studies concerning urban climatic planning strategies and application, it is useful to study past

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developments and projects of UCMap. This paper is the first review of the development of the UCMap tool. More than 30 relevant studies in the world are cited, and both significant developments and existing problems are discussed. Selected examples of UCMap studies from different countries are compared and summarized. Secondly, the structure and the map-making procedure of the UCMap are described by citing key examples. The analytical aspects and consideration parameters, as well as any planning instructions and climatic considerations in planning, are elaborated. Thirdly, the advantages and limitations of UCMap studies are discussed critically. Finally, the review delineates the opinions of the authors on the future of UCMap research and application. There is still the need to apply and to refine the methodology, and it is important to continue the communication and implementation of results in collaboration with city planners.

2. Review of the development of UCMap study

In the field of UCMap study, German researcher Prof. Knoch (1951, 1963) first proposed a climate-mapping system for planning purposes. He suggested a series of UCMapping with different scales in his publication *Die Landesklima-aufanhme,* which should be fitted into the local planning system. Since the 1970s, West Germany has intensified its geoscientific activities in presenting maps relevant to planning (Lüttig, 1972, 1978a, 1978b). Stuttgart climatologists led by Dr Baumüller were the first to conduct UCMap studies for mitigating air pollution problems under weak wind conditions, and to apply the climatic knowledge into land use planning and environmental planning (Baumüller and Reuter, 1999; Baumüller, 2006).

In the 1980s, with the aim to control heavy metal pollution in the old industrial areas of the Ruhr, the Association of Local Authorities of Ruhr Areas (Kommunalverban Ruhrgebiet: KVR, 1992) implemented clean air management programs using the UC-AnMap to differentiate the areas according to their different climatic functions and characteristics. More than 25 cities in the Ruhr Areas were involved in this project; they included Dortmund (Stock *et al*., 1986; Littlefair *et al*., 2000), Essen (Stock and Beckröge, 1985), Bochum (Stock and Beckröge, 1991), Duisburg (Baumüller and Reuter, 1999), Recklinghausen (Beckröge *et al*., 1988), and so on. With the aim of planning applications, this project was the first to relate urban climatic factors with spatial information and urban structure, and, based on the land use information and their climatic characteristics, it defined the various Climatopes, which present different urban climatic conditions as a spatial unite of UCMap. Meanwhile, in the Federal State of Bavaria, a comprehensive research project named '*STADTKLIMA BAYERN*' (Urban Climate of the State of Bavaria) was carried out in Augsburg, München, and Nürnberg/Fürth/Erlangen/Schwabach. This project aimed to investigate the impact of built-up areas and greenery on the urban climate and air quality of study areas. Analysis of the thermal image and meteorological data was conducted, and the car traverse measurement was also carried out for examining the air temperature profile of urban areas. A geographical distribution of topography, aerial views, thermal image, real land use, and urban air paths were synergized and mapped with a grid resolution of 250 m × 250 m with map drawings done manually (Mayer, 1988; Matzarakis, 2005; Matzarakis and Mayer, 2008).

In the 1990s, after the re-unification of Germany, several cities in the northern part of the country conducted synthetic climate function mapping (VDI, 1988; Helbig *et al*., 1999; Matzarakis, 2005). Since 1992, the Section of Urban Climatology of the Office for Environmental Protection in Stuttgart has conducted a series of climate analysis studies, consequently providing a set of climatic atlases for Neighborhood Association Stuttgart (Klimaatlas Nachbarschaftsverband Stuttgart), including synoptic maps, thermal maps, emission maps, climatic analysis map, and UC-ReMap in the geographic information system (GIS) (Klimaatlas, 1992). Thus, local planners could easily assess various climatic information and evaluation results using the Stuttgart UCMap. The project 'STUTTGART 21' developed over one hundred climatic map layers at diverse scales that could be implemented at regional, city, and district planning levels. In Berlin, another project titled 'Berlin Digital Environmental Atlas' has been conducted since 1995. The UCMap, as one of its eight environmental topics, has been produced for planning purposes to assist the design of settlement areas, green and open space, to control traffic-related air pollution, and to improve the air exchange of the urban areas (Berlin Government, 2008). For guiding practice in Germany, the National Guideline-VDI 3787: Part 1, namely, *Environmental Meteorology Climate and Air Pollution Maps for Cities and Regions*, was published in 1993 by the workgroup of UCMap at the German National Committee of Applied Urban Climatology. It aimed to define the symbols and representations used in UCMap studies to recommend methods of developing urban climatic and air pollution maps, and to create a standard for their application. Thus, this Guideline-VDI 3787 has become an important reference not only for German studies but also for studies worldwide.

From the mid-1980s, countries in Europe, such as Switzerland, Austria, Sweden, Hungary, Czechoslovakia, Poland, Portugal, and the United Kingdom have carried out UCMap studies (Sterten, 1982; Lindqvist and Mattsson, 1989; Paszynski, 1990/1991; Lindqvist, 1991; Parlow *et al*., 1995, 2001a; Scherer *et al*., 1999; Radosz and Kaminski, 2003; Ward, 2003; Unger, 2004; Hsie and Ward, 2006; Hsie, 2007; Gal and Unger, 2009; Smith *et al*., 2009). Following significant heat wave events in 2003 and 2006, many other European countries have begun climate-change-related spatial planning studies based on the UCMap framework. In France, for example, a multi-disciplinary study on the impacts of climate change, namely the EPICEA Project, has been conducted

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since 2008 for understanding the 2003 summer heat wave over Paris by mapping its vulnerability (Desplat *et al*., 2009). In this project, excess mortality data, together with selected environmental parameters, including surfaces of roof material and built, green, and water surfaces, have been considered and mapped as input analysis layers. Similar research programs have also been carried out recently in the Netherlands (ERDF, 2009; The Knowledge for Climate Research Programme, 2007).

UCMap has also been adopted and developed in South America (Evans and Schiller, 1990/1991; Nery *et al*., 2006) and in Asian countries since the 1990s (Ashie *et al*., 1998; Gao and Ojima, 2003; Jittawikul *et al*., 2004; Tan *et al*., 2005; Nery *et al*., 2006; Kim, 2007; Ng *et al*., 2009). Japan, with assistance from German researchers, has pioneered UCMap study in Asia. Major metropolitan areas in Japan such as Osaka, Kobe, Yokohama, Sendai, Fukuoka, and others have conducted UCMap studies and projects (Moriyama and Takebayashi, 1998; Yoda and Katayama, 1998; Ichinose *et al*., 1999; Moriyama and Takebayashi, 1999; Tanaka and Morlyama, 2004; Tanaka *et al*., 2004; Murakami and Sakamoto, 2005; TMG, 2005b; Yoda, 2005, 2009; Yamamoto, 2006; Mochida *et al*., 2007; Moriyama and Tanaka, 2008; Tanaka *et al*., 2009). Japan's Ministry of the Environment (MOE) and the Ministry of Land, Infrastructure, and Transport (MLIT) have been working actively on UCMap since 2000 (MOE, 2001, 2002, 2003, 2004, 2005, 2006, 2007, 2008). In 2005, the Tokyo Metropolitan Government (TMG) created and published the Thermal Environmental Map for Tokyo's 23 Wards, and developed relevant control measures and mitigation guidelines (TMG, 2005a, 2005b; Sera, 2006; Yamamoto, 2006, 2007). With the aim of mitigating the urban heat island (UHI) effect, these studies focused on analysing urban thermal environment from the aspects of anthropogenic heat release, surface cover, urban structure, and green space (AIJ, 2008a). In 2000, the Architectural Institute of Japan edited a reference book to introduce the methodology of UCMap, and to share the relevant research experiences based on various local case studies in Japan (AIJ, 2000).

Thus far, most UCMap studies have focused on low- and medium-density cities. Since 2006, the research team led by Professor Ng from the Chinese University of Hong Kong has worked to implement the UCMap studies for high-density urban scenarios. They have constructed a UCMap study for Hong Kong based on thermal load, dynamic potential, and wind information considerations (Ng *et al*., 2009). Their studies linked urban climatology, urban morphology, and planning parameters together, not only by relying on land use information as typically practiced in low- and medium-density city studies in Germany but also by using detailed building block and planning information such as building volume (measured by a building's external dimensions) and ground coverage ratio (defined as the buildable area over the total ground area). Both of the above are planning parameters used to analyse the impact of building density on urban climatic condition. The effort has taken into account biometeorology based on user survey and physiological equivalent temperature (PET) (Höppe, 1993, 1999), a thermal index and a synergetic indication of human thermal comfort to calibrate the classification of Hong Kong UCMap, has been used.

On the basis of the chronology of UCMap studies in the world (Appendix), more than 15 countries have conducted their own UCMap studies. Recently, UCMap has attracted increasing interest in the world (Figure 1). For example, researchers in China, Chile, Singapore, Macau, France, and the Netherlands are starting relevant projects and studies in pursuit of urban climatic information for good planning and sustainable development (Katzschner and Mulder, 2008; Wong and Jusuf, 2007; Ban *et al*., 2009).

3. The structure of the UCMap system

The UCMap system consists of a series of basic input layers and two main UCMap components (Figure 2). The

Figure 1. UCMap studies around the world. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

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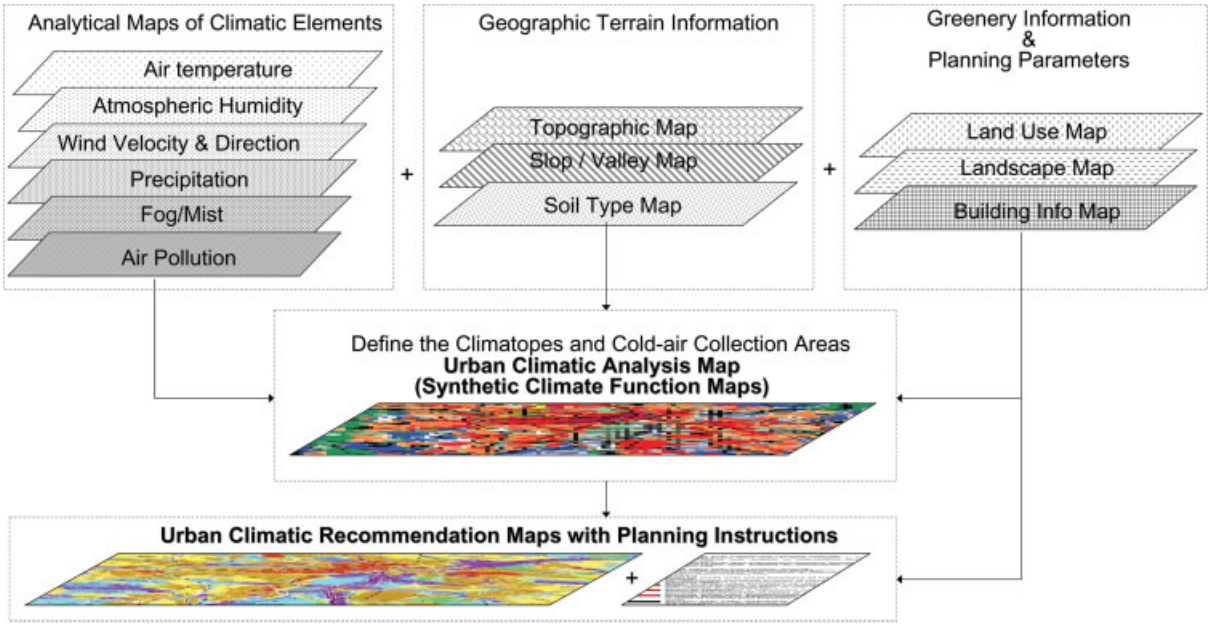

Figure 2. Structure of UCMap. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

basic input layers contain analytical maps of climatic and meteorological elements, geographic terrain data, greenery information, and planning parameters. There are two main UCMap components: the UC-AnMap, which visualizes and spatializes various climatic evaluation and assessment by different Climatopes, and the UC-ReMap, which includes planning instructions from the urban climatic point of view.

3.1. Urban climatic analysis map

The UC-AnMap provides a platform for climatic information and evaluation. It is also named 'Synthetic Climatic Function Map', summarizing and evaluating the 'scientific' understanding based on the input climatic parameters and land data under annual or specific seasonal scenarios (Stock *et al.*, 1986; Beckröge *et al.*, 1988; Stock and Beckröge, 1991; Wirtschaftsministerium Baden-Württemberg, 1993; Lazar *et al.*, 1994; Baumüller and Reuter, 1999; Littlefair *et al.*, 2000). As planners are used to reading maps and working on plans, different coloured graphics, arrows, and symbols with simple explanations in UC-AnMap present the analysis results of climatic conditions and variations. The UC-AnMap relies on careful collection and collation of meteorological data (long-term temperature, precipitation, wind, cloud, and solar radiation data), planning, land use, topography, and vegetation information, according to their relationships and effects on the energy balance on the pedestrian level to present local climatic variations at the meso- and micro-climatic scale. Thus, technically measured collections of selected climatic and geographic parameters are input as basic analytical maps to present regional and local meteorological conditions. These data and information are collected from the meteorology station and infrared aerial images, and from the simulation results of macro- and meso-scale calculation models, especially on air flow analysis and energy balance. For example, in Freiburg, researchers used the flow simulation model to understand and analyse the cold air flow from the Black Forest to the downtown areas (Röckle *et al.*, 2003). Another type of useful input information is topographic terrain data, mainly derived from the digital elevation model (DEM), which could also help in building up the calculation models and visualizing the ground terrain situations.

There are three climatic analytical aspects of UC-AnMap (Table I). The first, the wind environment, focuses on capturing the local air circulation patterns (e.g., channelling wind, land and sea breezes, mountain and valley wind, and local prevailing wind directions), existing and potential air paths, ventilation zones (e.g. cold air production zones), and the location of barrier effects by buildings or plants. The second, the thermal environment, focuses on analysing the UHI effect and the urban bioclimatic variations, especially the areas with cold or heat stress. The third focuses on exploring the areas of air pollution. Because these analytical aspects are taken as the basic input layers, studies on thermal environment, air ventilation, and air pollution situation within the UCL play a crucial role in forming the comprehensive understanding of the current urban climatic condition.

On the basis of the comprehensive understanding of the basic input information and analysis result, the climatopes as a basic unit of UC-AnMap could be defined to represent a spatial distribution of urban climate types that are the product of distinct urban land use and cover (Baumüller *et al.*, 1992; VDI, 1997). They vary from place to place depending on what the climate-based issues are at that location. Their spatial scales commonly range from several tenths to hundredths of metres (Scherer *et al.*, 1999; Alcoforado *et al.*, 2009). In the early days of UCMap studies, the types of

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Table I. Climatic Analysis and Phenomena in an UCAnMap (Katzschner, 1998; VDI, 1997).

UCMap Component	Climatic Characteristics & Phenomena		Climatic Analysis Scale
Urban Climatic Analysis Map	♦ Analysis of the local air circulation pattern (e.g., channeling wind, land, and sea breezes, mountain and valley wind) ♦ Analysis of the local prevailing wind direction ♦ Analysis of the existing and potential air paths ♦ Analysis of the ventilation zones (cold air production zones) ♦ Analysis of the location of barrier effects by buildings or plants	Wind (ventilation) Aspect	Meso- (regional)and micro-Scale (city and urban)
	♦ Analysis of the areas of urban heat island effect ♦ Analysis of the urban bioclimatic variations, especially the location of areas with cold or heat stress	Thermal Aspect	
	♦ Analysis of the air pollution of the area.	Air Pollution Aspect	

climatopes were commonly classified by urban land use(VDI, 1997). The development process of climatopes mainly relies on expert knowledge and qualitative and subjective assessment. For instance, in the UC-AnMap of Stuttgart city, German climatologists developed 11 categories of climatopes, including water surface, open land, forest, park, country, suburbs, city, city centre, small factory, factory, and railway (Figure 3). On the basis of the analysis of meteorological data, remote-sensing information, cold air flow simulation, and digital wind field simulation at the meso-scale, it was noted that the boundaries of different climatopes are not fixed in reality (Stanhill and Kalma, 1995). Thus, the boundary between two climatopes only shows the possible range of two neighbouring urban climatic conditions.

In some recent cases, calibration and verifications studies have been conducted for better understanding the distribution pattern of climatopes of the study areas and quantitatively defining climatopes. For example, in Japan, Moriyama and Takebayashi (1999) used a one-dimensional calculation model of the earth surface heat budget to discriminate the minimum temperature of each city area and define the climatopes of the Kobe UCMap. Meanwhile, in the study of UCMap for Basel, Swiss researchers utilized satellite images to analyse different urban physical surface properties and land use information for understanding the daily thermal variation and surface roughness and automatically defining the climatopes (Scherer *et al*., 1999). In the study of the Berlin Digital Environmental Atlas, the prognostic three-dimensional model named FITNAH (flow over irregular terrain with natural and anthropogenic heat sources) has been used to calculate the detailed wind and temperature conditions in Berlin (Groß, 1993; Richter and Röckle, 2009). The field measurement results were compared with the simulation results of the model application (SDUDB, 2008); they were found to be in good agreement (Figure 4).

Most UCMap studies in the world focus on low-density urban scenario. There is lack of application of UCMap studies to the urban planning of high-density city. Since 2006, Prof. Ng's research team with international professionals has attempted to adopt this method into the high-density urban scenario of Hong Kong for improving the thermal environment and urban ventilation in future development. Given the mixed land use situation in high-density cities, it noted that defining the climatopes merely based on land use and cover information needed to be improved and new thoughts and methods were required(Ng, 2009a). Thus, for the UC-AnMap of Hong Kong, not only land use, topography, vegetation, and wind information have been take into account but also further detailed urban morphology information, such as building tower, podium, street, and open space, have been incorporated to calculate the building volume and ground coverage for quantifying the urban density, which affects the urban surface roughness and heat capacity (Ng *et al*., 2008b). On the basis of the analysis of these selected planning parameters, three basic analytical input layers (building volume, ground coverage percentage, and the proximity of openness) are generalized with the fine resolution of 100 m $\times$ 100 m per grid. The efforts of the Hong Kong UCMap study follow an urban air ventilation study conducted in 2006 (Ng, 2009b). The climatic condition of a high-density city like Hong Kong is very complicated; therefore, Hong Kong researchers have also conducted spot field measurements, user surveys of thermal comfort, and model simulations and wind tunnel studies for calibrating the urban climatic understanding (Ng *et al*., 2008b). The basic layers of climatic factors and geographical parameters have been synergized to become the Hong Kong UC-AnMap (Figure 5). The Hong Kong UC-AnMap contains eight Urban Climatic Analysis Classes as Climatopes, categorized by the spatial distribution of PET to illustrate the urban climatic

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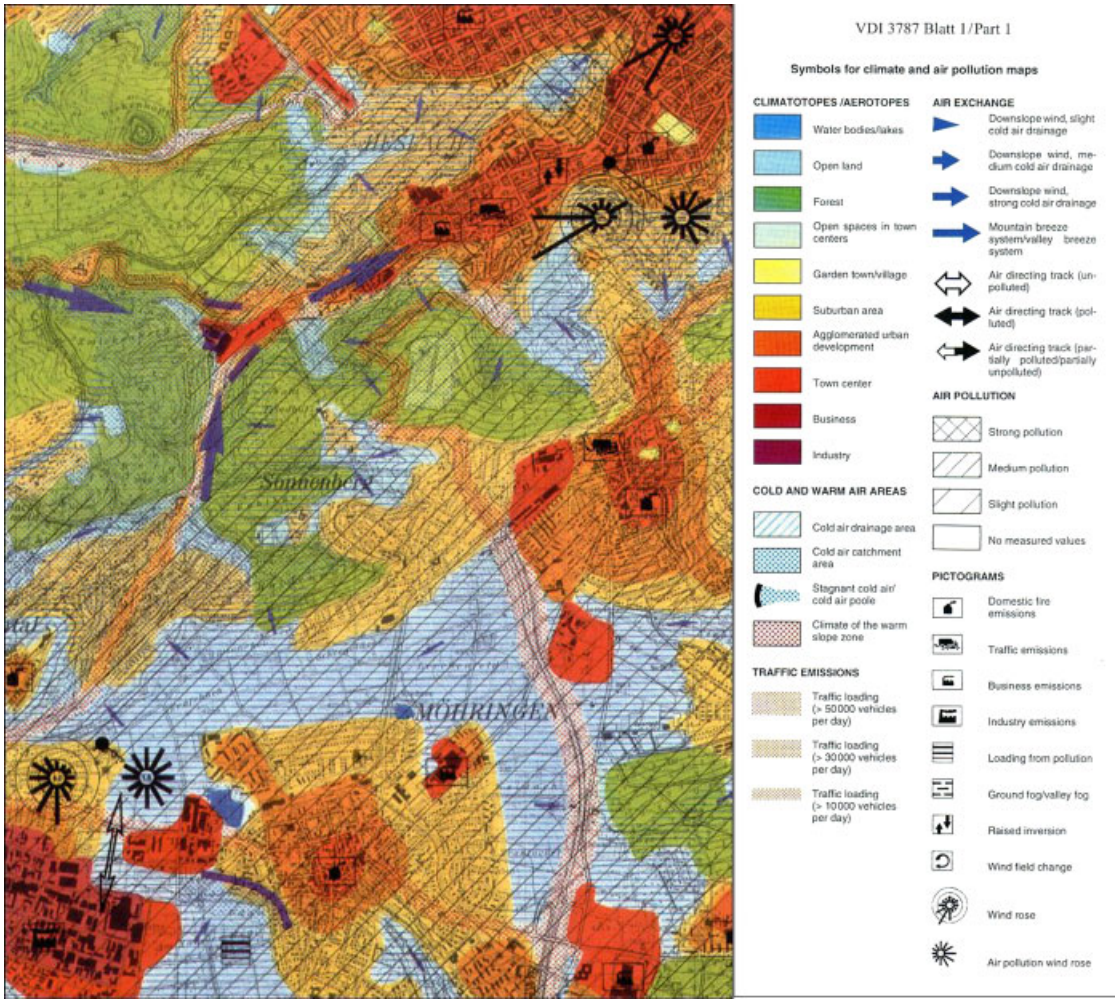

Figure 3. A partial plan of the UC-AnMap and legend for Stuttgart urban areas (Klimaatlas, 1992; VDI, 1997). This figure is available in colour online at wileyonlinelibrary.com/journal/joc

value and inhomogeneous high-density urban context under summer daytime condition (Table II). The map provides the planners a spatial overview of the urban biometeorological characteristics of the territory of Hong Kong under the condition of typical summer daytime. According to the UC-AnMap, clusters of Urban Climatic Analysis Classes 7 and 8 illustrate highly built-up urban areas as problem areas from the bioclimatic point of view, which create the need for improvement at the district level of planning implementation (Ng *et al*., 2008a). This implies that people in the outdoor environment of these urban areas may suffer high thermal load (stress) and less wind (low dynamic potential) at the pedestrian level. For calibrating and verifying the result of climatopes of UC-AnMap of Hong Kong, local researchers conducted some relevant studies, such as spot field measurements, model simulations, and wind tunnel tests (Ng *et al*., 2008b, 2008c). The result of the field measurement studies in the urban areas of Tsuen Wan and Tsim Sha Tsui has provided useful data as reference for calibrating the classification of the climatopes of the UC-AnMap for Hong Kong. It has been noted that 1 ΔUCMap Class equals to 1 °C of PET value, and that this correlation is strong ($R^2 \approx 0.74$) (Ng *et al*., 2008b, 2008c). From this study, it was derived that the classification of the climatopes of the UC-AnMap of Hong Kong and the predicted human comfort pattern in UC-AnMap in terms of PET were in good agreement with the real urban climate condition of the city.

3.2. Urban climatic recommendation map (UC-ReMap) and planning instructions

The UC-ReMap is an integrated, planning-action-oriented assessment base that could be operated at the city or the district scale. On the basis of the analysis obtained from the UC-AnMap, similar climatopes are grouped into zones to present the sensitivity of certain land areas affected by land use changes. These zones are represented by different colours and symbols, which show different hints for plan of action such as 'Place that requires improvement' or 'Place that should be conserved', from the urban climate point of view (Baumüller *et al*., 1992) (Figure 6). Detailed principles of developing the UC-ReMap and planning recommendations are presented in Table III.

The development process emphasizes the 'translation' from UC-AnMap to UC-ReMap to ensure that the

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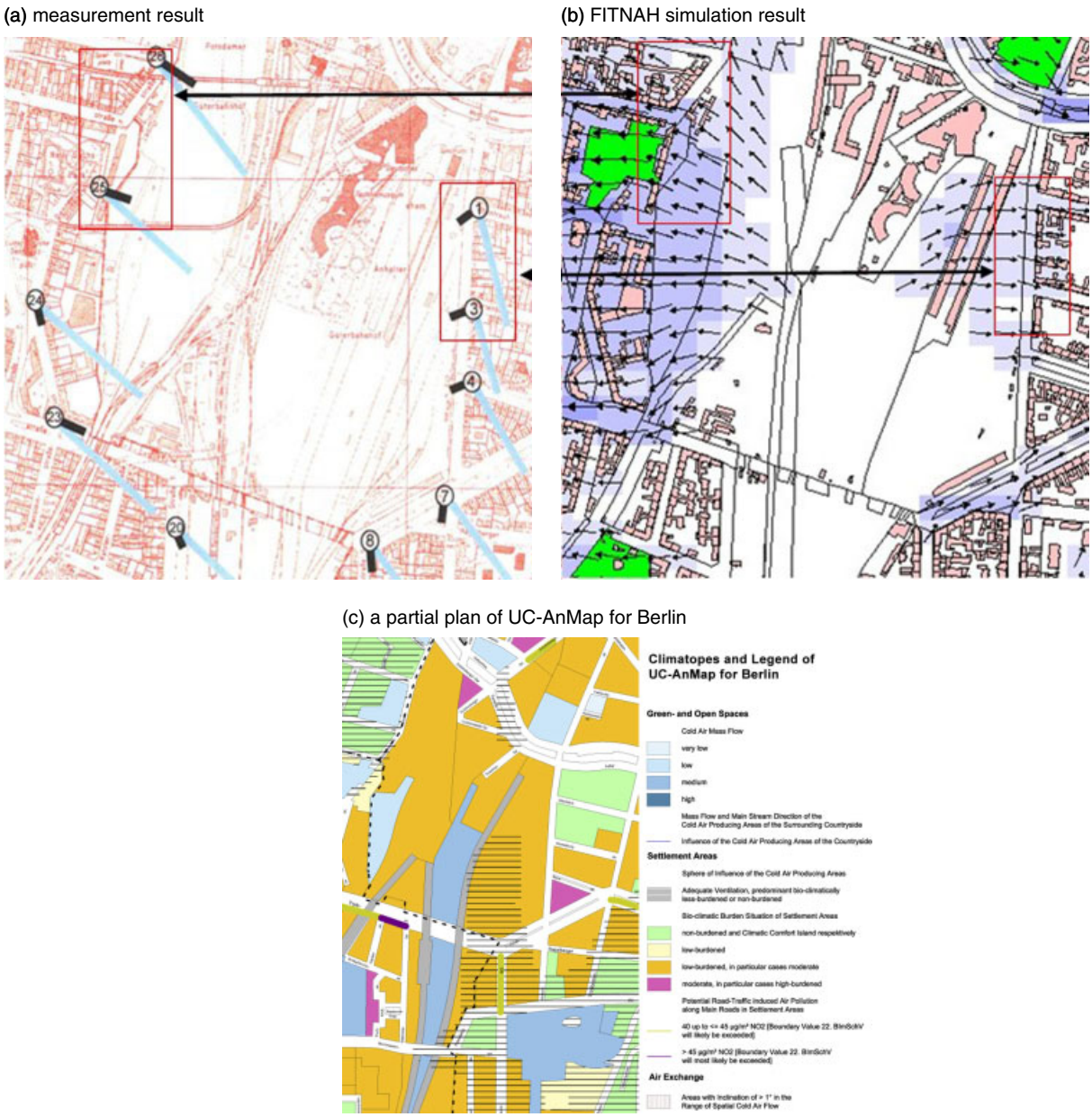

Figure 4. Verification of the climatopes of Gleisdreieck areas: (a) measurement result, (b) FITNAH simulation result, (c) a partial plan of UC-AnMap for Berlin (Vogt, 2002a, 2002b; SDUDB, 2008). This figure is available in colour online at wileyonlinelibrary.com/journal/joc

climatic knowledge and evaluation results are correctly presented in urban planning language. The UC-ReMap not only presents the evaluation of current climatic characteristics spatially but also identifies problem and climate-sensitive areas that are in need of strategic attention and further development. Therefore, at this stage, urban climatologists, planners, and policy makers need to work closely together. Planning recommendations and guidelines are developed with the aim of mitigating negative and protecting positive situations. As different cities have various urban planning systems and urban climatic problems, the implementation of UC-ReMap and planning recommendations may require emphasis on different aspects.

There are many vegetated hillsides around Stuttgart, and katabatic wind can be observed during the night. For protecting such kind of cold fresh air, the UC-AnMap of Stuttgart defined the cold air drainage areas. For example, one is located in Vaihignen areas (highlighted with a red circle in Figure 7(a)). As such, when the UC-ReMap was developed, further development was recommended to respect the local air exchange and to protect this area as an open site with significant climatic activity, while considering intervention changes in land use (Figure 7(b)). Local planners then revised the original land use plan of this area from buildable land to private and public greenery (Figure 7(c) and (d)). Currently, this area works as an air path (or ventilation corridor) to transfer the cold air mass to the surrounding areas (Figure 7(e) and (f)). The implementation of the UC-ReMap has also been applied to update the master plan of greenery, control building height, and create/protect air paths. Stuttgart UC-ReMap

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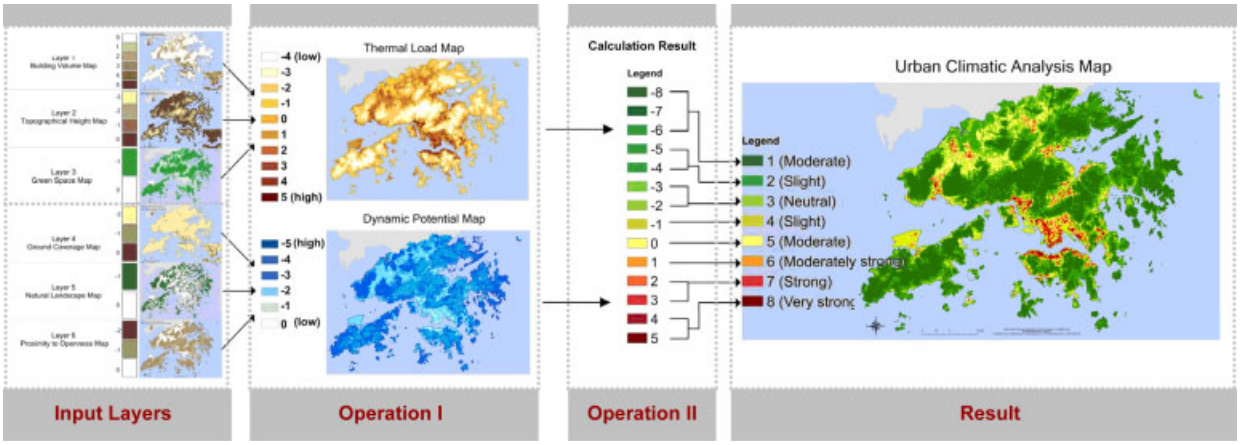

Figure 5. The working process of the UC-AnMap of Hong Kong (Ng *et al*., 2008a). This figure is available in colour online at wileyonlinelibrary.com/journal/joc

Table II. Description of Eight Urban Climatic Classes of the UC-AnMap of Hong Kong (Ng *et al*., 2008).

	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		

Note: • "cooling" impact
• "warming" impact
1 moderately negative Thermal Load due to higher altitude and adiabatic cooling, and greenery and trans-evaporative cooling
2 some negative Thermal Load due to vegetated slope and trans-evaporative cooling
3 to **8** various classes of warming impact due to increasing Thermal Load and decreasing Dynamic Potentials

contains the 'first-cut' nature of the zone boundaries and the general planning recommendations; therefore, it provides a useful reference for local planners in their actual practices. When further details are required, they could refer to the UC-AnMap together with their urban climatic advisers.

According to the thermal environment map (TEMap) (Figure 8), the TMG designated four focus areas with high UHI intensity and weak urban ventilation situation: the districts of Shinjuku, Urban Center, Osaki/Meguro, and Shinagawa Station. On the basis of this TEMap of Tokyo, the local government could invest appropriately for planning improvement action and research projects and conduct appropriate plan action to mitigate the UHI and improve poor urban ventilation in central Tokyo, such as increasing greenery converge, controlling frontal areas of building blocks, and decreasing anthropogenic heat release. The Japan Sustainable Building Consortium has worked with the MLIT to develop the national guideline of the Comprehensive Assessment System for Building Environmental Efficiency for Heat Island Relaxation (CASBEE-HI), assessing efforts exerted in buildings to alleviate the heat island effect in the surroundings (IBEC, 2006). Later, the study of 'Kaze-no-michi' was conducted by MLIT to form a scientific basis for urban air temperature and wind characteristics at ground level for Tokyo Metropolitan, and to analyse the impact of urban ventilation path and the cooling effect of sea breeze (AIJ, 2008b; Ashie *et al*., 2008).

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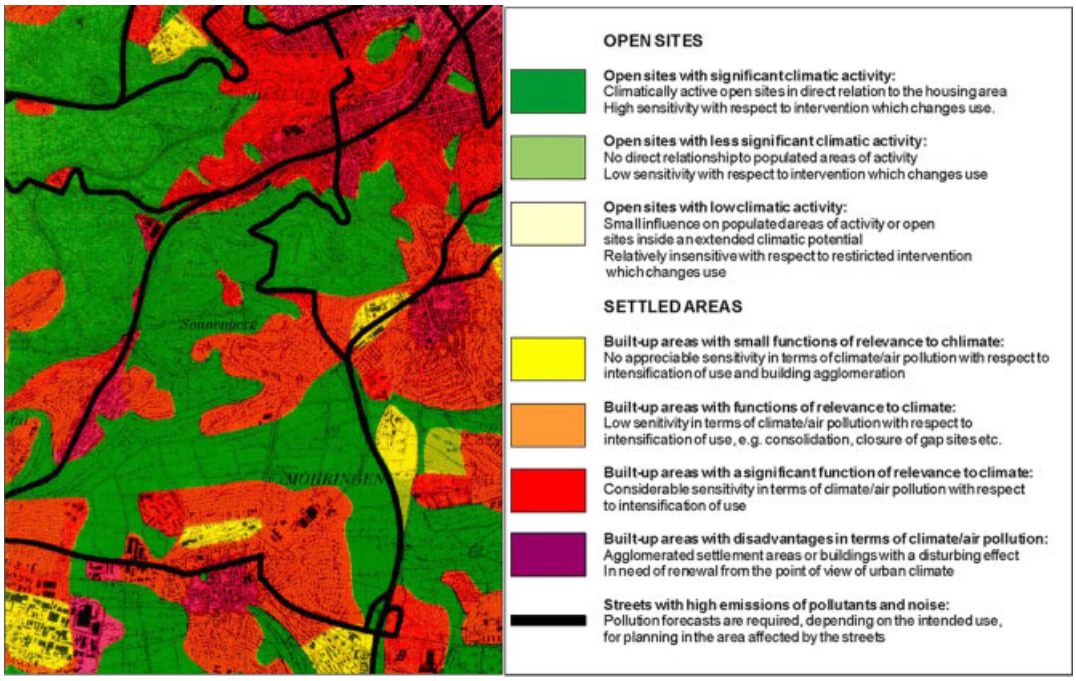

Figure 6. A partial plan of the UC-ReMap of Stuttgart city (Klimaatlas, 1992; VDI, 1997). This figure is available in colour online at wileyonlinelibrary.com/journal/joc

Table III. Analysis Aspects and Highlighted Zones of an UCReMap (Baumüller *et al*., 1992; VDI, 1997).

Type of UCMap	Zones with Septic Land Use	Climatic Impact and Function		Planning Level and Scale
Urban Climatic Recommendation Map	♦ Forest and wood lands on hill slopes or valleys	Generates and transfers cold/fresh air;	Wind Aspect	Municipality/City Master Plan (1 : 10 000–1 : 25 000)
	♦ Vegetation on the borders of built-up areas	Contributes to air exchange		
	♦ Large green belt and interconnected green space or network	Contributes to air exchange and transfers cold/fresh air from rural areas to urban areas		
	♦ Open space sensitive to the change of land use	Transfers cold/fresh air and improves the air exchange		
	♦ Built-up areas	Blocks air exchange		Zoning Plan (1 : 5 000–1 : 10 000)
	♦ Railway and several wide streets	Contributes to air exchange		
	♦ Urban greeneries and their surrounding areas	Mitigates urban heat island effect	Thermal Aspect	Landscape/Land Use Plan (1 : 5 000–1 : 10 000)
	♦ Open space	Mitigates urban heat island effect		
	♦ Built-up areas	Contributes to urban heat island effect		
	♦ Highly built-up areas	Processes heat thermal load		
	♦ Industrial and commercial areas	Causes air pollution and noise	Air Pollution Aspect	
	♦ Main traffic roads	Causes air pollution and noise		

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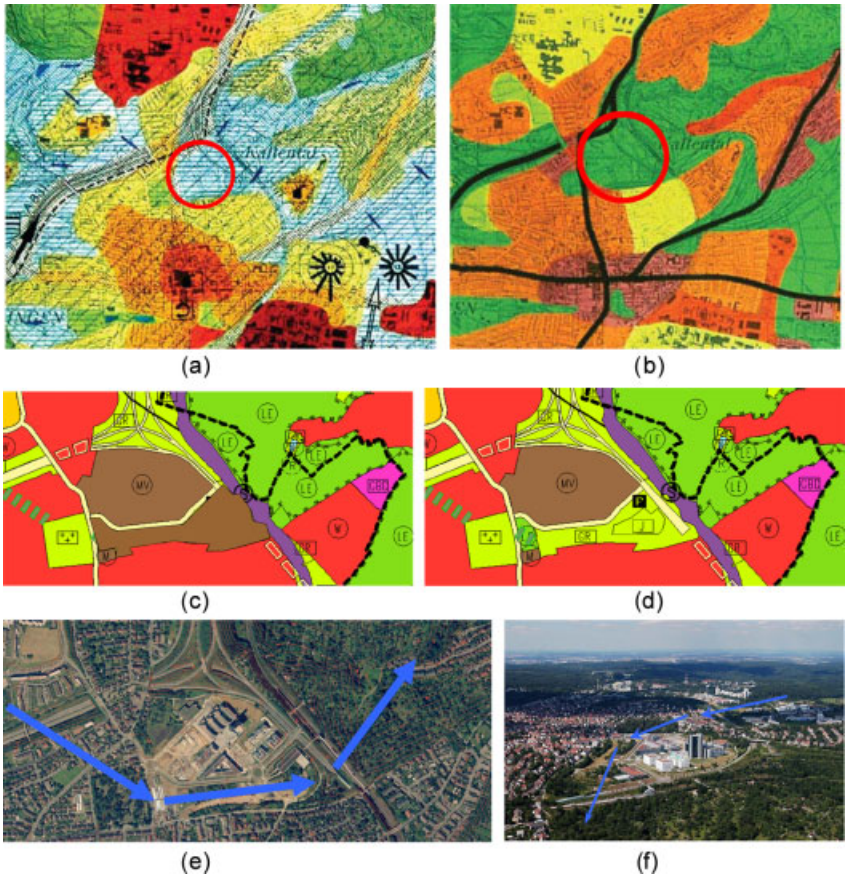

Figure 7. Successful implementation example of Stuttgart UCMap study: (a) UC-AnMap of Stuttgart, (b)UC-ReMap of Stuttgart, (c) original land use plan, (d) revised land use plan, (e) air path and (f) ventilation zone (Baumüller *et al.*, 1992; Baumüller, 2006). This figure is available in colour online at wileyonlinelibrary.com/journal/joc

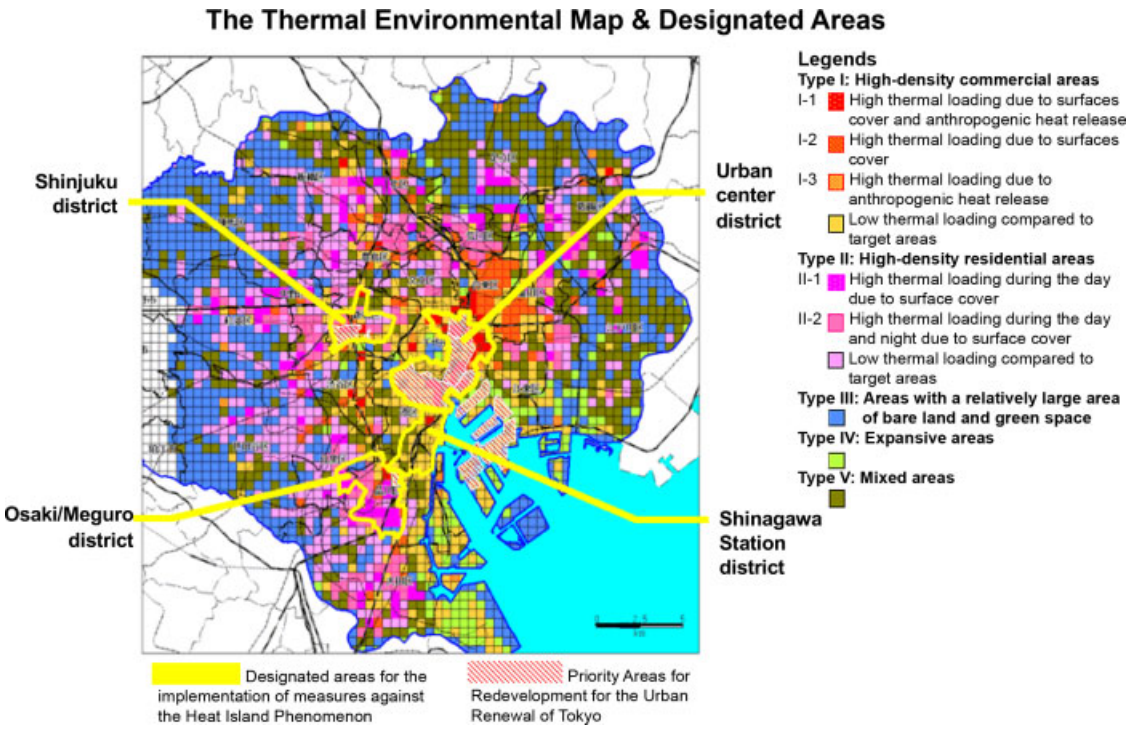

Figure 8. Thermal environmental map for Tokyo's 23 Wards and four designated areas(TMG, 2005b). This figure is available in colour online at wileyonlinelibrary.com/journal/joc

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Table IV. Lessons on strategies and measures for improving urban climate environment.

Objectives	Aspects	Action Plans and Strategies	Operation and Spatial Scale	Climatic Impact Scale
Bioclimate + urban heat island + urban air ventilation + air quality situation	Albedo	Cooling of building material and pavement	Material and surface-level intervention	Meso- and micro-scale
		Cooling of roof and facade		
		Water retention paving		
	Vegetation	Planting greeneries	Material and surface-level intervention	Meso- and micro-scale
		Parks and open spaces	Landscape/land use planning-level intervention	
		Green corridors	Landscape/land use planning-level intervention	
	Shading	Building geometric design	Building design-level intervention	Micro-scale
		Shelter design	Building design-level intervention	Micro-scale
		Street orientation	Urban planning/zoning-level intervention	Meso- and micro-scale
		Building height/Street width ratio	Building design-level intervention	Micro-scale
		Trees along both sides of streets	Landscape/land use planning-level intervention	Micro-scale
	Ventilation	Air path	Urban planning/zoning-level intervention	Meso- and micro-scale
		Building ground coverage and building bulks	Urban planning/zoning-level intervention	Meso- and micro-scale
		Building height/Street width ratio	Building design level intervention	Micro-scale
		Street orientation	Urban planning/zoning-level intervention	Meso- and micro-scale
		Layout of building dispositions	Urban planning/zoning-level intervention	Meso- and micro-scale
		Open spaces and greenery areas	Landscape/land use planning-level intervention	Meso- and micro-scale

The UC-ReMap of Hong Kong provides information for strategic and district planning at outline zoning plan with the scale of 1 : 2000. Given the high-density context of Hong Kong, the useful strategy planning instructions and recommendations focus on reducing ground coverage for improving air ventilation and pedestrian comfort, and on improving greenery coverage to the urban areas.

On the basis of the above reviews, it was found that planning instructions and recommendations can be elaborated with the help of UC-ReMap. As the goals of climate-sensitive planning need to be pursued to improve the living conditions and the quality relative to the bioclimate, UHI, urban air ventilation, and air quality situation, the main planning recommendations need to focus on the following aspects: reducing urban thermal (heat) load; controlling building volumes and sealing areas; improving urban dynamic potentials; preserving, maintaining, and improving the existing urban ventilation paths and network of the city, and charting new air paths if necessary; preserving, maintaining, improving, and respecting the cold air production and drainage areas of the countryside and vegetated hillsides near the urban areas; preserving, maintaining, improving, and respecting the land-sea breezes; preserving, maintaining, and improving urban greenery; and reducing the release of air pollutants, greenhouse gases, and anthropogenic waste heat.

Thus, the planning strategies could be taken from four aspects: albedo, vegetation, shading, and ventilation. Detailed action plans with various operation and climatic impact scales are summarized in Table IV. These opportunities for innovation to improve the urban climatic environment contain important lessons for sustainable urban development in the future.

The creation of the UCMap is only the beginning; sustainable efforts are still needed. Planners should consult urban climatologists to interpret UCMap and planning instructions appropriately. Concerns and issues must be balanced and optimized. To improve and update the UCMap, a professional team is required to monitor the use and the effectiveness of the application, to

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collect further data as the basis of evaluation, to refine scientific bases as new knowledge develops, and to update the map to cope with the changes in urban morphology.

4. Discussions

On the basis of the available information collated, a UCMap takes into account an expertly balanced evaluation of positive and negative effects of the local climate, topography of the land, vegetation and buildings of the city, and wind patterns. In the planning aspect, this approach provides an evaluation tool that makes use of available spatial data, and proposes solutions for planning use through knowledge-based expert evaluation. The advantages and limitation of UCMap are elaborated below. Furthermore, the future trend of UCMap study is also discussed from the aspects of the future role of UCMap in climate change, professional expertise, climatic planning education, and its application in developing countries.

4.1. Advantages

- UCMap is a cross-disciplinary study and practice, bridging urban climatology and urban planning, and focusing on the application of climatic knowledge in planning. The useful climatic understanding and planning recommendations could be implemented into actual physical planning processes such as municipality/city master plan, zoning plan, and land use plan. As planning-related statements refer to specific areas, the use of UCMap as an informational basis is recommended. Generated maps are regarded as being very significant visual tools for the planner, and as meaningful means of communicating information to political leaders and the interested public.
- Climatic phenomenon and data are visualized by colours and graphics presented with spatial information in maps. In the planning aspect, this approach provides an evaluation tool that makes use of available spatial data, and proposes solutions for planning use through knowledge-based expert evaluation that is easily understood by planners, developers, and policy makers. These solutions can also be attributed to detailed specific climatic information from the corresponding basic input layers.
- Climatically problematic and sensitive areas can be observed using the UCMap. Such areas require the local government to pay close attention and conduct necessary actions to improve the urban living environment in future developments.
- The use of GIS in UCMap studies has become common since the 1990s. Thus, the framework and database of UCMap could be managed and updated digitally. Exporting maps with different scales and layouts is possible for flexible planning use. Various data and information could be overlaid with accurate spatial information in the GIS platform.
- UC-ReMap with relevant planning instructions is the result of communication between climatologists, meteorologists, planners, and local governors; thus, it could meet the actual needs of planners, developers, and local governors.

4.2. Limitations

- The UC-AnMap and UC-ReMap are a 'synthetic' and 'evaluative' result for planning purposes. The defining of climatopes and the making of climatic assessment and planning recommendation in UCMap studies depend not only on objectively and empirically collected climatic information and evidence but also rely on the expert experience and qualitative evaluation of urban climatologists. There may be a need for better and more appropriate procedures and standardization of evaluation and recommendation to ascertain the improvement effect on the urban living environment after applying planning recommendations.
- Climatopes are mainly defined by land use; to better understand the distribution pattern of the climatopes of the study areas, researchers have tried to quantitatively calibrate and verify the climatopes. Tracer gas experiments, wind tunnel tests, mobile traverse temperature measurements, computer model simulation tests, and so on, have been conducted to examine the generic climatic variations of urban areas. However, the methods must be improved further with the effort and support of urban climatologists.
- To understand city planning, it is necessary to mention the spatial and landscape planning system, which takes place at different scales, levels, and responsibilities. UCMap and planning instructions with different scales and themes should be generated and adopted to meet different planning uses.
- Urban planning is the result of balancing and weighting many sectors. The study results of UCMap and planning recommendations should be presented as simply and as clearly as possible. Otherwise, they may not be understood and used by the planners, developers, and policy makers.

4.3. Future trends

Currently, more than half of the world population lives in urban areas. With increasing concern on urban living quality and public health, additional spatial analyses on the bioclimatic condition of urban areas should be conducted in UCMap studies to understand the real needs and reveal existing and potential problems.

In facing the global issues of climate change and continuing warming, one of the future roles of UCMap is to offer assessment and to visualize the relevant impact of these phenomena on the urban environment in order to help planners, developers, and policy makers make better decisions on mitigation and adaptation.

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Once a UCMap is generated, numerous additional tasks are required, such as updating the map and planning instructions, adding new information and knowledge, offering expert advice on using and reading methods, and so on. Professional expertise on UCMap in the local government is highly recommended to continue the effort and provide sustainable and up-to-date information to enable better planning and decision making. For example, in Stuttgart during the 1970s, a section for climatology was set up in the Environmental Department. Thus, communication between climatologists, planners, and governors has been made common and frequent.

Planners, developers, and policy makers are accustomed to solving the complex problems from social, environmental, and economic aspects; however, the climatic aspect is generally neglected. Owing to limited knowledge on urban climatology, they have less ability to adopt and transfer the climatic knowledge in planning, application, and design. Thus, relevant training and education on urban climatic application and climatic spatial planning is urgently required.

Currently, fast urbanization and urban congestion are urgent concerns among developing countries and regions whose climatic environments have been gravely affected, even degraded. Comprehensive climatic assessment and evaluations are seldom incorporated into local urban developments and planning. Thus, it is necessary to conduct international research programs on UCMap studies in these countries and regions to guide local developments in these areas more sustainably. Likewise, sharing the learned lessons and accumulated experiences on UCMap studies with local researchers, planners, and governors is strongly recommended. Considering the lack of geographic databases, climatic information, and meteorological measurements in these areas, a simplified method of UCMap study is suggested.

5. Conclusion

This paper summarized and reviewed the latest concepts, key methodologies, selected parameters, structure and development process, mitigation countermeasures, and relevant planning instructions in UCMap studies. Various climatic phenomena, geographic information, and planning parameters were discussed and described. It was concluded that the thermal environment and air ventilation situation within the UCL play the most important roles in the analytical aspects and climatic-environmental evaluation. Similarly, it was concluded that possible mitigation measures and action plans could be undertaken by decreasing anthropogenic heat release, improving air ventilation at the pedestrian level, providing shading, increasing greenery, creating air paths, and controlling building construction. Future research should focus on spatial analysis of the bioclimate in urban outdoor areas and in climate change impacts and adaptation. Sharing the learned lessons and experiences with planners and policymakers in the rapidly expanding cities of developing countries and regions is also important.

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APPENDIX

Table AI. Chronology of Urban Climatic Map studies in the world

Year		References	Country
1960s	1963	Kar Knoch, 1963. Die Landesklima-aufanhme	Germany
1970s	1978	Hoffman U. 1978. City climate of stuttgart. In *City Climate: Data and Aspects for City Planning (T. Literature Research Company, Trans.),* E. Franke (ed.). FBW-A publication of Research, Building and Living	Germany
	1978b	Lüttig GW. 1978. Geoscientific maps of the environment as an essential tool in planning. *Geologie en Mijnbouw* **57**(4): 527–532	Germany
1980s	1982	Sterten AK. 1982. A thematic mapping system and a description of local climatic conditions developed for urban planning purposes. *Energy and Buildings* **4:** 121–124	Norway
	1983	Lindqvist S, *et al*. 1983. Lokalklimatiska kartor for anvandning i kommunal oversiktlig planering. *Byggforskiningsradet* **38**	Sweden
	1984	Schirmer H. 1984. Climate and regional land-use planning. *Energy and Buildings* **7**: 35–53	Germany
	1985	Stock P, Beckröge W. 1985. *Klimaanalyse Stadt Essen*. Kommunalverband Ruhrgebiet: Essen; 123	Germany
	1986	Stock P, *et al*. 1986. *Klimaanalyse Stadt Dortmund*. Planungshefte Ruhrgebiet, P.O. 18. Kommunalverband Ruhrgebiet: Essen	

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1988	Beckröge W. 1988. Climate as a factor of a planning project – Demonstrated by the example of Dortmund Bornstrasse. *Energy and Buildings* **11**: 129–135	Germany
1988	Beckröge W, *et al*. 1988. *Klimaanalyse Stadt Recklinghausen*. Kommunalverband Ruhrgebiet; 73	Germany
1988	Katzschner L. 1988. The urban climate as a parameter for urban development. *Energy and Buildings* **11**: 137–147	Germany
1988	Mayer H. 1988. Results from the research program 'STADTKLIMA BAYERN' for urban planning. *Energy and Buildings* **11**: 115–121	Germany
1989	Lindqvist S, Mattsson J. 1989. Topoclimatic maps for different planning levels-some Swedish examples. *Building Research and Practice* **5**: 299–304	Sweden
1990s 1990/1991	Akasaka H. 1990/1991. A study on drawing climatic map related to human thermal sensation. *Energy and Buildings* **15–16**: 1011–1023	Japan
1990/191991	Paszynski J. 1990/1991. Mapping urban topoclimates. *Energy and Buildings* **15–16**: 1059–1062	Poland
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1992	Baumüller J, *et al*. 1992. *Climate booklet for urban development*. Ministry of Economy Baden-Wuerttemberg (WirtschaftsministeriumBaden-Württemberg), Environmental Protection Department (Amt für Umweltschutz)	Germany
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1992	Matzarakis A, Mayer H. 1992. *Mapping of Urban Air Paths for Planning in Munich. Planning Applications of Urban and Building Climatology*. Wiss. Ber. Inst. Meteor. Klimaforsch. Univ. Karlsruhe 16; 13–22	Germany
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1995	Parlow E, *et al*. 1995. Analysis of the Regional Climate of Basel/Switzerland	Switzerland
1996	Matzarakis A., Mayer H. 1996. Bioclimate Maps of Greece for Touristic Aspects. Paper Presented at the 14th International Congress of Biometeorology	Germany
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	2001	Fehrenbach U, Scherer D, Parlow E. 2001. Automated classification of planning objectives for the consideration of climate and air quality in urban and regional planning for the example of the region of Basel/Switzerland. *Atmospheric Environment*	Switzerland
	2001	Nielinger J, Kost WJ. 2001. Klimaanalyse der Stadt Sindelfingen. Stuttgart, Germany	
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