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Creating breathing cities by adopting urban ventilation assessment and wind corridor plan – The implementation in Chinese cities

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ABSTRACT

In recent years, urban ventilation assessment and urban ventilation corridor plan have been conducted and adopted in the urban planning of Chinese cities in response to the national call from the Central Government of China as well as the public concern on the quality of living environment. Therefore, a national technical guide is needed to provide a state-of-the-art standard methodology and scientific technology on urban ventilation assessment, and to serve as an aid for decision-making in the initial stage of town planning and urban design. This paper first reviews the urban ventilation corridor plan related activities in Chinese cities since 2000 and points out the needs and problems. Secondly, it introduces the newly developed national technical guide 'Specifications for climatic feasibility demonstration – Urban Ventilation Corridor'. Thirdly, a case study of Chengdu Urban Ventilation Corridor Plan is presented to demonstrate the implementation of such considerations in local planning exercises. Lastly, it discusses the future trend of urban ventilation assessment and urban ventilation corridor plan in China.

1. Introduction

Since the reform and opening up in 1978, China has been experiencing fast urbanisation at an average annual rate of 1.04%. In 2016, the urbanisation rate in China reached 57.35%. However, the traditional urbanisation development model comes at the expense of high resource consumption and environmental degradation (Wang, 2004). According to historical meteorological records, the urban warming trend has been observed since the mid-1980s (Ren et al., 2005). In the meantime, the urban wind environment has been deteriorating, and the urban wind speed has generally declined in most Chinese cities (Ren et al., 2005). With the increase of near-surface aerosol pollution, urban visibility reduces and pollutant dispersal becomes difficult, resulting in frequent urban haze events especially during wintertime in China (Wu, 2012). These urban environmental problems affect the physiological and psychological conditions of urban residents, both directly and indirectly, leading to a constant increase in the incidence of diseases (Bai et al., 2006). However, according to the Central Government's 13th five-year plan, this urbanisation trend may continue for another 20–30 years before the whole process completes, and the ecological and natural environment will still be under unprecedented pressure. Therefore, urban planners and decision-makers in the government must take into account of the increasing public demand for quality of life and create a healthy and comfortable urban environment when planning upcoming developments (Ng and Ren, 2018). A series of recent policy documents and political actions shows that both the Central Government of China and local governments in cities have put emphasis on environmental protection and ecological recovery (Wang et al., 2015) by introducing urban climatic evaluations into town planning and design practices. Among the many recommended initiatives on improving urban living environment, urban ventilation corridor (a.k.a. wind corridor) plan is the most popular one for all cities at and above the prefecture level in China (Hang et al., 2012; He et al., 2015; Hsieh and Huang, 2016; Qiao et al., 2017; Ren, 2016; Ren et al., 2015; Su et al., 2016; Wong et al., 2010; Yim et al., 2014; Yuan et al., 2014a,b). Thus, there is an increasing need to review the relevant needs and issues, and establish a standard methodology to regulate daily practices accordingly.

This paper aims to fill this gap. First, urban ventilation corridor plans

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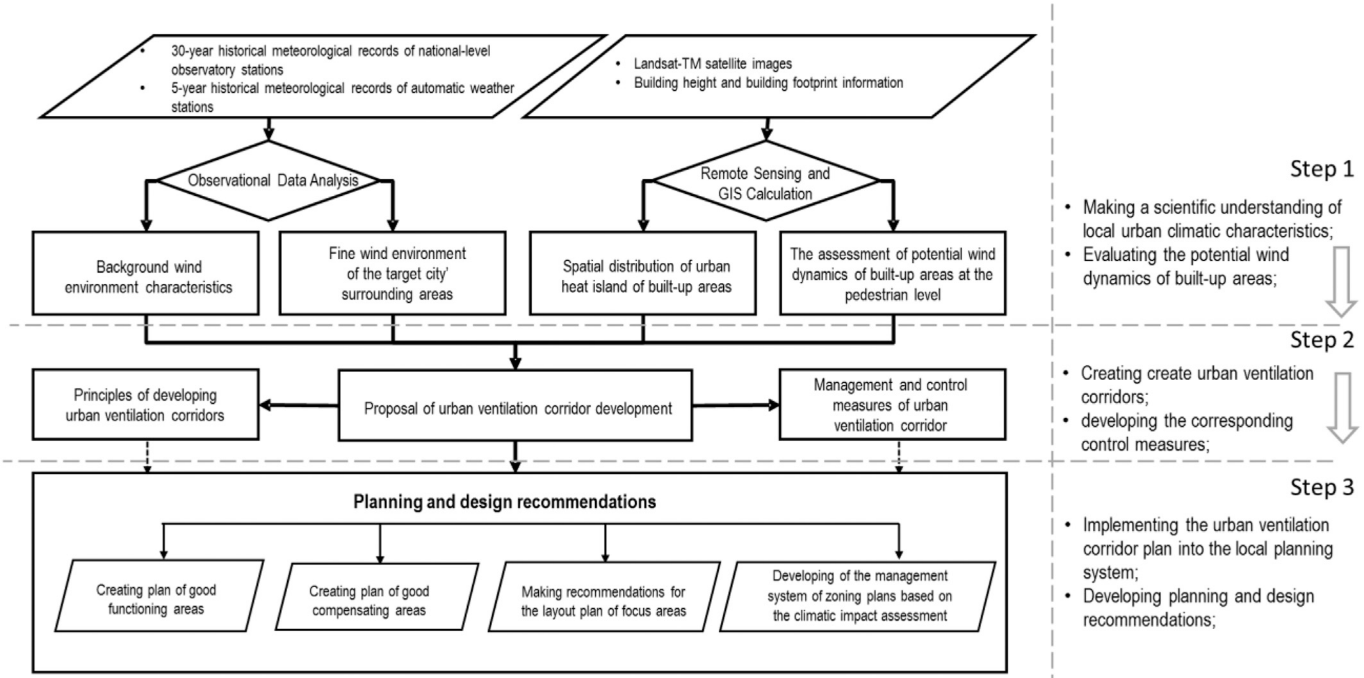

Fig. 1. Workflow and main steps of the urban ventilation corridor application research framework.

Table 1
Classification of potential wind dynamics.

Classification	Description	Surface roughness length(m)	Sky View Factor
1	None or very low	>1.0	/
2	Relatively low	(0.5, 1.0)	<0.65
3	Moderate	(0.5, 1.0)	≧ 0.65
4	Relatively high	≦ 0.5	<0.65
5	High	≦ 0.5	≧ 0.65

Table 2
Classification of UHII.

Classification	Description	Daily UHII (°C)	Monthly or Seasonal UHII (°C)
1	Strong cool island effect	≦ −7.0	≦ −5.0
2	Relatively cool island effect	(-7.0, −5.0)	(-5.0, −3.0)
3	Slightly cool island effect	(-5.0, −3.0)	(-3.0, −1.0)
4	No heat island	(-3.0, 3.0)	(-1.0, 1.0)
5	Slightly heat island	(3.0, 5.0)	(1.0, 3.0)
6	Relatively heat island effect	(5.0, 7.0)	(3.0, 5.0)
7	Strong heat island effect	>7.0	>5.0

Table 3
Classification of cool fresh air sources.

Classification	Description	Land use type	Area (m^2)
1	Strong	Water bodies	≥3600
2	Relatively strong	Woodland or Greenery area	≥20,000
3	Moderate	Woodland or Greenery area	16,000–20,000
4	Weak	Woodland or Greenery area	12,000–16,000
		Agriculture land	≥12,000

and relevant studies since 2000 are reviewed and analysed to point out the difficulties and potential problems. Secondly, based on an understanding of the functions and elements of an urban ventilation corridor, it explores the position of its application in the urban planning system of China. Thirdly, it introduces the developed method and techniques for detecting urban ventilation corridors and incorporating them into a city master plan. Fourthly, it discusses the implementation of urban ventilation corridor evaluation at the regional, city and neighbourhood levels. Furthermore, one case study is selected to demonstrate local practices of urban ventilation assessments and ventilation corridor plans in China.

2. Review

2.1. *Development mode and policy changes in China*

The end of the international financial crisis in 2008 marked a new era of economic development in China. The National Government has started to pay more attention to the development mode and its impacts on environmental quality rather than solely on the economic growth rate. Changes in development concepts and policies emerged, especially in the increased attention and management for environment-related issues, such as the construction of ecological recovery and civilisation, environmental pollution control, and the response to climate change. From the recently promulgated series of national-level inter-ministerial policy and planning documents, urban planning has been identified to have a leading role in achieving such transformations in the new development mode through taking real action at the city level. For example, national policy action plans, such as The Action Plan on Prevention and Control of Air Pollution (SC, 2013), the National Plan for Climate Change (2014–2020), China's Polices and Actions for Addressing Climate Change (NDRC, 2011), National City Environmental Protection and Development Policies (2015–2020) (Draft version), 2015 Guidelines for Environmental Performance Assessment of Urban Ecological Construction (Trial Version), and Climate Change Adaptation Action Plan for Cities (CCAAPC) (MOHURD and NDRC, 2016), all clearly point out three objectives: 1) to incorporate urban climatic information as well as air

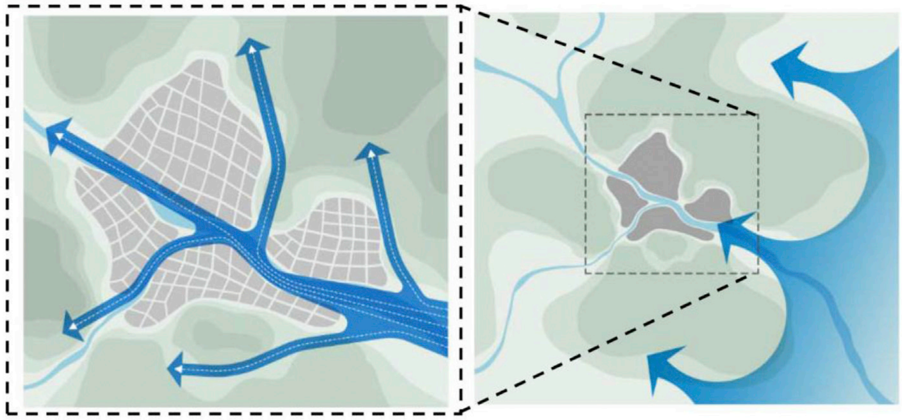

Fig. 2. Major urban ventilation corridors at the city level (left) and the regional level (right).

Table 4
Two recommended plans for developing major urban ventilation corridors.

Level	Key Aspects	Criteria	Detailed descriptions
Plan A. **Strongly recommended**	Control measures	Direction of MUVC	• Following major prevailing wind directions under soft and light breeze; • the angle between planned corridors and the prevailing wind direction $\leq 30°$*
		Width of MUVC	• Should be more than 500 m
	Functioning areas	Potential Wind Dynamics	• Class 4-5
		Cool Fresh Air Sources	• Class 1-2
		Ventilation volume	• 20% of planned areas with top values
	Compensating areas	UHII	• Class 6-7
		Ventilation volume	• 20% of planned areas with bottom values
Plan B. **Recommended**	Control measures	Direction of MUVC	• Following major prevailing wind directions under soft and light breeze; • the angle between planned corridors and the prevailing wind direction $\leq 30°$*
		Width of MUVC	• Should be more than 200 m
	Functioning areas	Potential Wind Dynamics	• Class 3-5
		Cool Fresh Air Sources	• Class 1-3
		Ventilation volume	• 40% of planned areas with top values
	Compensating areas	UHII	• Class 5-7
		Ventilation volume	• 40% of planned areas with bottom values

* When the streets lie at small angle up to 30° to the prevailing winds, urban ventilation penetration easily occurs(Brown et al., 2000; Givoni, 1998).

quality evaluation into urban ecological assessments; 2) to optimize urban functions and land use in the spatial layout plans; and 3) to create urban ventilation corridors at the city level. In the CCAAPC, it even mentioned that hopefully by the end of 2017, all cities at and above the prefecture level in China should complete their urban ventilation corridor plans. This 'mission impossible' task involves nearly 300 Chinese cities.

2.2. Definition of urban ventilation corridor and its function

The concept of 'urban ventilation corridor' which can also be called 'wind corridor' originated from a German word "*Ventilationbahn*" developed by Kress (1979). To improve air exchange and ventilation conditions of downtown areas, he suggested that people should consider two important elements, namely the 'functioning area' and the 'compensating area', before creating any urban ventilation corridor which serves to link these two areas together to let cool fresh air move more easily within the city centre. Later, Mayer et al. (1994) classified urban ventilation corridors into four types according to the air quality and different sources of air: normal, polluted, cool fresh air, and biometeorological-related. In Germany, ventilation corridor plans, as a part of their urban climate maps, have been conducted in many cities and regions (Barlag and Kuttler, 1990; Baumüller et al., 1998; Katzschner, 1988; Matzarakis and Mayer, 1992). The German national guideline 'Environmental meteorology climate and air pollution maps for cities and regions (VDI 3787-Part 1)' names it as 'Ventilation Lane' and also gives a clear and detailed definition, which is the "*Area for the mass transport of air near the ground which is preferred owing to direction, nature of the surface and width. Air-directing tracks, also termed ventilation or aeration tracks are intended to facilitate horizontal air exchange processes by means of low roughness (no high buildings, only individual trees), an alignment which is as far as possible rectilinear or only slightly curved, and a relatively large width (as far as possible more than* 50 m*).*" (VDI, 1997).

In Japan, urban ventilation corridor is called 'Kaze-no-Michi'. Japanese researchers adopted the concepts and learnt from the experiences of Germany in implementing ventilation corridors but mainly used them to cool down the downtown areas and to improve human thermal comfort conditions in the summertime. Tokyo metropolitan region and many Japanese cities such as Yokohama, Nagoya, Osaka and Fukuoka have conducted their wind environment studies and urban ventilation corridor plans since 2007. The Architectural Institute of Japan (AIJ) has conducted numerous studies on the urban wind environment of Japanese cities and in 1993 published a book titled 'Analysis and Design for Wind Environment in Urban Area', which introduces the assessment of urban wind environments under weak wind conditions and how to implement the results into urban planning. Later in 2013, the National Institute for Land and Infrastructure Management (NILIM) published 'Urban Development Guidance for Urban Heat Island (UHI) Countermeasures Utilizing Kaze-no-Michi'. It mainly introduces the classification of urban ventilation corridors, the way to create these corridors for mitigating the UHI effect, as well as the implementation mechanism of urban ventilation corridors and the parties involved in planning and design (Ashie and Kagiya, 2013; Kagiya and Ashie, 2008).

Since 2000, in China, many new terms have been used in local news articles, governmental documents, and academic journal papers to

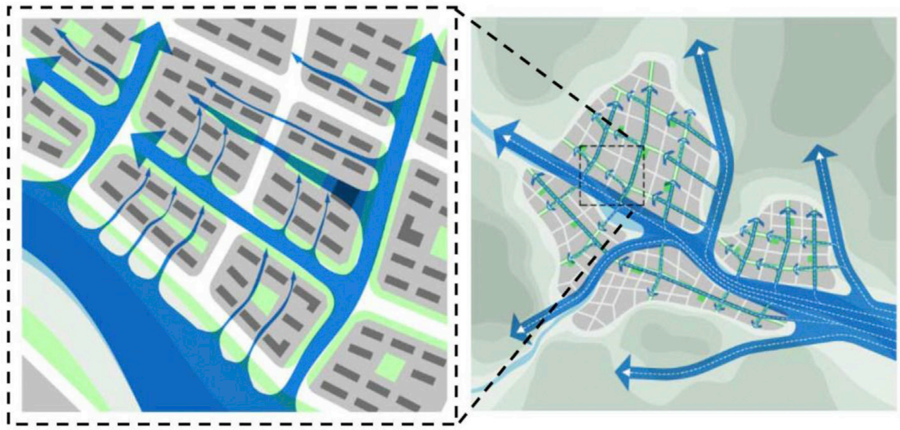

Fig. 3. Major and secondary urban ventilation corridors at the district level (left) and the city level (right).

describe urban ventilation corridors, such as, 'urban wind corridor', 'ventilation corridor', 'ventilation lane', 'air path', 'urban wind channel', 'eco-wind channel', 'green wind channel', 'clean air corridor' and 'fresh air path' (Ren, 2016; Ren et al., 2014). The China National Urban Ecological Conservation and Construction Plan (2015–2020) published in 2015 has been the first government document to mention 'urban ventilation corridor' officially. However, it did not provide any technical details. Later, in February 2016, the Ministry of Housing and Urban-Rural Development (MOHURD), with the National Development and Reform Commission (NDRC), released a joint document CCAAPC, which again refers to the 'urban ventilation corridor'. In this document, one of the key actions recommended for future urban planning exercises states the need to "*use existing urban green space, road network, river and water bodies, and other public open spaces to create the urban ventilation corridors, so as to increase air exchange in urban areas, to mitigate urban heat island effect and to reduce haze events and/or other environmental problems*". Today, more than 48 cities from 20 provinces in China have done or are preparing to formulate their ventilation corridor plans, and to develop design actions and control measures for local planning practices (Ren, 2016). It is found that building and urban morphological data in Geographic Information System (GIS) format have been used to calculate the urban surface roughness length and building fontal density to detect the permeability of urban morphology under the prevailing wind conditions. The Weather Research and Forecasting (WRF) model and computational fluid dynamics (CFD) models are often used to simulate the wind environment conditions to get a better understanding of urban ventilation at the city and neighbourhood levels. CFD simulation results are also used to make cross-comparisons between different planning proposals and design schemes. Most of the application studies and projects on urban ventilation corridors have been mainly conducted by the prefecture-level governments. Very often, a multi-disciplinary approach is adopted, involving overall urban wind environment evaluation, air pollution prevention, UHI effect, urban thermal environment, summer human thermal comfort, ecological network system, ecological function, ecological adaptability, prevention of acid rain pollution, greenery master plan, road traffic plan, urban growth control plan, and open space plan. However, this review shows that there is yet to be a national standard on urban ventilation corridor plan to be followed.

3. Background and objectives of the technical guide

Since 2014, a working group has been formed to develop the national technical guide 'Specifications for climatic feasibility demonstration – Urban Ventilation Corridor (Technical Guide)'. This group consists of researchers from the Urban Meteorology Centre of Beijing Metrological Service and The Chinese University of Hong Kong, and planners from the China Academy of Urban Planning and Design and Beijing Academy of Urban Planning and Design. Most of them have more than 10 years of practical experiences on the urban climatic application in different Chinese cities. The primary objective of this technical guide is to explore the feasibility of establishing protocols for conducting urban ventilation assessments, especially to evaluate the permeability of built-up areas under soft and light breeze conditions, with values between 0 and 2 in the Beaufort wind force scale (Beaufort, 1805), and to provide a recommended workflow and a standard methodology for creating urban ventilation corridor plans at early stages of the city master plan.

4. Outline of the technical guide

The Technical Guide recommends a three-step workflow shown in Fig. 1.

Step 1 focuses on obtaining a scientific understanding of local urban climatic characteristics and evaluating the potential wind dynamics of built-up areas. For the detailed tasks, they include the collection of recommended data (30-year historical meteorological records of local national-level observatory stations, Landsat-TM images, building height and building footprint information) and analyses focusing on four key aspects, namely background wind environment characteristics, fine wind environment of the target city's surrounding areas, spatial distribution of UHI, and potential wind dynamics of built-up areas at the pedestrian level.

Step 2 focuses on creating urban ventilation corridors and developing the corresponding control measures. Based on the results from step 1, it includes three parts of work: 1) principles of developing urban ventilation corridors; 2) proposal of urban ventilation corridor development; and 3) management and control measures of urban ventilation corridors.

Step 3 focuses on developing planning and design recommendations, which should have four tasks including creating two plans of good functioning areas and good compensating areas, making recommendations for the layout plan of focus areas, and developing the management system of zoning plans based on the climatic impact assessment.

4.1. Technique and methods

4.1.1. Background wind conditions

Background wind conditions are analysed for times when the wind speed is below 3.3 m/s. It is obtained by calculating the wind frequency in all directions, the static wind frequency, and the soft and light breeze frequency based on observed wind records from local observatory stations of the target city (at least using the records of the three most recent years), and drawing wind rose diagrams under such conditions. If records from local stations were good enough, it is suggested that an appropriate

Table 5
Two recommended plans for developing secondary urban ventilation corridors.

Level	Key Aspects	Criteria	Detailed descriptions
Plan A **Strongly recommended**	Control measures	Direction of SUVC	• Following major prevailing wind directions under soft and light breeze; • the angle between planned corridors and the prevailing wind direction ≤45° • The width of inside obstacles should be less than 10% of urban ventilation corridor's width; • The length of planned SUVCs should be longer than 2000m;
		Width of SUVC	• Should be more than 80 m
	Functioning areas	Potential Wind Dynamics	• Class 3-5
		Cool Fresh Air Sources	• Class 1-3
		Ventilation volume	• 40% of planned areas with top values
	Compensating areas	UHII	• Class 5-7
		Ventilation volume	• 40% of planned areas with bottom values
Plan B **Recommended**	Control measures	Direction of SUVC	• Following major prevailing wind directions under soft and light breeze; • the angle between planned corridors and the prevailing wind direction ≤45° • The width of inside obstacles should be less than 20% of urban ventilation corridor's width; • The length of planned SUVCs should be longer than 1000 m;
		Width of SUVC	• Should be more than 50 m
	Functioning areas	Potential Wind Dynamics	• Class 2-5
		Cool Fresh Air Sources	• Class 1-4
		Ventilation volume	• planned areas with above average values
	Compensating areas	UHII	• Class 5-7
		Ventilation volume	• planned areas with below average values

interpolation method should be adopted to obtain the wind speed at intervals of 0.5 m/s and to get a spatial distribution map of soft and light breeze with a resolution of not less than 1 km.

4.1.2. Mesoscale numerical model

An appropriate mesoscale numerical model should be selected and approved by urban climate experts. The terrain and characteristics of the urban canopy layer should be considered when setting up the model's boundary layer. A mesoscale numerical simulation through multi-nesting or coupling of small-scale meteorological models can be conducted to obtain the wind environment information of a typical month with a higher frequency of soft and light breeze, and the background wind environment under typical weather conditions with no rainfall and a high frequency of soft and light breeze. The horizontal resolution of the simulated wind field should be no less than 1 km and its time resolution should be no less than 1 h. The simulation results should be validated and corrected by local meteorological observation data.

4.1.3. Local wind circulation system

Local wind resources and circulation system (including mountain-valley wind, land-sea breeze, lake-land breeze etc.) can be evaluated by using statistical methods and numerical simulations. The expected results should determine prevailing wind directions and obtain the effective time periods and impact areas of these local wind circulations.

4.2. Calculation of ventilation volume

The ventilation volume can be calculated by integrating the horizontal air speed from the ground to the mixing layer height (MLH). The spatial distribution of ventilation volume of the target city can be developed through analysing its seasonal and daily changes and making a comparison between rural and urban areas, so that the poorly and well ventilated areas can be easily detected. In this study, ventilation volume (V_E) can be expressed as follows:

$$V_E = \int_0^H u\,(\,z\,)\,\mathrm{d}z \tag{1}$$

Where H is the mixing layer height, z is the vertical height (m), which means the absolute height above the ground, and u is the corresponding horizontal wind speed at z. The calculation of H should referred to another national standard namely 'Technical methods for making local emission standards of air pollutants (GB/T13201-91)' (AQSIQ, & MEP, 1992).

4.3. Classification of potential wind dynamics

Potential wind dynamics can be classified by considering both the sky view factor (SVF) and the surface roughness length (SRL). The classification is shown in Table 1. For the calculation method of SVF and SRL, they can be found in parts 1 and 2 of the appendix. According to Chen and Ng (2011), Chen et al. (2012), it is found that SVF can directly show the potential urban heat island intensity. When the value of SVF is above 0.65, it has no impact on thermal load. Since urban ventilation has the effect of alleviating the urban heat island effect, this study considers the threshold value of SVF with wind dynamic potential to be 0.65.

4.4. Classification of urban heat island intensity (UHII)

Surface temperatures derived by satellite images and remote sensing techniques are used to calculate UHII. The classification of UHII can be found in Table 2. For the UHII, its calculation method can be found in part 3 of the appendix.

4.5. Classification of cool fresh air sources

Cool fresh air sources can be classified by considering both the land use types derived by satellite images and their corresponding areas (Table 3). Due to seasonal differences in satellite images, the corresponding classification can be slightly changed accordingly. For the calculation method of cool fresh air sources, it can be found in part 4 of the appendix.

4.6. Preliminary version of urban ventilation corridor (UVC) plan

The evaluation results of background wind conditions, potential wind dynamics, UHII and cool fresh air sources can be synergized and overlaid on the current land use plan or master plan of the target city in the GIS, so the preliminary version of major and secondary urban ventilation corridors can be developed at the city master plan and the regional plan levels.

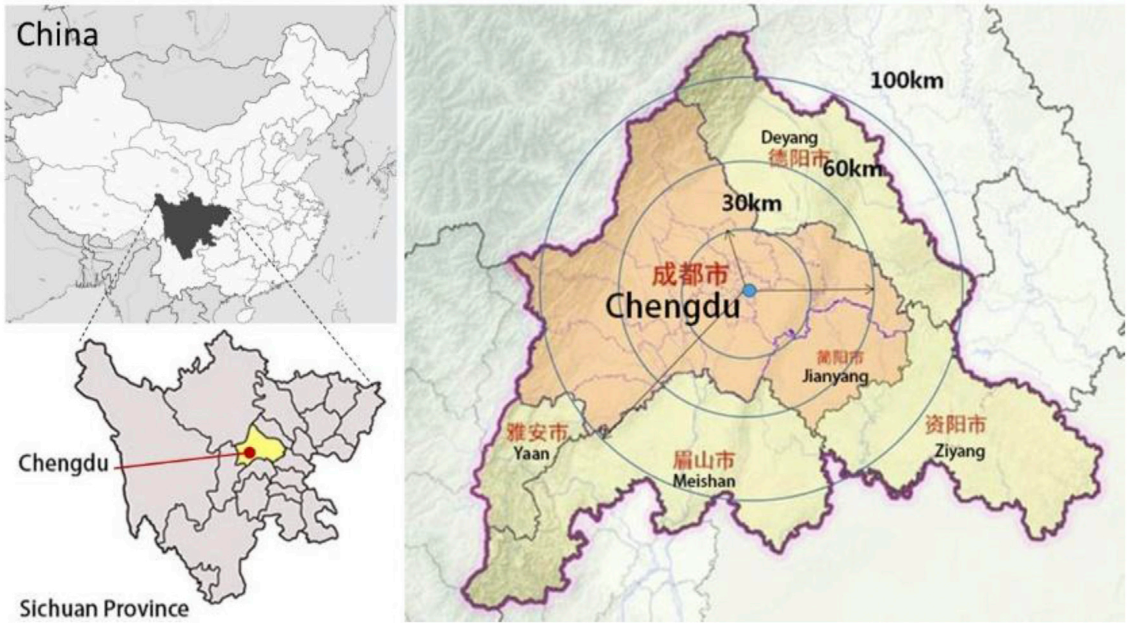

Fig. 4. Geographic location of Chengdu city (source: Internet).

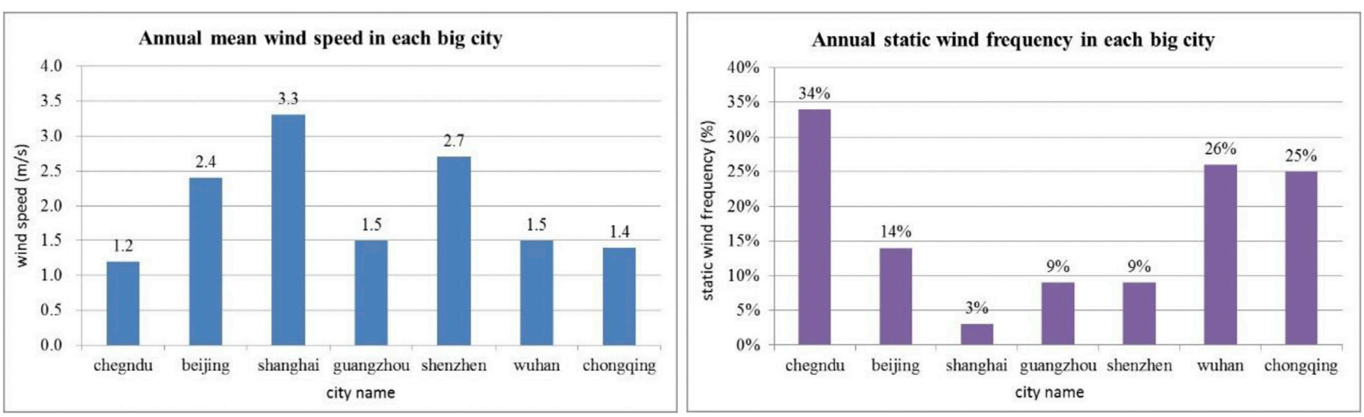

Fig. 5. Comparison of the Annual Mean Wind Speeds (left) and Static Wind Frequencies (right) between Chengdu and other Major Cities in China (the above wind data were measured at 10 m height above the ground).

4.6.1. Major urban ventilation corridor (MUVC)

The main functions of major urban ventilation corridors are to improve the air exchange and urban ventilation in the city centre and to mitigate high UHII (Fig. 2). When they are planed, at least one of following criteria should be met:

- to cross the target city following the prevailing wind directions;
- to be along those areas with low surface roughness and relatively high potential wind dynamics;
- to link the city centre and cool fresh air source areas; and/or
- to link the rural areas with high ventilation volume and the urban areas with low high ventilation volume.

For the land use type of these major ventilation corridors, it can be a new category or can be existing traffic network, river channels, parks, greenery areas, ground areas of high-voltage power lines, linked leisure spaces, and other types of open spaces.

There are two major urban ventilation corridor plans recommended in Table 4. Local planners and policymakers can decide to choose Plan A (strongly recommended) or Plan B (recommended) according to the practical conditions. Three key aspects for planning urban ventilation corridors, including the control measures, functioning areas and compensating areas which those planned major urban ventilation corridors aim to link, should be considered.

4.6.2. Secondary urban ventilation corridor (SUVC)

Secondary urban ventilation corridors should assist the major urban ventilation corridors and help enlarge their functioning areas (Fig. 3). When they are planned, at least one of the criteria below should be met:

- to be along those areas with relatively high potential wind dynamics;
- to make a link between the densely built-up areas city and cool fresh air source areas; and/or
- to make a link between two neighbouring areas with a relatively large difference of urban ventilation volume.

For land use type of these secondary urban ventilation corridors, it can use the existing road network, river channels, parks, greenery areas, and built-up areas with low development intensity but high permeability.

Similar to the major urban ventilation corridor plans, there are also two plans recommended for developing secondary urban ventilation corridors (Table 5), but with slightly different criteria.

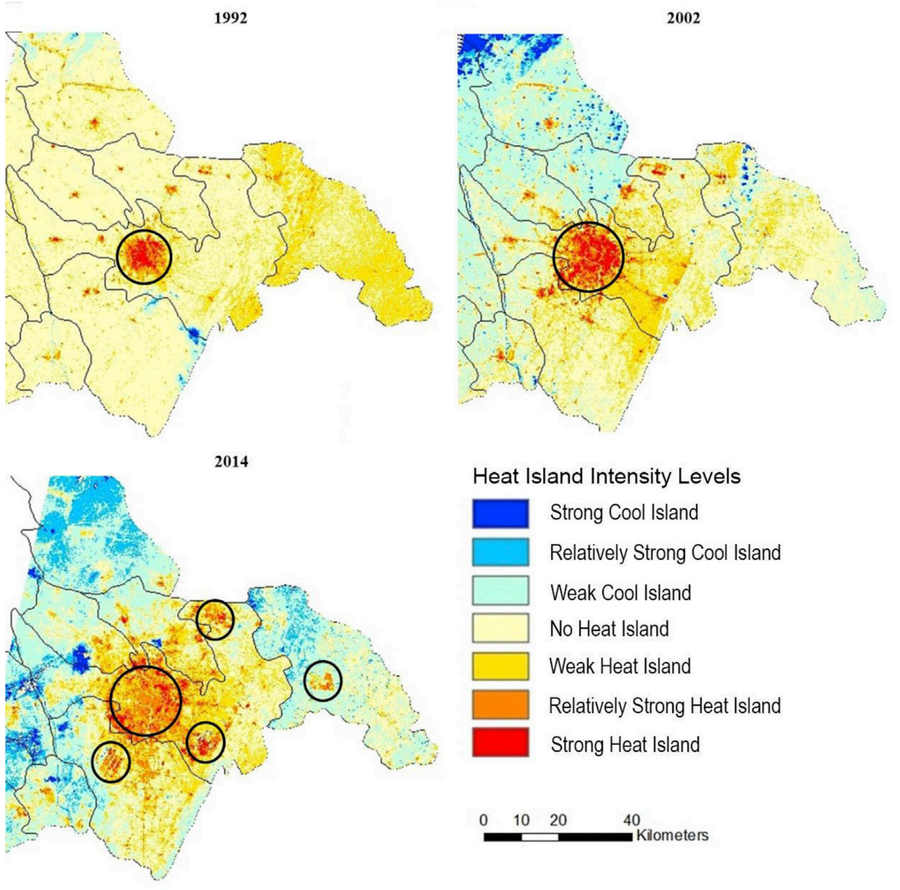

Fig. 6. Spatial Distribution of UHIs in Chengdu in Different Years (strong UHI centres are indicated with black circles).

4.7. Finalised urban ventilation corridor plan

Given the realistic situation and other practical difficulties that may be encountered during such planning implementation, the aforementioned criteria (such as direction, width etc. listed in Tables 4 and 5) can be revised based on the negotiation and discussion with local planning departments and other related government departments before developing a finalised urban ventilation corridor plan.

Since different cities may have different environmental issues or urban climatic focuses, such urban ventilation corridor plan can be considered to assist the city master plan. Sometimes it can also be combined and/or applied to the greenery plan/greenbelt plan, road network plan, and ecological protection plan.

5. A case study of Chengdu's urban ventilation corridor plan

5.1. Background

Chengdu is located in the central part of China and the western part of Sichuan basin. It is the capital city of Sichuan Province. Its terrain is higher in the northwest and lower in the southeast (Fig. 4). Its humid subtropical climate brings abundant heat and rain to the city. Ventilation in the city at lower altitudes is often impaired due to its special topography and natural climate characteristics.

A study of 30 years of weather observation records measured at a height of 10 m above the ground reveals that compared to most other first-tier cities in China (such as Beijing, Shanghai, Guangzhou, Wuhan and Chongqing), Chengdu has a lower annual mean wind speed (1.2 m/s) and a higher static wind frequency (34%), as shown in Fig. 5. The meteorological conditions for diffusing low-altitude air pollutants in Chengdu are not ideal, making the city prone to air pollution. As the economy of Chengdu develops and the city grows rapidly, the impacts of anthropogenic activities on the local climate and atmospheric environment are becoming more significant. The UHI effect within the Chengdu city is sprawling and the affected area has expanded considerably. In the 1990s, there was only one UHI centre (the city centre); in 2014, a few more emerged (the city centre and the surrounding areas). In 1992, the area with stronger UHI was only 53.6 km^2; it then grew to 533 km^2 in 2002 and 798 km^2 in 2014. The urban thermal environment is suboptimal due to strong urban heat island intensity (Fig. 6). However, it is found that the areas of cool island in Fig. 6 have increased due to the implementation of ecological rehabilitation and the returning of farmland to forest or dense tree covers since the 1990s. At the same time, with the growth of industry and the increasing use of motor vehicles, Chengdu faces immense pressure on its atmospheric environment. Coal smoke and exhaust from motor vehicles are becoming more significant sources of air pollution. In general, the city's living quality is deteriorating.

Thus, the city of Chengdu has set "Garden City" as its urban development target recently. The relationship between the meteorological environment and urban living conditions is particularly emphasized in the city's master plan. Specifically, the impacts of urban development, industrial structure and energy consumption should be considered. In light of this, '*the Study of Urban Ventilation Corridor Construction and Planning Strategies in Chengdu*' was launched in 2015. It also serves to support the work of "Urban Master Plan of Chengdu (2016–2035)".

5.2. Information and data

Three types of information were involved in the research process, as detailed in Table 6: urban planning, remote-sensing and GIS, and

Table 6
List of information and data used in the study.

Data Type	Data Name	Main Use
Urban Planning	Current land use information and plans of the study area as stipulated in the city master plan; detailed plans of the study area for control.	Atmospheric environmental studies for city plans.
	Plans for greenfield, waters and rivers and other ecological corridors.	Analysis of cooling and local wind circulation at green corridors and waters; study of thermal environment improvement.
GIS and Remote Sensing	High-resolution digital elevation model (DEM), rivers and waters, roads and GIS vectors as detailed as township and county administrative regions.	Grasping the basic regional geographic conditions and the city's geographic location; producing drawings of the final results.
	The study area's latest land use plan in.shp format showing building heights, land use nature and density category.	Calculation of ground surface roughness, evaluation of ground surface ventilation and support for the construction of urban ventilation corridor.
	High-resolution remote sensing images that cover the whole study area.	Enabling more detailed analysis on the city's urban heat island effect and ground surface ventilation.
Climate information and Weather records	Collated climate information (including wind direction, wind speed, temperature, precipitation, relative humidity and pressure) of the past 30 years (at least 10 years) from the national meteorological observation stations in the study area.	Background environmental and climatic analysis, such as the prevailing wind environment of the study area.
	Hourly data (10 min wind direction, 10 min wind speed, temperature, precipitation, relative humidity and pressure) of the past five years recorded at the automatic meteorological stations in the study area.	Allowing for finer analysis on the wind and thermal environment in the study of ventilation corridor and UHI.
	Final Operational Global Analysis (FNL) data.	Providing the initial field of numerical simulation by WRF model.

meteorology. The data and information were retrieved from the city government of Chengdu and China Meteorological Administration.

5.3. Methodology and workflow

The background wind environment of Chengdu was studied through an analysis of the data collected by meteorological stations and meteorological model simulations. A particular focus was placed on the wind environment under soft and light breeze conditions and other wind field characteristics in the main development area of the city's urban ventilation corridor. Besides, quantitative indicators to evaluate the wind field at ground level of the main development area were calculated by combining data of building heights, density and land use with remote sensing and GIS techniques. The general principles of urban ventilation corridor planning were thoroughly studied, and the background wind environment and ground surface ventilation were analysed. An urban ventilation corridor system was then constructed, and strategies to plan, construct and evaluate ventilation corridors were suggested. Fig. 7 shows the research workflow.

In this study, the WRF model was selected as the mesoscale numerical model for simulating the wind environment. It is a new generation of mesoscale forecast models jointly developed by a number of research institutes and universities in the United States. The WRF model features advanced numerical methods, data assimilation techniques, and well-developed physical process solutions. It can also perform simulations using multiple nested grids. For the simulation of urban meteorological elements, the land surface process model in WRF can be coupled with urban canopy models to reflect the influence of different underlying urban surfaces on meteorological elements, allowing for more detailed descriptions of the thermodynamic and kinetic effects in cities. Therefore, the WRF model has remarkable capabilities in simulating the heat storage effect, temperatures, and the flow field distribution. The WRF simulation in the present study consisted of four nested grids with horizontal spatial resolutions of 27 km, 9 km, 3 km, and 1 km, respectively. In the WRF model, the parameterization schemes of physical processes include: WRF Single Moment 6-class (WSM6) microphysics scheme; the rapid and accurate radiative transfer model (RRTM) longwave radiation scheme and Dudhia shortwave radiation scheme, with a radiation timestep of 10 min; ETA Monin-Obukhov Similarity surface layer scheme; Boulac Planetary Boundary Layer (PBL) Schemes; Noah land surface scheme; UCM Urban Canopy Model; Grell 3D Ensemble Scheme for cumulus parameterization, which was invoked once per step and was not used for the nested grids 3 and 4 (with horizontal spatial resolutions of 3 km and 1 km). The urban canopy model was then invoked to simulate a 1 km $\times$ 1 km spatial resolution 10-m altitude wind field covering typical metropolitan areas under typical weather conditions.

5.4. Results

5.4.1. Wind environment information

The study of WRF model simulation analysed the prevailing and seasonal wind directions of the city by collating data of wind directions and wind speeds from 1981 to 2010 (Fig. 8). The 30-year data were obtained from the 13 national meteorological stations in Chengdu City. It can be seen that the annual prevailing wind is north-easterly, whereas the summer wind could be southerly. Therefore, the north-easterly wind of 21 January 2014 and southerly wind of 26 July 2014 were set to represent the typical weather conditions.

Fig. 9 shows the wind field simulation of the typical north-easterly wind weather scenario in Chengdu. Despite the prevailing north-easterly wind in the city, the wind field bears local characteristics influenced by mountain-valley circulation at different times of a day. In the early hours (02.00), the areas along the mountains in the west feature mountain wind from the western mountainous areas to the plain; in the morning (08.00), the effect of the mountain wind weakens; in the afternoon (14.00), valley wind blows from the plain to the western mountainous areas; in the evening (20.00), the mountain wind returns. It can be seen that the areas along the mountains in the west of Chengdu are influenced by a mountain-valley circulation.

According to China's national standard of wind scale, wind of 0.3 m/s~3.3 m/s is defined as soft and light breeze. It is the range where the ventilation effect by urban ventilation corridors is the most obvious after that of the calm and fresh wind conditions. The diagram on the left in Fig. 10 shows an analysis of the wind environment under soft and light breeze conditions in Chengdu's main development area, whereas the one on the right displays a temperature analysis under soft and light breeze conditions.

It can be seen that Chengdu's soft and light breeze is mostly north-easterly and north-westerly. As it approaches the urban area, restriction occurs at the urban-rural boundary, leading to turbulence and lower wind speeds in the urban area when compared to that in the rural area. It is difficult for soft and light breeze to penetrate through the southern part of the city centre, which is at a downwind location. Thus, the area has a higher temperature compared to areas in the west and the north. Urban surfaces have a significant impact on soft and light breeze, which in turn affects the ground surface temperature.

5.4.2. Potential wind dynamics

Fig. 11 shows a layout of ground surface roughness lengths calculated

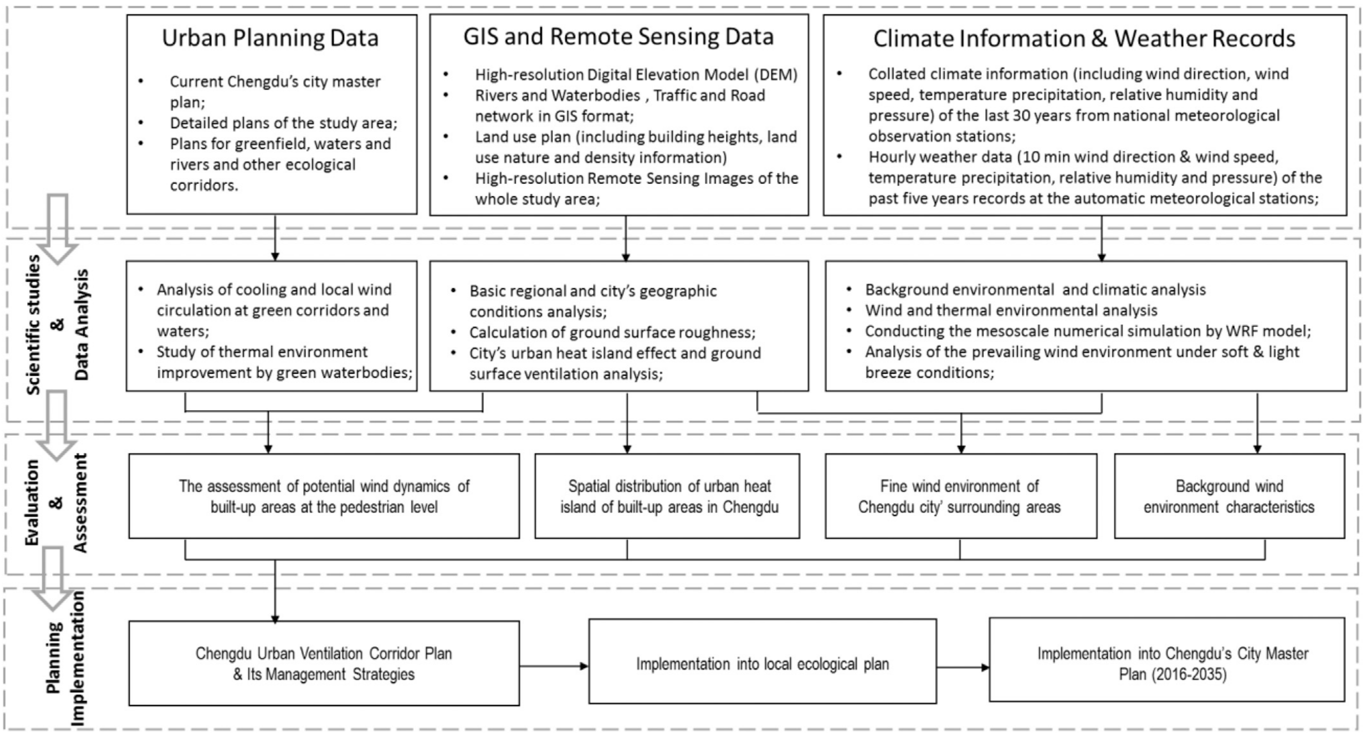

Fig. 7. Research workflow chart.

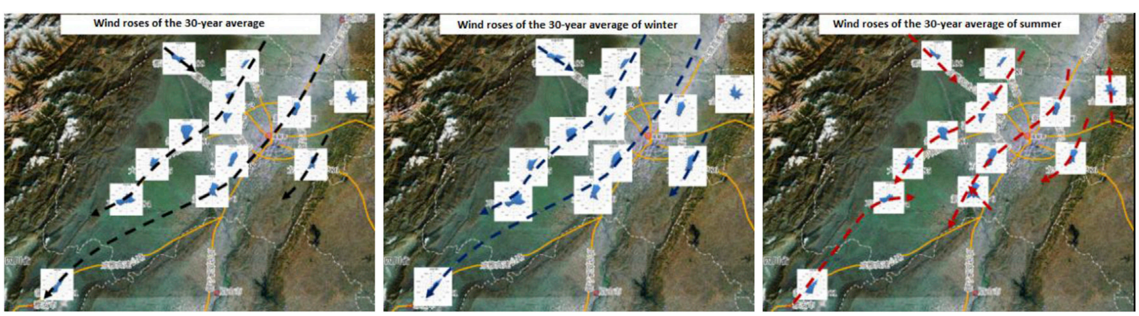

Fig. 8. Wind Roses of the 30-year Average (left), Winter (middle) and Summer (right) wind environment from the National Meteorological Stations in Chengdu.

from the average heights of lots and building coverage. It can be seen that the ground surface roughness lengths (Z0) in most areas outside the second ring are smaller (Z0<3.6 m). However, in the southern, south-eastern and western areas, there are some parts with larger roughness lengths (Z0>5.6 m). Particularly in the south, the roughness lengths of some parts exceed 8.5 m.

5.5. *Chengdu Urban Ventilation Corridor Plan (CUVCP)*

5.5.1. *Principles of the construction of CUVCP*

By combining the research results of the city's meteorological conditions, ground surface ventilation evaluation and the general principles used in overseas ventilation corridor construction, the following principles were suggested for the construction of a ventilation corridor system in Chengdu:

1) Align with the prevailing wind direction. Research has shown that the angle between the major ventilation corridor and the prevailing wind should be no larger than 30° to maximize the ventilation and air movement effects in the urban area. In Chengdu, the prevailing wind, as well as the soft and light breeze, is north-easterly and northerly. Therefore, focus should be placed on directing the north-easterly and northerly prevailing wind and soft and light breeze into the city centre.
2) Make use of the local circulation. Local circulation (such as mountain-valley and water-ground wind) may exist in the city's peripheral areas because of the heat effect. The construction of ventilation corridors can make use of these local wind field characteristics. According to the analysis and the numerical simulation of observational meteorological data in Chengdu, the Longmen Mountain areas feature mountain wind blowing from the mountainous areas to the plains. It is an important source of clean air for the plains. Therefore, the construction of ventilation corridors should also take advantage of the north-westerly mountain wind.
3) Make local considerations and respect the city's original features. The city centre of Chengdu is densely structured. There are little expansive green fields, water bodies or roads inside the third ring. Its ribbon area that has a lower roughness length and better ventilation is also small. When building an urban ventilation corridor system, the main ventilation corridor should connect with secondary ventilation corridors after reaching the city centre. In that way, the whole urban area can be penetrated.
4) Use rivers, road networks and other lots of stronger ventilation effects, instead of undertaking major demolition and construction

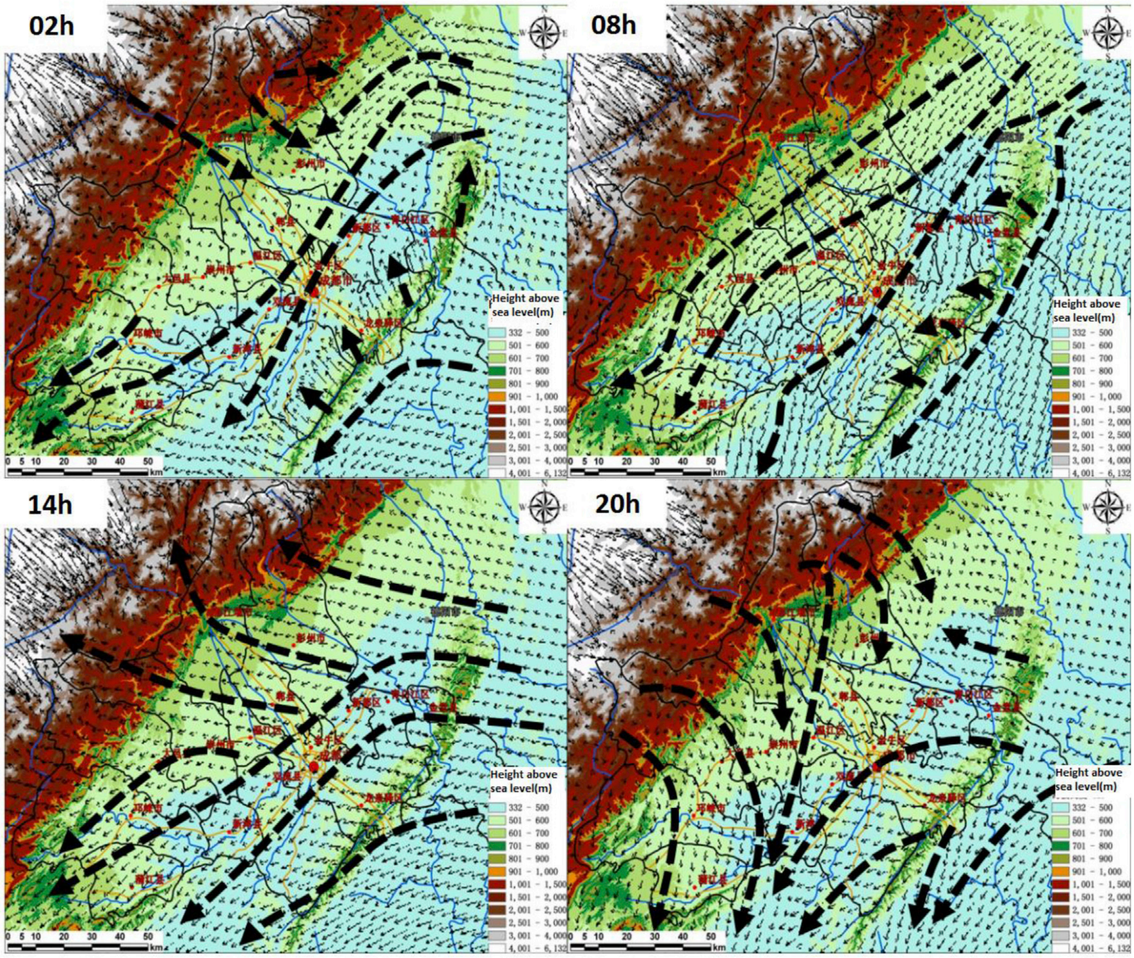

Fig. 9. Wind field simulation results under typical north-easterly wind weather scenario in Chengdu.

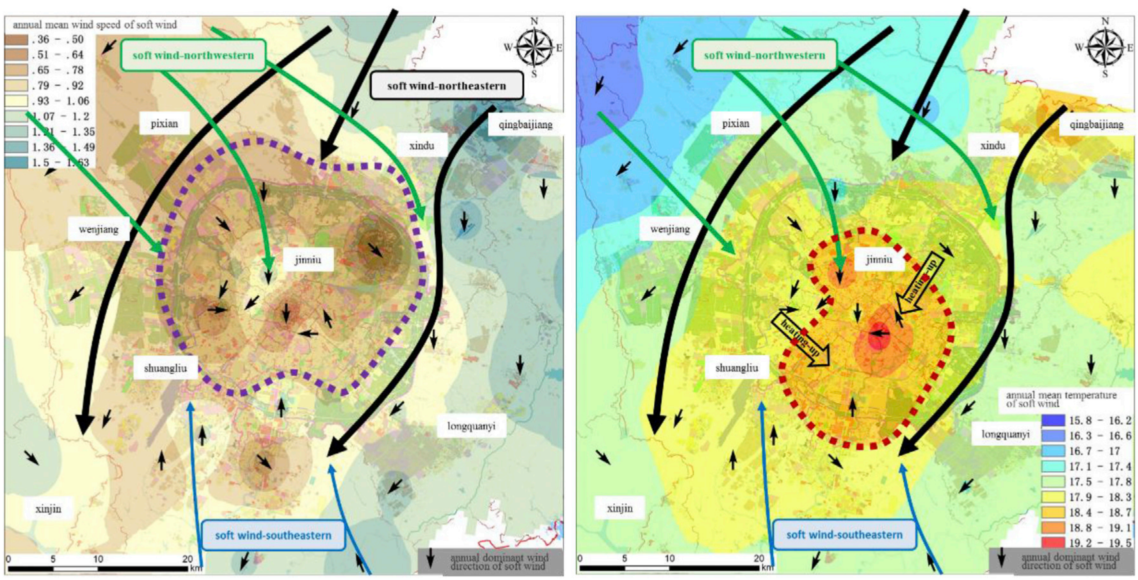

Fig. 10. Annual soft and light breeze analysis (left) and temperature analysis under soft and light breeze conditions (right) in the main development area of Chengdu.

works. The ground surface roughness of roads and rivers are lower. They are more open, have stronger ventilation effects, and can act as urban ventilation corridors. Select suitable roads and rivers according to the wind field characteristics and land-use plans; plant densely on the two sides of the road; refurbish, widen and protect rivers; control the heights, density and layout of buildings on both sides of the ventilation corridor.

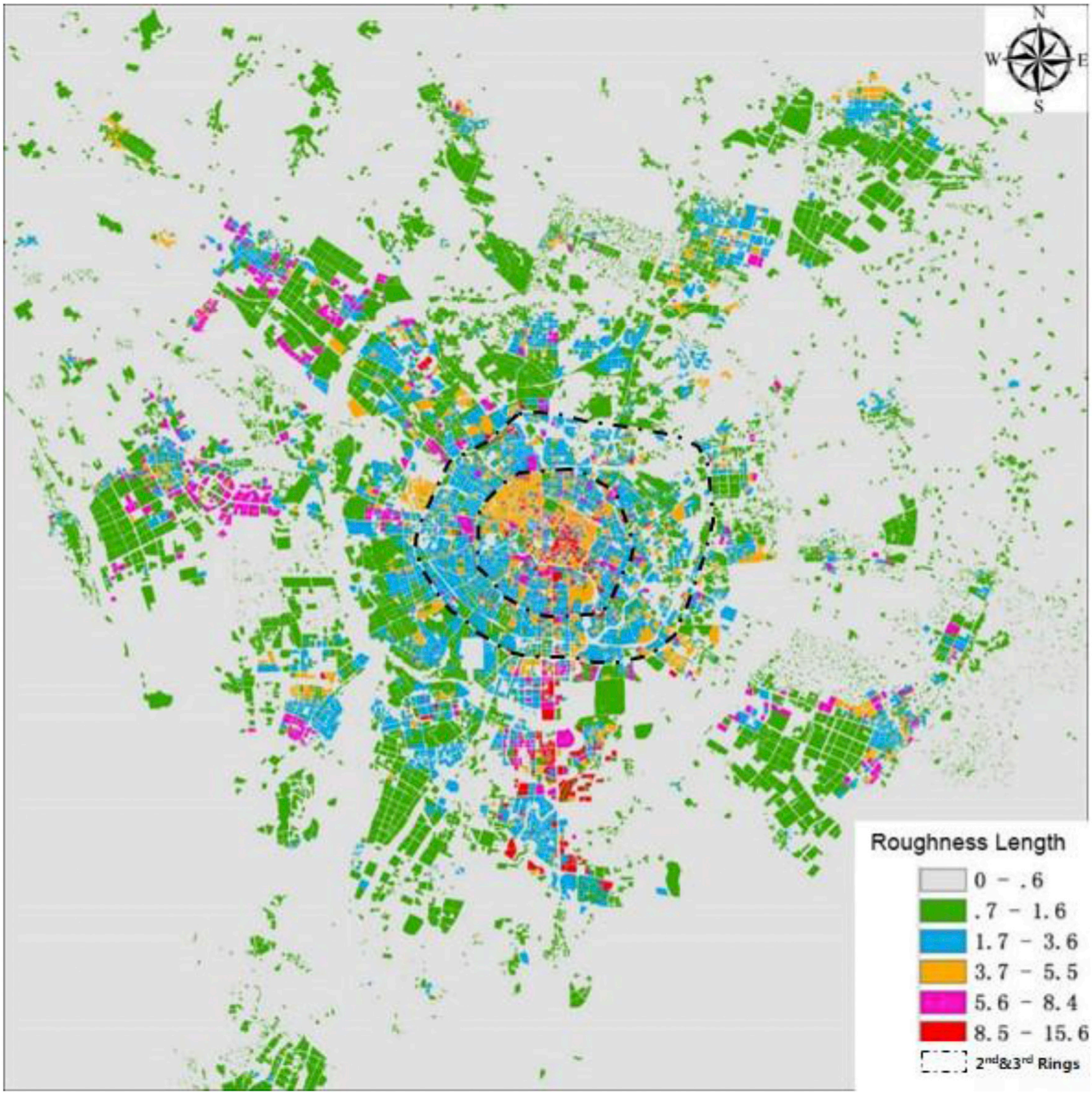

Fig. 11. Distribution of ground surface roughness lengths in the main development area.

5) Take special care of areas with little wind and high temperatures. The fine details of a city's wind and temperature fields should be taken in consideration. The ventilation corridor should penetrate urban areas with lower wind speeds to improve local ventilation. At the same time, hotter areas should be segmented to enhance the local thermal environment. Open spaces should be maintained to prevent the intensification and spreading of UHI.
6) Combine ventilation corridor construction with ecological planning. In the construction of urban ventilation corridors, natural cooling systems with ventilation and heat dissipation functions should be considered. Some examples include the natural landscape, green spaces, rivers, lakes and other water bodies. Research has shown that the temperature at a large urban green space is 1–2 °C lower than its surroundings (Chen & Wong, 2006, 2009). Green space also lowers the temperature of neighbouring areas, particularly those downwind, by increasing the surrounding wind speeds. The cooling effect can extend to areas 3 km away (Tong et al., 2005). Therefore, fresh air from cool sources identified in Chengdu's landscape and ecological planning can be directed into the urban area by considering the wind field characteristics of the city. The circular ecological zone in the centre of Chengdu city shown in Fig. 12 is the result of urban ecological planning. The major urban ventilation corridor is connected with the circular ecological zone, following the above principle of urban ventilation corridor development.

5.5.2. *Chengdu Urban Ventilation Corridor Plan and its Management Strategies*

Six main ventilation corridors and 24 secondary ones were therefore formed, with reference from overseas and local research, and the city's master plan. The ventilation corridor system comprises ecological buffer zones, greenbelts, roads, rivers, parks and green spaces (Fig. 13). Suggested strategies to control and manage the urban ventilation corridors in Chengdu are listed in Table 7.

5.5.3. *Planning implementation*

An analysis of land use suitability in the main development area was conducted according to the urban ventilation corridor plan and the layout of different city functions and land uses. A plan for the management of and control in areas along the corridors was then drawn up (Fig. 14). The key control area in Fig. 14 is buildable urban land defined by the city master plan. However, unfortunately, it is located inside the proposed urban ventilation corridor. Given its sensitivity to the urban ventilation penetration, this piece of land has been highlighted in the urban ventilation corridor plan and it is suggested that architects and

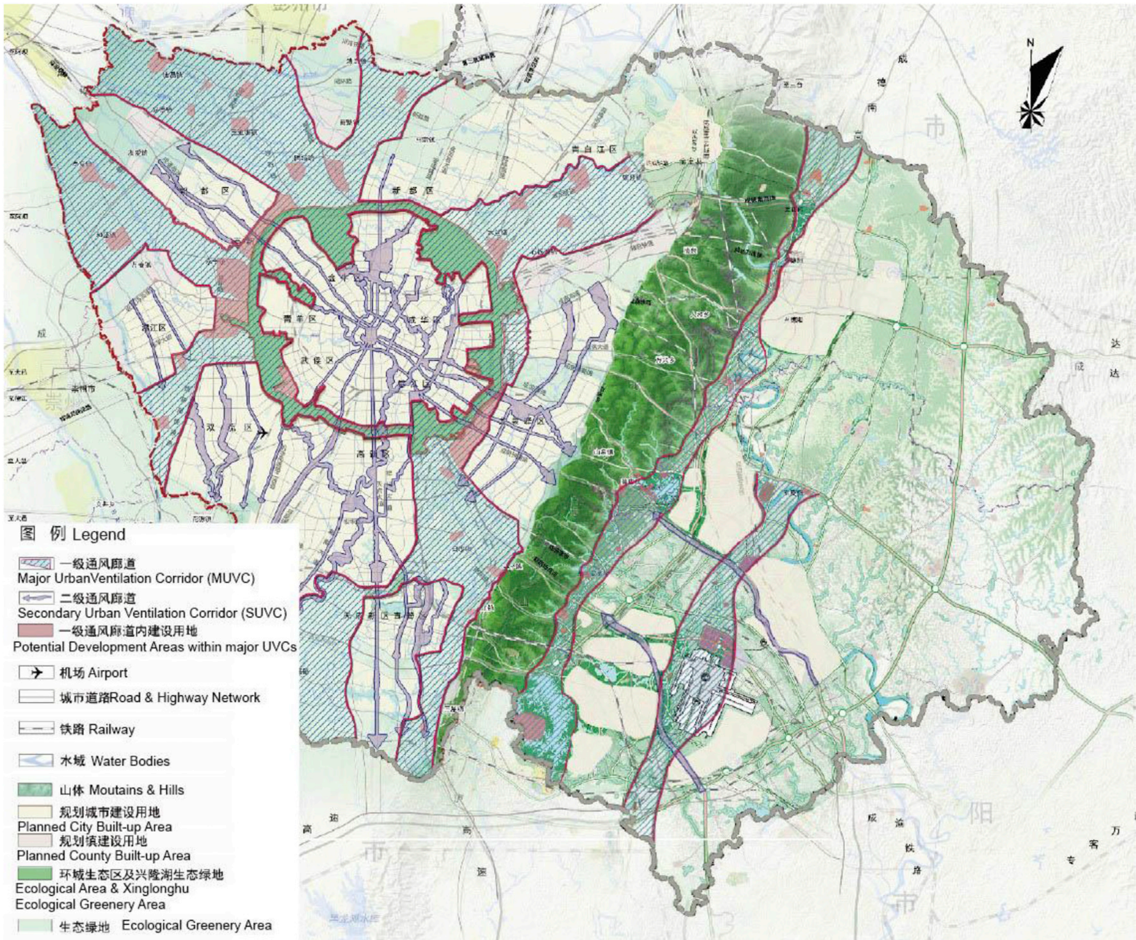

Fig. 12. An Excerpt of the Urban ventilation Corridor Plan from the City Master Plan of Chengdu (2016–2035) bill.

planners should make their proposals carefully at the design stage.

The drafting of the "Urban Master Plan of Chengdu (2016–2035)" bill was completed in March 2018 (Fig. 12). In April 2018, the document for public consultation states that '*The city's layout should respect the wind environment and local wind circulations. Urban ventilation corridors are formed by ecological buffer zones, greenbelts, roads, rivers, parks and green spaces. There will be six major urban ventilation corridors and 26 secondary ones in the city centre and new development area in the east. Land use, properties and building forms in the ventilation corridor areas will be strictly controlled.*' Fig. 14 shows an excerpt of the urban ventilation corridor plan from the "Urban Master Plan of Chengdu (2016–2035)" bill.

6. Discussion and conclusion

This paper provides a much-needed standardisation of the required data, the workflow process, and the methodology and control strategies for developing urban ventilation corridor plan for Chinese cities. Through the selected case study, it also demonstrates the fundamental principles for the construction of urban ventilation corridors and climatic-sensitive design actions for planners and policymakers at the urban master plan level. Here, the authors would like to share some practical experiences and lessons learnt from this guide development and from other previous urban climatic application projects in Chinese cities.

6.1. The need for interdisciplinary collaboration and communication

In the process of creating an urban ventilation corridor plan, it is apparent that such urban climatic application involves expert knowledge from numerous disciplines, ranging from the fundamental scientific pursuit of urban ventilation and local climatic characteristics (including background wind environment, local wind circulation systems, potential wind dynamics and UHI effect) to planning and design practices, and from scientific evaluation to policy and planning decision-making. For such application-based governmental consultancy projects, scientists, researchers, planners and officials from different goverment departments often need to work together. Even within the scientific and technical study community, researchers, experts and scientists with multi-disciplinary backgrounds in remote sensing, GIS, geography, environmental science, climatology and meteorology need to synergise their scientific findings into an impact assessment of the built-up environment on local climatic conditions, which serves as scientific evidence and basis for planning and design. In a later stage, the implementation and development of corresponding planning instructions and design actions also require joint efforts from planners and policymakers. So, every step in between involves a significant amount of knowledge transfer in both ways. Because of the different backgrounds, expertise knowledge and working languages, working meetings often end up as a discussion, or sometimes even more like a negotiation. For example, scientists and climatologists can use numerical models to simulate wind environment for different seasons and obtain precise wind speed information. Whereas for planners, they may only be interested in knowing the most critical and predominant conditions which require better design features, so that they can make better decisions on planning scheme selection and urban/building morphology controls, such as the ground coverage ratio, plot ratio, building layout and orientation, land use allocation and other design parameters. GIS and mapping technologies are often adopted to create an information platform for visualizing and spatializing scientific data and analysis results for planners and policymakers.

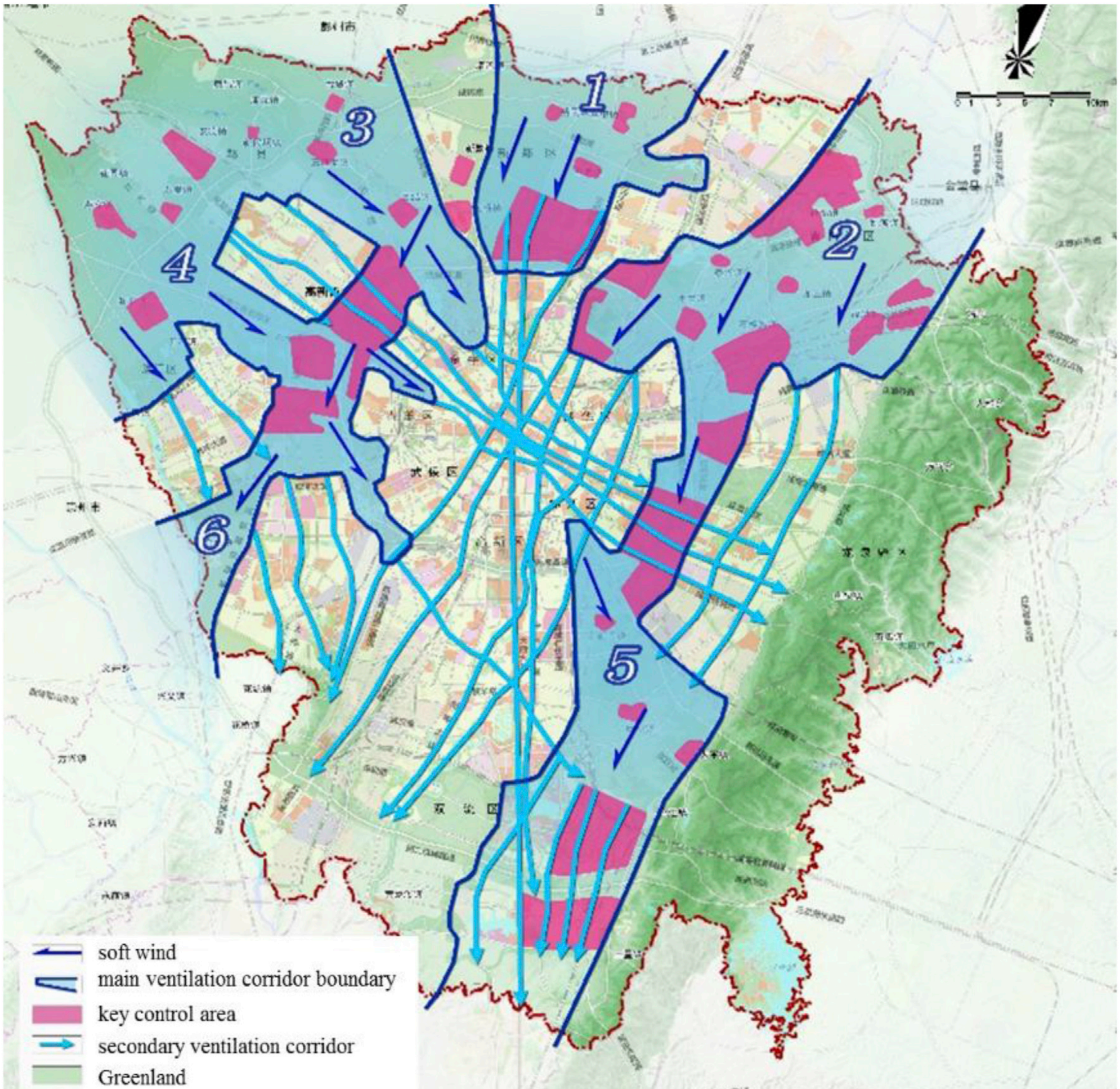

Fig. 13. Chengdu urban ventilation corridor plan.

Table 7
Control and management strategies for ventilation corridor planning.

	Major Ventilation Corridor	Secondary Ventilation Corridor
Composition	Open spaces consisting of wedge-shaped green space and greenbelt	Rivers, parks, green space, roads, roadside greening and low and scattered building clusters in the city's built-up area
Width	500 m	≥50 m
Length of Prevailing Wind	5000 m	≥1000 m
Width of obstacles perpendicular to air flow	≤10% of the corridor's total width	≤20% of the corridor's total width
Remarks on management and control	Strict management according to the corridor boundaries, gradual displacement of polluting industries, strict control of ratio of construction land; more greening in built-up areas to further improve the ventilation power of the corridors; strict height and density control in new development areas, evaluation of impact on the meteorological environment, adopting layout that promotes ventilation._	

6.2. The timing of planning implementation and intervention

Planning and design exercises each have their own processes and timeframes. In China, it normally involves five steps, including initiation, development of the spatial plan (the overall urban planning plans and detailed construction plans), coordination, public engagement, and approval and registration. In practice, the results of planning at one level will be followed by corresponding hierarchal processes to inform the next level's plan. Thus, the timing of climatic implementation is critical. It is often found that climatic-sensitive planning and design features cannot be applied properly because people miss the opportunities to suggest changes before the final decision has been made. Therefore, being able to make a quick knowledge transfer at an early development stage of the spatial plan is essential.

For example in Hong Kong, urban ventilation assessments and the implementation of urban ventilation corridors in the outline zoning plan have been initiated and conducted by the Planning Department (PlanD) of the Hong Kong Government since more than ten years ago. Its implementation system includes expert evaluation (EE), initial study and detailed study. The EE is particularly beneficial and cost-effective. Registered and qualified experts employed by the PlanD provide a qualitative assessment on good design features, potential problem areas

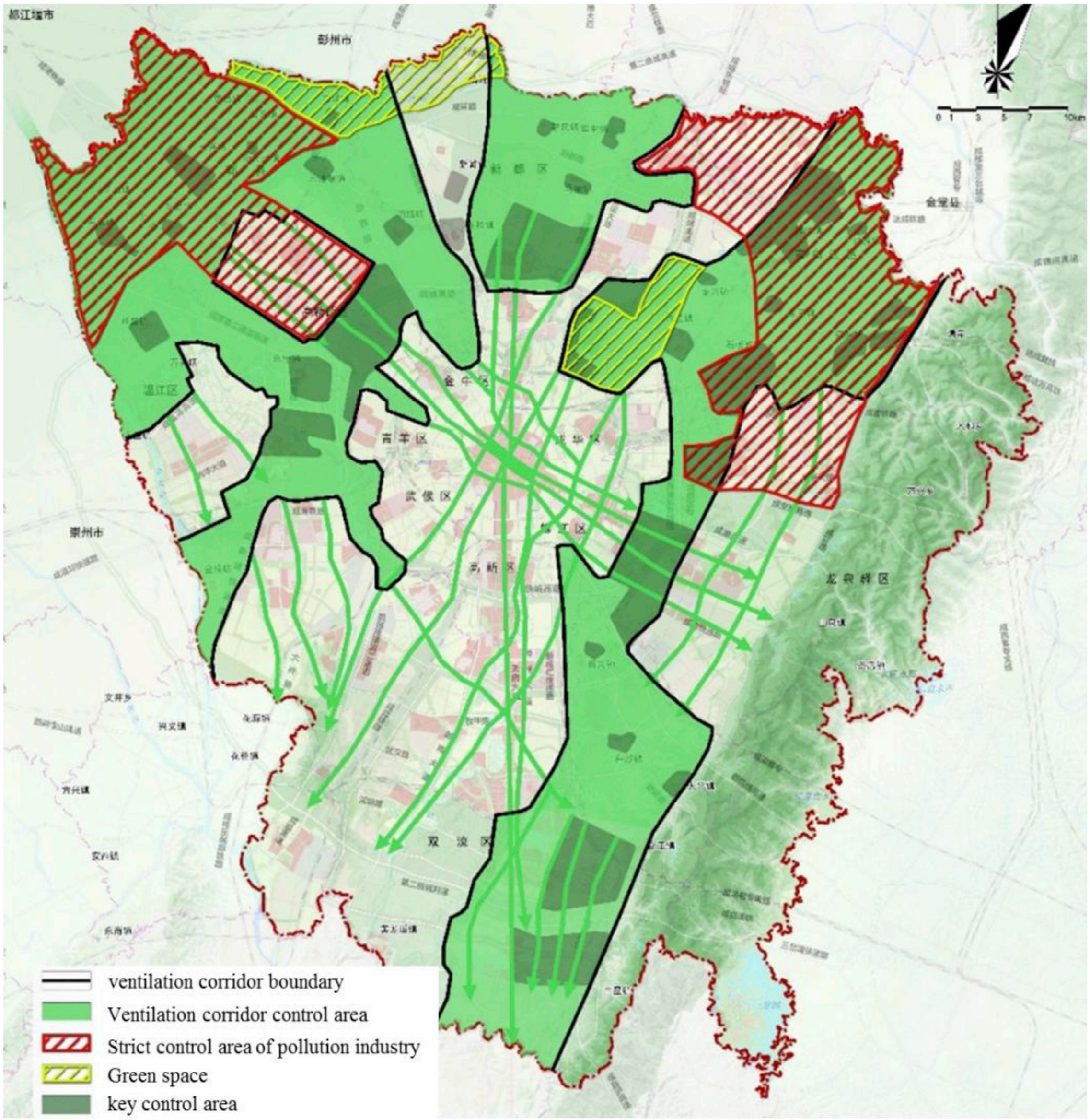

Fig. 14. Control areas for developing urban ventilation corridors in Chengdu.

and propose corresponding mitigation measures, and also determine the need for further studies (the initial and/or detailed studies) and their corresponding focuses and methodologies (Fig. 15). A recent Air Ventilation Assessment (AVA) for Mong Kok district was conducted. The planning area of Mong Kok is known for its high density old town with weak wind and air pollution problems. Local experts adopted a newly developed modelling-mapping approach (Yuan and Ng, 2012) to quickly quantify the potential impacts of planned changes to a baseline scenario using the concept of building frontage (defined as the vertical surface area of a building façade as a percentage of the maximum possible surface area of that building façade), which is dependent on the height, ground coverage, and permeability of a building façade (Kwok and Ng, 2018). Another example is the urban microclimate study from Hong Kong Green Building Council. Its guidebook suggests that the majority of urban microclimate design strategies should be implemented before the detailed design stage and a qualitative analysis is needed to provide a scientific basis for decision-making in planning and design (Ng et al., 2018).

6.3. The need for data collection and assembly

From a series of recent policy documents, it can be seen that the Central Government of China regards and highlights urban planning as an important basis and method for guiding environmental protection and recovery, and is actively putting climate change adaptation into practice through rational development, construction and administration. Most Chinese cities operate like management systems that respond by mitigating the actions that cause undesirable changes and then adapting the system to cope with environmental hazards. The recent development of urban ventilation corridor plan is just an example in response to issues of poor air quality and weak wind in most Chinese cities. Different cities often have different capacities to respond and adapt, based on their governmental operation systems, available resources, social-economic situations, political agenda, local needs and so on. However, a common challenge faced by the authors during their working experiences with different Chinese cities in the past ten years is the lack of a standard database on urban morphology and natural landscapes for urban climatic

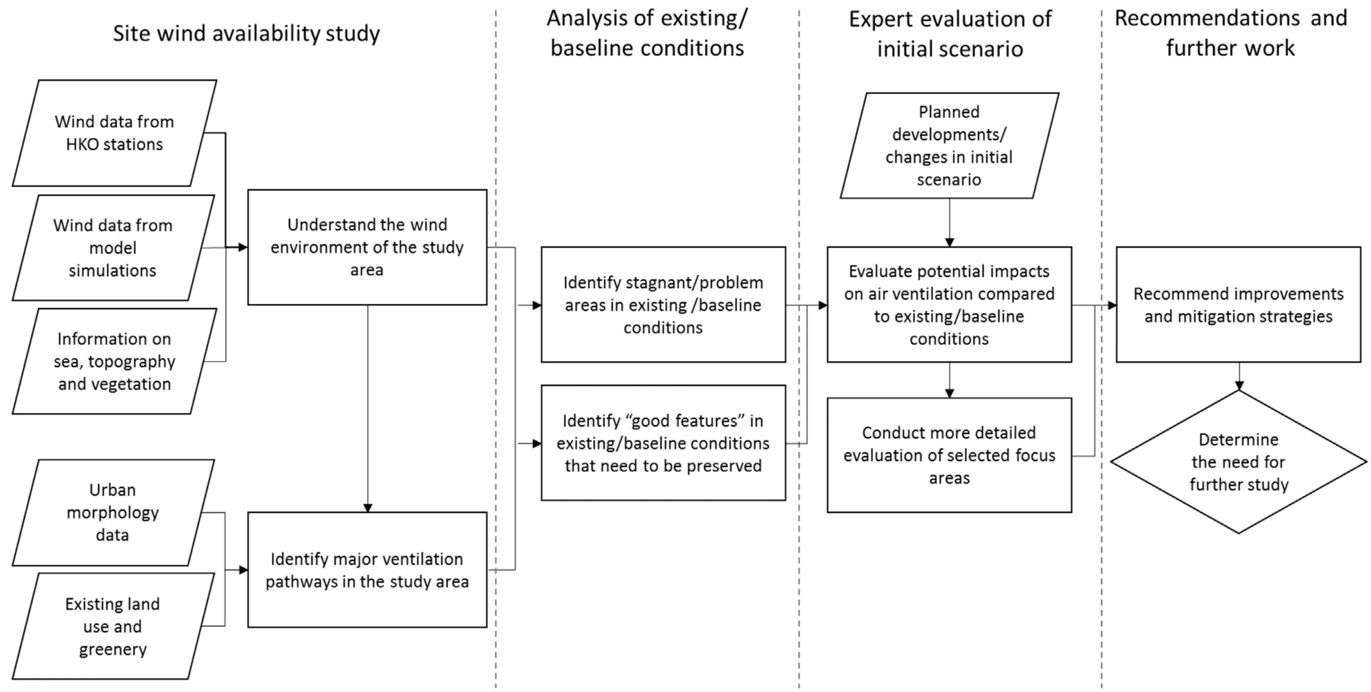

Fig. 15. Workflow diagram of Hong Kong Air Ventilation Assessment Expert Evaluation.

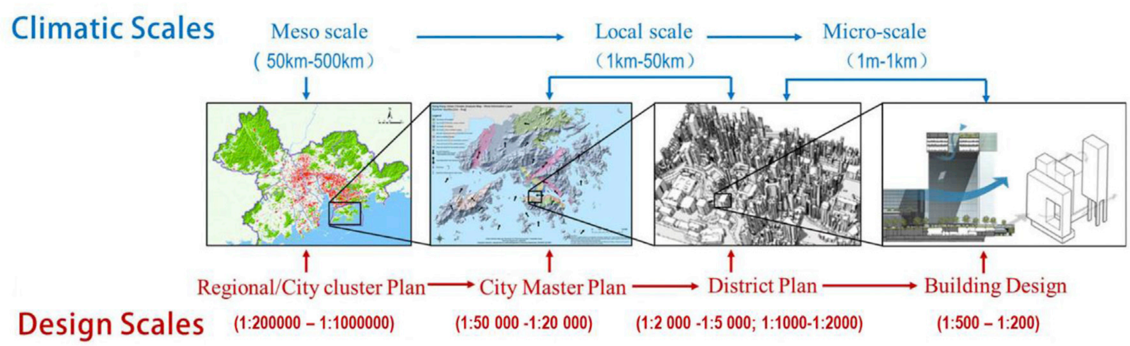

Fig. 16. Climatic scales vs. design scales.

studies. Underlying reasons may include: building information not existing or is still in the process of digitalisation in local city governments; databases not accessible for the public, and not even consultant teams commissioned by the government; unwillingness of some governmental departments to share databases and the lack of corporation between departments. Thus, an open but standardised urban morphological database is much needed for urban climatic application studies and projects. Since 2015, a research team led by Prof. Chao Ren at the Chinese University of Hong Kong has worked on developing an urban morphology database for Chinese cities and regions. Some newly acquired data have already been used in urban climatic application projects and research studies in Chinese cities and regions (Cai et al., 2018; WANG et al., 2018a; Wang et al., 2018b; Xu et al., 2017).

6.4. Implementation: climatic scales vs. planning scales

When climatologists and meteorologists conduct their research, they often work on three climatic scales, namely mesoscale, local scale and micro-scale. In the planning and design field, however, town planners, architects and policymakers also have their own commonly adopted working hierarchy with four different scales, including regional plan, city master plan, district plan and building design. As such, communication problems may arise due to the different working scales amongst scientists and practitioners. Thus, it is important for both communities to understand each other and make a smooth knowledge transfer between the two working scale systems. Ren's study (2016) creates a diagram (Fig. 16) to show these two different working scale systems and how they relate to each other.

Besides taking into account of urban climatic or wind-related factors, planners and policymakers also need to balance considerations in the social, economic and environmental aspects when making decisions in land use zoning and capacity for future development, defining development intensity and urban morphological indices, and selecting planning and design proposals. As pointed out by Ng (2012), an overload of information from the scientific community may actually hinder the implementation of climate-responsive planning as it causes confusion for planners and make them unconfident to take proper actions in a timely manner.

6.5. Future work

The Technical Guide presented in this paper is the first attempt of the Central Government of China to incorporate urban climatic application into town planning and design at the national level. It is by no means an easy task, but there is still a long way ahead. In Germany, the urban climatic application has been conducted for more than 70 years. In Japan, researchers have been doing such studies and projects for over 30 years. The Hong Kong government has introduced a range of measures and has conducted a variety of consultancy and technical studies to improve the urban climate since 2003. Scientific and technological development, practice and design, supporting policy, as well as public awareness and education are equally important for the success of planning implementation (Ng et al., 2018). Thus, apart from formulating technical notes, design guidelines and other legal documents, it is necessary to develop a proper implementation mechanism system which may involve a carrot-and-stick approach for developers in the industry, and general education to the public. The joint effort among the scientific community, different governmental departments, industrial practitioners and the public is essential to improve the living environment and urban climatic conditions in cities.

Ipsos MORI released their 2018 global survey of 25 countries on what most people worry about. It reveals that for China, 'threats against the environment (44%)' and 'climate change (25%)' are the top two concerns of people from all the countries (Ipsos, 2018). Fortunately, there is an increasing interest in sustainable urban development and healthy cities from local citizens in China. The general public requests and pushes local governments to consider and implement the control measures of air pollution dispersion in town planning and design practices. A recent research shows the most influential building morphological design features the pollution dispersion dynamic potential and translates the sophisticated research outputs into a set of straightforward and practice-ready design recommendations for planners (Shi et al., 2018; Yuan et al., 2014a,b). Futhermore, health impact analysis is another consideration that should be incorporated into town planning and policy decision-making (Sarkar et al., 2014; Yang et al., 2018).

With the implementation of the Urban Ventilation Corridor Technical Guide and practical experiences from Chinese cities, the authors look forward to the future developments of urban climatic application to improve the environmental quality and to create healthy cities for urban citizens in China.

Acknowledgements

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jweia.2018.09.023.

Appendix. Index calculation method

Part 1: sky view factor

A raster calculation model based on digital elevation is used to estimate the sky openness SVF. The calculation principle is shown in Fig. A.1.

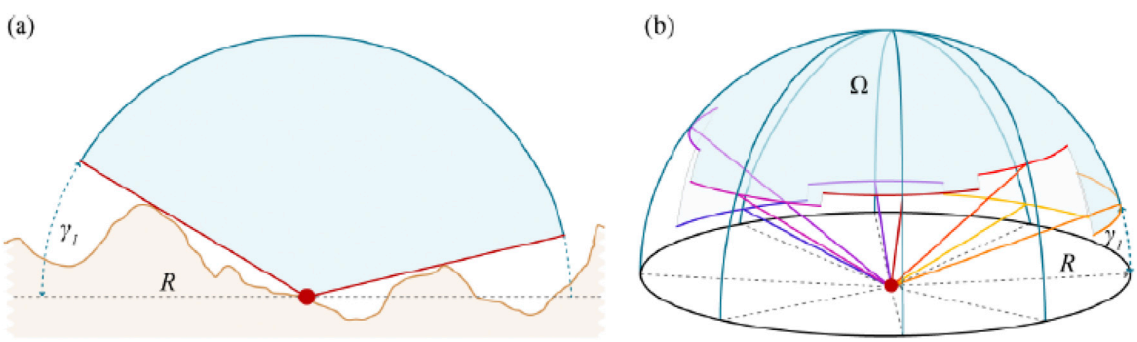

Figure A.1. The calculation diagram of sky view factor a) A cross section of SVF influenced by terrain. b) The spatial diagram of SVF influenced by terrain. Explanation: *R*——The influential radius by the terrain, in meters (m). The recommended R value should not be less than 20 times the grid resolution; γ_i——The zenith angle of the terrain at the ith azimuth, in radians; *i*—— The number of azimuth; Ω——Sky view solid angle, in radians.

Sky view solid angle Ω and sky view factor SVF calculation formula is shown in A.1 and A.2.

$$\Omega = \sum_{i=1}^{n} \sum_{\gamma_i}^{\pi/2} \cos\varphi . d\varphi = 2\pi . [1 - \frac{\sum_{i=1}^{n} \sin\gamma_i}{n}] \tag{A.1}$$

$$SVF = 1 - \frac{\sum_{i=1}^{n} \sin\gamma_i}{n} \tag{A.2}$$

Where, the meaning of the variable with the same name is same as above, and other variables in the formula:

SVF——Sky view factor, value ranges from 0 to 1.0, dimensionless;
Φ——Azimuth angle in radians;

n—The number of calculated azimuths. The value of n should not be less than 36.

Part 2: roughness length

The formula for estimating roughness length in urban areas (Bottema, 1995; Corrigenda, 1995; Grimmond and Oke, 1999; Raupach, 1992, 1994):

$$\frac{Z_d}{Z_h} = 1.0 - \frac{1.0 - \exp[-(7.5 \times 2 \times \lambda_F)^{0.5}]}{(7.5 \times 2 \times \lambda_F)^{0.5}} \tag{A.3}$$

$$\frac{Z_0}{Z_h} = (1.0 - \frac{Z_d}{Z_h})\exp(-0.4 \times \frac{U_h}{u_*} + 0.193) \tag{A.4}$$

$$\frac{u_*}{U_h} = \min[(0.003 + 0.3 \times \lambda_F)^{0.5}, 0.3] \tag{A.5}$$

Where:

Z_d——Zero-plane displacement height, in meters (m);
Z_0——Roughness length, in meters (m);
Z_d/Z_h——Height-normalized values of zero-plane displacement height;
Z_0/Z_h——Height-normalized values of roughness length;
U_h——Wind speed, in meters per second (m/s);
u_*——Friction velocity (or shear velocity), in meters per second (m/s);
λ_F——Building Frontal Area Index;
Z_h——Building height, in meters (m).

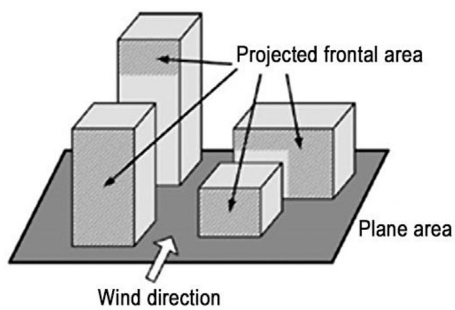

Figure A.2. The calculation diagram of building frontal area index.

The calculation principle of building frontal area indexλ_F is shown in Fig. A.2:

$$\lambda_{F(\theta,z)} = \frac{A_{(\theta)proj(\Delta z)}}{AT} \tag{A.6}$$

$$\lambda_{F(z)} = \sum_{i=1}^{n} \lambda_{F(\theta,z)} P_{(\theta,i)} \tag{A.7}$$

Where:

$A_{(\theta)proj(\Delta z)}$——Building frontal area (projected frontal area along the wind direction θ);
θ——Different direction angles of the wind;
AT——Plane area for the calculation;
ΔZ——The height range of the building frontal area calculation;
$P_{(\theta,i)}$——The average frequency of occurrence of the wind at the ith direction;
n——The number of wind directions counted by the weather station, where n = 16.

Part 3: urban heat island intensity

3.1 The calculation of urban heat island intensity

With reference to the relevant literature and guidelines for environmental performance assessment of urban ecological construction, the land surface temperature retrieved from satellite image is used to calculate the intensity of urban surface heat islands. The difference between land surface temperature of urban area and suburban background temperature (average surface temperature in rural areas) is defined as the surface heat island intensity in the study area.

The detailed calculation is as follows:

$$SUHI_i = T_i - \frac{1}{n}\sum_{j=1}^{n} T_{crop_j} \tag{A.8}$$

Where:

$SUHI_i$——The intensity of the surface heat island corresponding to the ith pixel on the image in degrees Celsius (°C);
T_i——The surface temperature of the ith pixel in degrees Celsius (°C);
T_{cropj}——The surface temperature of the jth pixel in the suburban farmland area in degrees Celsius (°C);
n——The total number of all valid pixels in a suburban area.

The selection of suburban farmland area should refer to the following principles:

—— Plains (the difference in elevation between the urban area and the plain is less than 50 m);
—— Types of farmland in remote suburbs;
—— Vegetation coverage ≥ 80%;
—— Impervious coverage ≤ 20%.

For monthly and seasonal heat island intensity calculations, MODIS 1-km resolution satellite data is recommended; for typical daily fine-resolution heat island intensity calculations, Landsat series satellite data (spatial resolution about 100 m) is recommended.

3.2 The estimation of vegetation coverage and impervious coverage

Vegetation coverage and impervious coverage can be estimated based on Landsat satellites or satellite data of equivalent resolution using the vegetation-impervious surface-soil composition model (V—I—S—W model). Surface pixels (usually mixed pixels) can be represented by a linear combination of vegetation, water impervious surface (high-albedo impervious surface and low-albedo impervious surface), bare soil, and water bodies:

$$R_i = f_{low}R_{low,i} + f_{high}R_{high,i} + f_{veg}R_{veg,i} + f_{soil}R_{soil,i} + e_i \tag{A.9}$$

Where:

R_i——Pixel reflectance;
f_{low}——Percentage of the area of low-albedo impervious surface in pixels;
f_{high}——Percentage of the area of high-albedo impervious surface in pixels;
f_{veg}——Percentage of the area of vegetation in pixels;
f_{soil}——Percentage of the area of bare soil in pixels;
R_{low}—— Reflectance of the area of low-albedo impervious surface in pixels;
R_{high}—— Reflectance of the area of high-albedo impervious surface in pixels;
R_{veg}—— Reflectance of the area of vegetation in pixels;
R_{soil}—— Reflectance of the area of bare soil in pixels;
e_i——Reflectance random error;
i——pixel number.

Vegetation coverage can be represented by the percentage of the area of vegetation in pixels f_{veg}, while impervious coverage is the sum of the percentage of the area of low-albedo impervious surface in pixels f_{low} and the percentage of the area of high-albedo impervious surface in pixels f_{high}.

Part 4: cool fresh air sources

Using Landsat vegetation index - NDVI to estimate the areas of cool fresh air sources (S):

$$S = 1/(1/30000 + 0.0002 \times 0.03^{NDVI}) \tag{A.10}$$

$$NDVI = (\mathrm{Ref}_{Nir} - \mathrm{Ref}_{\mathrm{Red}})/(\mathrm{Ref}_{Nir} + \mathrm{Ref}_{\mathrm{Red}}) \tag{A.11}$$

Where:

S——The areas of cool fresh air sources, in square meters (m^2);
Ref_{Nir}——The reflectance of the near infrared (NIR) band of Landsat satellite image;
Ref_{Red}——The reflectance of the red band of Landsat satellite image.

The derivation of the equation for estimating the areas of cool fresh air sources is referred to Di et al.'s study results (2012). This standard uses SPSS data processing software to solve various parameters. According to the principle of maximum correlation coefficient, the optimal model is selected as the regression model of the simulated NDVI and green quantity. According to the comparison of various regression results, the logistic model is adopted to comprehensively consider the model correlation and fitting effect. The formula (A.10) is obtained by calculating the green quantity of the TM remote sensing image NDVI.

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