Identification and Planning of Potential Ventilation Corridors: A Case Study of Wuhu, China

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Abstract
Ventilation corridors have a significant effect on the improvement of urban climate adaptation as well as the improvement of habitat quality. In the context of climate change leading to the frequent occurrence of extremely high temperatures, it is necessary to research urban ventilation corridors to optimise the urban wind environment and thermal comfort. In the past, wind speed measurement and computational fluid dynamics methods have had limitations in their application to large-scale urban spaces. In this study, with Wuhu City as a case study, a geographic information system (GIS)-based method was adopted to design an urban ventilation corridor suitability assessment framework for identifying potential ventilation corridors, which can support the identification and planning of ventilation corridors in large-scale urban planning and design.

Keywords: Urban Wind Environment; Ventilation Corridors; Compensation Space; Urban Heat Island (UHI)

1. Introduction

The world is currently experiencing significant changes characterized mainly by warming. Climate change is one of the most important challenges facing the global community in the 21st century, as it is causing problems such as sea level rise and the frequency of extreme weather events, which in turn are leading to a series of meteorological disasters and will continue to have significant impacts on natural and human systems (IPCC, 2021) The greenhouse gas (GHG) emissions lead to thermal changes in the built-up area. The deterioration of the thermal environment in built-up areas due to greenhouse gas emissions, the heat island effect, and the transformation of green spaces into impervious surfaces have also become one of the major concerns for global sustainable development, and how to cool cities has become a hot topic of research worldwide (Mirabi & Davies, 2022).

The heat island effect is closely related to urbanisation (Su et al., 2012). The problems of insufficient green space, over-concentration of population, and a large number of artificial heat sources all make cities heat islands. China is one of the significant regions in the global urbanisation process; in the rapid urbanisation process, the increase of urban population density and development intensity has led to a rise in the intensity of capacity release within the city. At the same time, the continuous expansion of the area of the urban construction area and the transformation of the land use type have led to a weakening of the ability of the city to communicate with the surrounding natural environment, especially in the urban construction area of the wind blockage by the building complex, the hardening of the urban underlay, industrial waste gas and traffic exhaust emissions, etc., all of which have led to the heat island effect. In particular, the blockage of wind by buildings in urban construction areas, the

hardening of the urban subsurface, and the emission of industrial and traffic exhaust have all had a negative effect on the urban atmospheric environment.
In the context of climate change, the heat island effect has become one of the major concerns of urban planners and designers today. The great potential of ventilation corridors in mitigating the urban heat island effect has been proven to be an effective urban cooling method in planning studies in Japan and Germany (Barlag & Kuttler, 1990; Kagiya & Yasunobu Ashie, 2009).

Ventilation corridors are an essential part of the urban wind environment, and urban canopy ventilation is considered to have great potential for improving urban heat islands. Many regions have incorporated them into their urban planning. To improve thermal comfort in cities, the 2016 Climate Change Adaptation Action Plan for Cities (CCAAPC) of China proposes the creation of urban ventilation corridors to improve the ventilation benefits within cities. Cities such as Shanghai, Beijing, Wuhan, and Nanjing have proposed "ventilation corridor planning" in their urban planning, intending to improve the urban ventilation environment through the study and planning practice of ventilation corridors.

Identifying spaces with ventilation potential is a prerequisite for ventilation corridor planning. To provide a reliable urban ventilation corridor planning method, this study uses Wuhu City as an experimental case to calculate the ventilation potential within the study area. The purpose of this study is to propose a quantitatively calculable method for identifying urban ventilation corridors, to estimate the suitability of ventilation corridors through heat island identification and built environment morphology analysis, and to provide a reference basis for ventilation corridor system planning.

2. Literature Review

The term "urban ventilation corridor" is derived from the German word "Ventilationsbahn", which refers to the channel constructed to improve the air mobility of the city, alleviate the heat island effect, improve the comfort of human beings, introduce fresh, cold and humid air into the urban area, which is an integral part of the urban wind environment. Urban natural ventilation comes from the local circulation system formed by the wind pressure difference and heat pressure difference. Kress carried out studies on air circulation in regional areas and pointed out that the urban ventilation system mainly consists of effective space (Wirkungsraum), compensation space (Ausgleichsraum) and ventilation paths (Luftleitbahn) (Kress, 1979). Ausgleichsraum refers to areas of the city where the wind environment urgently needs improvement, such as high-intensity built-up areas, densely populated areas, etc., and usually also areas with an intense heat island effect. Compensation space refers to areas that provide a source of fresh air, generate cool air, and promote air circulation, usually including broad blue-green spaces such as lakes and urban green spaces. Air-guided channels are air transfer paths that connect the compensation space to the action space. Based on the characteristics of the air flow, these passages can be divided into three categories: ventilation corridors (Ventilationsbahn), fresh air passages (Frischluftbahn), and cold air passages (Kaltluftbahn). Figure 1 demonstrates the relationship between the compensation space, effective space, and ventilation path.

The most commonly used technical approaches in the study of urban ventilation corridor analysis methods are wind speed analysis and computational fluid dynamics (CFD) methods (Ramponi et al., 2015) K. Niachou et al. conducted in wind speed measurements of street

canyons in Athens, Greece, to analyse the influence of urban morphology on airflow, environmental thermal effects (Niachou et al., 2008). The wind speed was measured in the street canyons of Athens, Greece. Because in situ measurements are time- and resource-intensive for data collection and are susceptible to unstable meteorological conditions (Schatzmann & Leitl, 2011), wind tunnels have been introduced to simulate urban wind environments. Previous studies have validated the correlation between building density and mean wind speed using wind tunnel test results (Kubota et al., 2008). The method can scale down the urban space and simulate the airflow in the laboratory by emulating the wind environment's characteristics such as wind speed, direction, and air pressure. This technique is simple, controllable, less susceptible to external environmental disturbances, and capable of continuous observation. However, it is more dependent on equipment and funding (He et al., 2022). Either field measurements or wind tunnel tests require costly experiments, limiting the method's practicality. With the advancement of computer science and technology, the computational fluid dynamics (CFD) method has been widely used in the simulation study of urban wind environments due to its advantages of lower cost, high accuracy, and speed (Ling Chen et al., 2017; Peng et al., 2017). Although CFD methods can simulate wind flow conditions in a small area with a high degree of refinement, they have a high demand for computational resources, and the modelling of CFD methods is too complex for many large-scale urban applications. In recent years, some scholars have used geographic information system (GIS)-based spatial morphology analysis methods to analyse building morphology and assess the urban wind environment using indicators such as surface roughness and building density for the identification of ventilation corridors (Hsieh & Huang, 2016; Peng et al., 2017; Liu et al., 2022).

Considering the limitations of wind speed analysis and CFD methods in large-scale urban space and the advantages of GIS-based wind environment analysis methods in large-scale spatial computation, this study will use GIS-based methods to assess wind environments and identify ventilation corridors at a large scale.

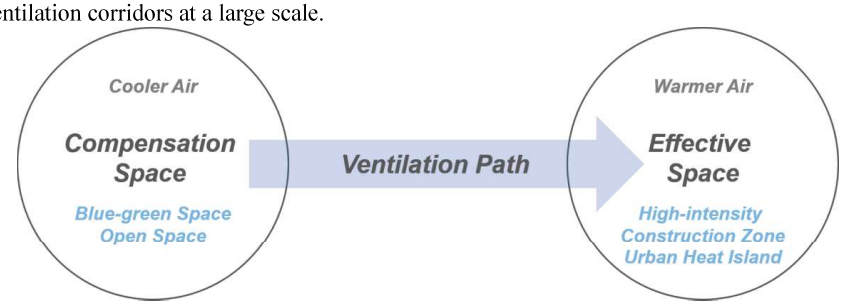

Figure 1. Relationship between compensation space, effective space and ventilation path

3. Materials and Methods

3.1 Study Area

Wuhu City is located in Anhui Province, China, on the lower reaches of the Yangtze River. The study area of this study is located along the Yangtze River in Wuhu City, north of the Qingyi River, about 30 kilometres along the river, with a total area of about 82 square kilometres. The year-round dominant wind direction in the study area is easterly, with an annual maximum wind speed of 18 m/s and an annual average wind speed of 2.8 m/s.

In summer, Wuhu City is controlled by the subtropical high pressure in the western Pacific Ocean, and there is more high-temperature and high-humidity weather. In the summer of 2022, the number of high-temperature warnings (≥35°C) in the area reached 41 days, in which there is a large slice of the high-temperature slice in the northern industrial agglomeration of the study area with a noticeable heat island effect. In terms of cold island areas, more cold island areas are distributed in the study area, including the Yangtze River, mountains, lakes, etc., forming more compensation space. Figure 2 shows the study area of this paper, a wind rose map with wind frequency statistics for different months of the year in the region, and urban heat islands identified by land surface temperature retrieval based on the August 2022 Landsat 9 OLI/TIRS data.

Given the high-temperature problems in the area, it is necessary to evaluate the wind environment in the area, identify and construct potential urban ventilation corridors, harmonise the characteristics of the urban climate environment, and improve the urban air circulation system.

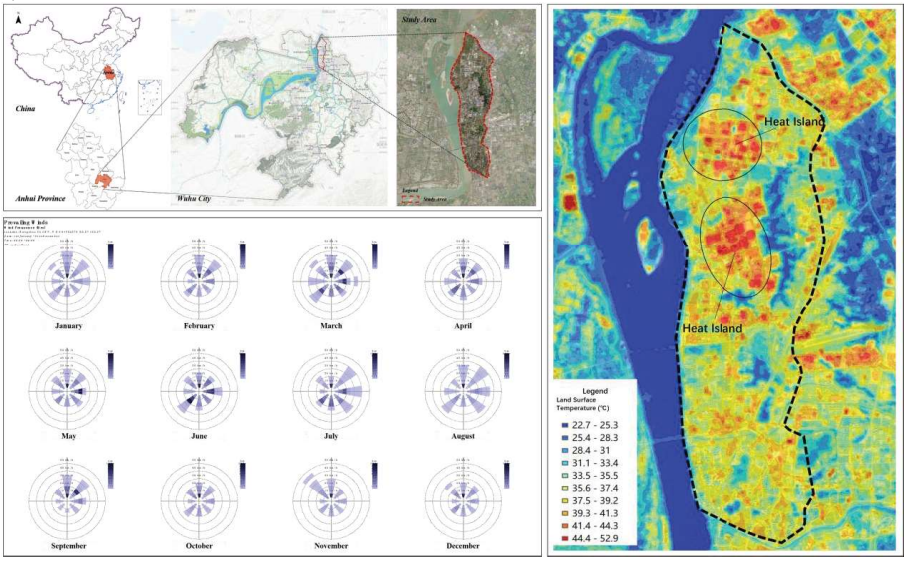

Figure 2. Study area boundaries, wind rose diagram, and land surface temperature

3.2 Data

Data were obtained from various sources, as shown in Table 1. All the data used in this study were calculated with the CGCS2000 coordinate system as recommended by the national government.

Table 1. Data sources and descriptions

Data	Data Source	Year
Landsat 9 OLI/TIRS data	United States Geological Survey (USGS) (https://earthexplorer.usgs.gov)	2022

Land use data (land use type)	Wuhu City Planning and Natural Resources Bureau	2022
Building data (footprint, height)	Wuhu City Planning and Natural Resources Bureau	2022
Road network data	Wuhu City Planning and Natural Resources Bureau	2022

3.3 Methods

This study aims to construct a wind environment assessment method based on a GIS multi-factor overlay to support the identification of ventilation corridors. The framework of the methodology used in this study is shown in Figure 3.

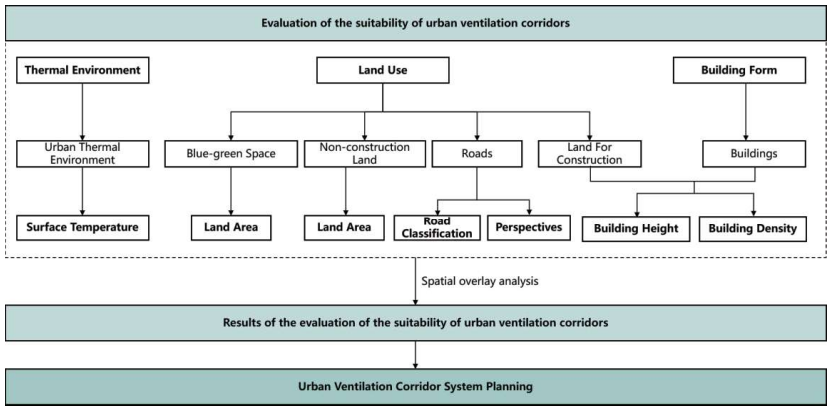

Figure 3. The framework assesses the wind environment and identifies urban ventilation corridors.

This study established a ventilation suitability evaluation method based on spatial superposition analysis, mainly considering the thermal environment, land use, and building form.

3.3.1 Thermal Environment

Land Surface Temperature (LST), a key parameter in the determination of urban heat islands, is the temperature of the Earth's surface as measured by thermal radiation and is one of the most important physical parameters examined in the modelling of land surface processes (Stewart & Kremer, 2022). This study used Landsat 9 OLI/TIRS data to retrieve the surface temperature to evaluate the urban thermal environment. In the analysis process, data from August 2022 were used, severe weather events such as rainy days were excluded, and the steps shown in Figure 4 were followed to calculate land surface temperatures within the study area using the atmospheric correction method and to identify heat island areas in the region.

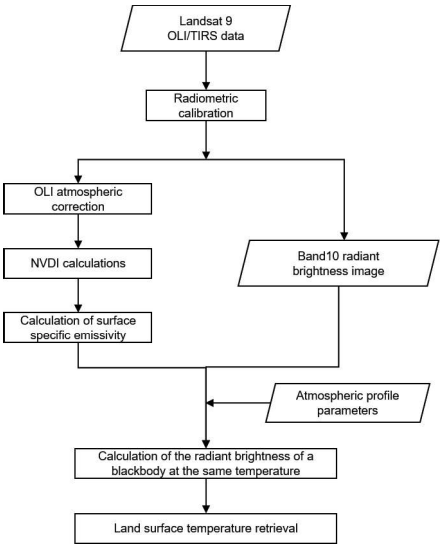

Fig. 4. Workflow of satellite image processing for land surface temperature

3.3.2 Land Use

The form of land use has an essential impact on the urban heat island effect, with different land use types having a heating or cooling effect on air temperature, affecting air movement (Hsieh & Huang, 2016). For example, blue-green space and non-built-up land use have a significant cooling effect and can serve as compensation space for urban ventilation systems; built-up land use acts as a heating effect on air temperature, while roads provide space for air circulation and has the potential to reduce temperature.

In this study, the land use types were divided into four types: blue-green space land, non-construction land, construction land, and roads, where blue-green space land, non-construction land, and construction land were assigned values based on the land area of the parcel, as well as the grade of the road and the angle to the dominant wind direction, which were used to calculate the suitability of the ventilation corridor.

3.3.3 Building Form

Building form affects urban ventilation mainly through building height and windward surface density (Yuan et al., 2014). Buildings are resistant to wind, and the higher the average building height and density in a plot, the more excellent the resistance to airflow. In this study, the average building height and windward surface density in each plot were calculated using building data as an indicator to evaluate the impact of building form on the wind environment.

3.3.4 Overlay Analysis

In this study, the data of three types of thermal environment, land use, and building form, were pre-processed, unified spatial reference coordinate system, resolution, rasterised and graded according to the ventilation potential for suitability evaluation, and the assignment rules are shown in Table 2. Among them, the very strong/strong suitability zone is an important wind

promotion element in the region and has the potential to become an important compensation space and ventilation corridor in the region; the very weak/weak suitability zone is an area with more serious thermal and air pollution problems, and it is a role space that needs to be considered for the construction of ventilation corridors in the future. After completing the assignment, the weighted overlay tool in ArcGIS Pro is used to performe the calculation. Finally, the evaluation results of the suitability of the ventilation corridor in the study area are obtained.

Table 2. Criteria for evaluating the suitability of ventilation corridors

Factor		Value	Suitability scale	Ventilation corridor suitability
Thermal environment (land surface temperature) (℃)		25-38	1	Excellent suitability
		38-40	3	Strong suitability
		40-42	5	Medium suitability
		42-44	7	Weak suitability
		>44	9	Very weak suitability
Blue-green space (waters, green spaces) (ha)		0-30	5	Medium suitability
		30-50	3	Strong suitability
		>50	1	Excellent suitability
Non-construction land (ha)		0-10	7	Weak suitability
		10-30	5	Medium suitability
		>30	3	Strong suitability
Land for construction (building height) (floors)		1-2	3	Strong suitability
		2-5	5	Medium suitability
		5-10	7	Weak suitability
		>10	9	Very weak suitability
Road (angle to prevailing wind direction) (°)	**Expressway**	0°-30°	1	Excellent suitability
		30°-60°	3	Strong suitability
		60°-90°	5	Medium suitability
	Main road	0°-30°	3	Strong suitability
		30°-60°	5	Medium suitability
		60°-90°	7	Weak suitability
	Secondary roads, branch roads	0°-30°	5	Medium suitability
		30°-60°	7	Weak suitability
		60°-90°	9	Very weak suitability

4. Results

The optimisation strategy of the ventilation corridor system in this plan mainly consists of compensation space and ventilation corridors, and the locations of the compensation space and ventilation corridors are determined using the results of the suitability evaluation in combination with the surrounding environment of the study area. The large agricultural and forestry land on the east side of the study area and the Yangtze River on the west side can be regarded as a considerable compensation space outside this ventilation corridor system, where cooler air can be blown by the prevailing easterly winds from the agricultural and forestry land on the east side to the action space within the study area, thus mitigating the impacts of the urban heat island and air pollution and evacuating the warmer air to the Yangtze River to improve the thermal environment in the study area.

The optimised ventilation corridors align with the prevailing wind direction in Wuhu City. This plan also grades the ventilation corridors and proposes the control requirements for urban construction in the areas around the ventilation corridors and recommendations for the width of the ventilation corridors. Figure 5 shows the ten ventilation corridors of the optimised ventilation system. In the first-level ventilation corridor, building height and density in the upwind direction of the city should be controlled as much as possible, and high-rise buildings should be appropriately dispersed to reduce building density and surface roughness. Appropriately increase the construction of open space in the upwind direction, maintain openness, create various forms of open space, appropriately increase the water area, and reasonably create ecological barges. Within the secondary ventilation corridor, the urban road system should be optimised as much as possible, keeping the road direction and the dominant wind direction all the time, improving the regularity of the road network and the number of straight lines to the road network. Improve the road section and design the combination of arterial roads and walking paths; both sides should be set up with a large width of the dense forest belt, planting sparse, low plants, which is conducive to air circulation—appropriate construction of green berms on both sides of the water system to improve airflow rate. Tables 3 and 4 show the compensation space and ventilation corridor in the Optimised ventilation system, respectively.

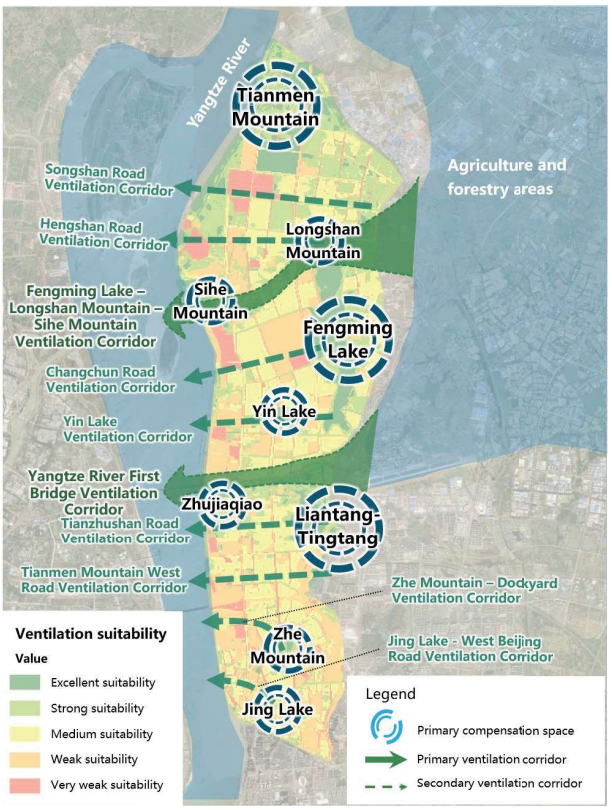

Figure 5. Optimised ventilation system.

Table 3. Compensation space in the optimised ventilation system

Type	Name
Compensation space outside the study area	Yangtze River
	Agriculture and forestry areas
Primary compensation space	Tianmen Mountain
	Fengming Lake
	Longshan mountain
	Sihe Mountain
	Yin Lake

	Liantang-Tingtang
	Zhujiaqiaowei Water Ecological Park
	Zhe Mountain
	Jing Lake

Table 4. Ventilation corridor in the optimised ventilation system

Type	Name	Function	Widths	Guidance for urban construction
Primary ventilation corridor	Fengming Lake – Longshan Mountain – Sihe Mountain Ventilation Corridor	Primary airways improve the quality of the urban atmosphere at the macro-overall level by integrating wind-promoting factors, including large-scale ecological resources such as lakes, forests, and farmland within and near the city, to lower the city's temperature and generate more cool winds for the city.	≥200m	Within the urban primary wind channel, building height and density in the upwind direction of the city should be controlled as far as possible, and high-rise buildings should be dispersed appropriately to reduce the density of buildings and reduce the roughness of the ground surface. Appropriately increase the construction of open space in the upwind direction, maintain openness, create various forms of open space, appropriately increase the water area, and reasonably create ecological barges.
	Yangtze River First Bridge Ventilation Corridor		≥200m	
Secondary ventilation corridor	Songshan Road Ventilation Corridor	The secondary wind channel mainly relies on roads and rivers parallel to or with a small angle to the dominant wind direction as a carrier to establish a secondary wind corridor with compensation space and action space to alleviate thermal and air pollution in local urban areas.	≥50m	Within urban secondary wind corridors, the urban road system should be optimised as much as possible to keep the road aligned with the dominant wind direction all the way and to improve the regularity of the road network and the number of straight lines to the road network. Improve the road cross-section and design roads combining arterial roads and footpaths, which should be flanked by dense forest belts of larger widths and planted with sparse, low-growing plants
	Hengshan Road Ventilation Corridor		≥50m	
	Changchun Road Ventilation Corridor		≥50m	
	Yin Lake Ventilation Corridor		≥50m	

	Tianzhushan Road Ventilation Corridor		≥30m	that are conducive to air circulation. Appropriate green space berms are constructed on both sides of the water system to improve air movement.
	Tianmen Mountain West Road Ventilation Corridor		≥50m	
	Zhe Mountain – Dockyard Ventilation Corridor		≥30m	
	Zhe Mountain – Dockyard Ventilation Corridor		≥30m	

5. Discussion and Conclusion

Ventilation plays an essential role in mitigating the heat island effect and improving air quality, and the evaluation of ventilation potential is a prerequisite for the identification of ventilation corridors. In this paper, by comprehensively considering various factors closely related to urban ventilation, we propose a framework for evaluating urban ventilation corridors based on GIS spatial overlay analysis, which is used to identify areas with ventilation potentials in a large-scale urban space. Based on the evaluation results, we propose a strategy to optimise the urban ventilation corridor system and clarify the ventilation corridors and compensatory spatial layout of the study area, which is inspiring for the study of urban ventilation corridors.

The method adopted in this paper can quickly quantitatively evaluate the ventilation potential of a city using only remote sensing data, land use, and building datasets and optimise the urban ventilation system accordingly. Compared with traditional techniques such as wind speed analysis and CFD, this method shows significant advantages in terms of efficiency and cost. It is well-suited for urban planning and design in large-scale spaces. In addition, we have also applied this method in the conceptual planning project along the Yangtze River in Wuhu City, and we hope that it can provide a convenient and intuitive scientific basis for urban planning decision-makers to promote more effective planning and decision-making.

Nevertheless, many factors affect the urban wind environment, and this study mainly analyses the thermal environment, land use, and building form for computational convenience. However, different types of construction land use have different impacts on the thermal environment, and various land use types should be further differentiated in future studies; meanwhile, the relationship between the orientation and frontal area density of the building form and the prevailing wind direction, as well as the frontal area density of the building, may also have different impacts on the ventilation efficiency. In future research, it is necessary to refine the specifics of the evaluation indicators to achieve a more refined analysis and improve the accuracy of this method.

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