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Quantitative Control of Residential Morphology for Wind-Heat–Related Health Risks in the Yangtze River Delta Region

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ABSTRACT

This study focuses on urban residential areas in the Yangtze River Delta and establishes a quantitative correlation model between wind-heat environments and health risks. By integrating the Intergovernmental Panel on Climate Change (IPCC) high-temperature health risk assessment framework, Air Quality Index (AQI)-based air quality risk evaluation, and Computational Fluid Dynamics (CFD) wind environment simulations, the study quantifies and optimizes residential morphological parameters—particularly building height difference—to enhance ventilation efficiency, reduce pollutant accumulation, and mitigate health risks associated with extreme heat. The key findings include: Building height difference is significantly positively correlated with ventilation efficiency, making it a critical variable for microclimate improvement; High temperatures and air pollution exhibit a synergistic effect, necessitating the consideration of their nonlinear coupling in health risk models; A three-stage response pathway—"height difference–wind speed–health risk assessment"—enables the derivation of morphology control thresholds based on health risk indicators. This research provides a scientific basis for quantitatively setting building height difference indices in regulatory detailed planning and recommends incorporating height difference as a mandatory control parameter to reduce health-related risks.

1. INTRODUCTION

1.1 Research background and significance

Under the background of global climate change and accelerated urbanization, the impact of urban residential morphology on residents' health has become increasingly prominent. Especially under the guidance of the Healthy China 2030 strategy, the construction of healthy cities has become an important path to achieve the goal of national health. According to the *Outline of the Healthy China 2030 Plan*, health priority has been established as a national development principle, requiring the health concept to be deeply integrated into the entire process of public policy formulation, implementation, and evaluation, and to build a health security system covering the whole life cycle through optimizing health services, improving health security, and constructing healthy environments [1].

The definition of healthy cities by the World Health Organization (WHO) further emphasizes the importance of multi-dimensional coordination, namely, through efforts in politics, economy, culture, and other aspects, to implement health-oriented principles throughout the full cycle of urban planning, construction, and management, and to form a sustainable development model of harmonious coexistence between people and cities [2]. As one of the most economically developed and highly urbanized regions in China, the residential morphology in the Yangtze River Delta has a particularly significant impact on residents' health. The region's climatic characteristics of hot summers and cold winters, coupled with high-density population and building layouts, make issues of thermal environment and air quality in residential areas particularly prominent.

Specifically, the Yangtze River Delta has high temperature and high humidity in summer, and cold and damp conditions in winter. These extreme climate conditions aggravate the heat island effect and air pollution problems inside residential areas. Studies have shown that the frequency of heatwaves in the Yangtze River Delta is increasing at a rate of 3.2 days per decade, while the proportion of calm wind days in winter reaches as high as 47%, leading to the accumulation of pollutants inside residential areas and further worsening the living environment of residents when superimposed with the heat island effect [3]. In addition, the high-density population and building layout restrict natural ventilation, making air circulation inside residential areas poor and pollutants difficult to disperse, thereby increasing residents' health risks.

1.2 Research objectives and questions

Therefore, it has important practical significance to quantitatively regulate residential morphological parameters, especially building height difference, to improve ventilation efficiency, reduce pollutant accumulation, and mitigate heat-related health risks. This study aims to construct a quantitative correlation model between wind-heat environment and health risks, providing scientific basis for the optimization of residential morphology in the Yangtze River Delta region and promoting the sustainable development of healthy cities.

Air pollution and extreme high temperatures are the two major environmental factors affecting urban residents' health. Epidemiological studies further reveal the deep association between ventilation and health risks. Traditional planning focuses on static indicators such as floor area ratio and building density but lacks dynamic regulation of wind-heat coupled health risks. This study takes "residential morphology–wind-heat environment–health effects" as the logical chain to quantitatively analyze the ventilation efficiency of parameters such as building height difference. Taking typical residential morphologies in the Yangtze River Delta region as examples, this study constructs a wind-heat environment simulation and health risk assessment model to explore quantitative control strategies. In addition, existing health residential area evaluations often focus on post-construction assessment, with few guiding quantitative reference standards for the early design and planning stage. This study holds that, during the residential planning stage, if natural ventilation in key areas can be effectively quantitatively controlled through morphological indicators of buildings, it will have important significance for improving residential thermal comfort, reducing the accumulation of atmospheric pollutants, and increasing the positive impact on residents' psychological and physiological health.

The core objective of this study is to construct a quantitative correlation model between residential morphology and wind-heat–related health risks in the Yangtze River Delta region, and to improve ventilation efficiency and reduce health risks through the quantitative regulation of key morphological parameters such as building height difference. Specifically, this study aims to answer the following key questions:

- The mechanism of the impact of building height difference on residential ventilation efficiency. Building height difference, as one of the important parameters of residential morphology, has a significant impact on ventilation efficiency. This study will explore how building height difference changes the internal flow field distribution of residential areas, promotes or hinders airflow circulation, and how such changes affect ventilation efficiency.
- The synergistic effect of high temperature and air pollution on health risks in residential areas. There is a complex synergistic effect between high temperature and air pollution. Their combined action may exacerbate the health threats to residents. This study will analyze the interaction mechanism between high temperature and air pollution inside residential areas and how this synergistic effect affects residents' health risks.
- Methods for reducing residential health risks through the quantitative regulation of morphological parameters such as building height difference. Based on the research results of the above two problems, this study will propose specific quantitative control strategies. By optimizing morphological parameters such as building height difference, the aim is to improve ventilation efficiency and thermal environment in residential areas, thereby reducing residents' health risks. These strategies will provide a scientific basis for urban planning and management departments and promote the sustainable development of healthy cities.

2. LITERATURE REVIEW

2.1 Heat hazards and health risks

The impact of heat hazards on human health has become an important issue in the field of public health. Multiple epidemiological studies have shown that high-temperature weather is closely related to cardiovascular diseases, respiratory diseases, and heatstroke [4, 5]. A study pointed out that for every 1°C increase in daily average temperature in summer, the mortality rate of cardiovascular diseases increases by 2.1% (95% CI: 1.8-2.4%). High-density residential areas experience more than a 30% increase in heat risk due to poor ventilation, highlighting the health threats posed by high temperatures to specific populations. At the residential area level, land surface temperature (LST) is significantly correlated with residents' health status. Yi et al. [6] proposed a view different from the traditional hypothesis (that increasing surface reflectivity generally reduces urban temperatures), arguing that high albedo can effectively reduce LST but instead increases the human-perceived heat exposure, highlighting the complexity of the role of albedo in thermal perception and its implications for urban design. This conclusion also indicates the necessity of implementing customized strategies such as improving ventilation performance in residential areas in urban planning [6-9].

Further studies have revealed the specific impact mechanisms of high-temperature exposure on different health outcomes. The team of Wu et al. [10] proposed a quantitative method for evaluating health risks associated with high temperatures at the grid scale, which helps identify areas susceptible to high-temperature stress and provides a reference for high-temperature risk management strategies. In addition, the synergistic effects between high temperature and air pollution have also attracted wide attention, and their combined action may further exacerbate the threat to residents' health [11].

2.2 Airborne pollutants and health risks

Under high-temperature conditions, chemical transformation of pollutants such as $PM_{2.5}$ and O_3 is enhanced, forming compound pollution. Wong et al., based on residential area data, established a Cox proportional hazards model, revealing that for every 10 μg/m³ increase in $PM_{2.5}$ concentration, the risk of hospitalization due to respiratory diseases increases by 4.2% (95% CI: 3.1-5.3%). Residential areas with poor ventilation experience pollutant retention, and the asthma incidence rate in children is 18% higher than in well-ventilated areas. Exposure to both indoor and outdoor pollutants poses a major threat to health [12]. Han et al. [13] from the perspective of health equity, pointed out that air purifiers can reduce indoor $PM_{2.5}$ concentrations by 54-72%, but their annual use cost accounts for 2.1-3.4% of the per capita GDP in low-income countries, forming significant economic barriers. Li and Zhu [14] further pointed out that the penetration rate of household air purifiers in Africa and Southeast Asia is less than 5%, with prominent inequality in exposure intervention, calling for combining passive building design (such as optimizing natural ventilation) to reduce dependence on mechanical equipment and protect the health rights of vulnerable groups.

Recent studies emphasize the interaction among wind speed, temperature, and pollutants. References [15-17] proposed a corrected model of the Universal Thermal Climate Index (UTCI) with wind speed, finding that when wind speed > 2m/s, the risk of heat stress is reduced by 15-20%, accompanied by a 35% improvement in PM10 diffusion efficiency. Such coupled models provide quantitative tools for the optimization of residential morphology.

2.3 Residential morphology and wind environment health

The regulatory effect of urban spatial morphology on atmospheric environmental quality has become a hot topic in interdisciplinary research. At the macro-meso scale, existing studies mainly focus on the correlation mechanisms between urban morphological characteristic parameters and pollutant dispersion [18]; while at the micro residential scale, the influence mechanisms of spatial morphological parameters on the near-ground flow field have formed systematic cognition. Studies have shown that changes in building height gradient can significantly alter the local wind environment. When the height of the first row of buildings on the windward side increases by 20%, the stagnant wind area on the leeward side expands by 35%, but matching with a 5°–10° building rotation angle can effectively break the airflow separation and improve ventilation conditions [19-21].

Specifically, residential morphological parameters such as floor area ratio, building density, average building height, spatial openness, building height standard deviation, and height differences between adjacent buildings all have significant impacts on the residential wind environment. Reasonable residential morphology design can promote airflow circulation, reduce the accumulation of pollutants and heat exposure risks. For example, increasing the height difference between buildings can form effective wind corridors to guide airflow through the residential area and carry away heat and pollutants. In addition, optimizing building layout and orientation can also improve the natural ventilation efficiency of the residential area, reduce the demand for mechanical ventilation, and thus reduce energy consumption and carbon emissions [22].

In recent years, with the advancement of information technology, research has gradually developed into multi-dimensional coupling studies including wind environment, heat hazards, pollutant dispersion, and physiological and psychological health. Studies showed that improving natural ventilation not only reduces air conditioning energy consumption by 15–20%, but also alleviates the scores of the Center for Epidemiological Studies Depression Scales (CES-D) by up to 12%, highlighting the dual health benefits of physiology and psychology [23]. Through CFD simulation, researchers can evaluate the impact of different morphological parameters on ventilation and health performance, thereby proposing optimization suggestions [24-26].

2.4 Development and application of health risk assessment models

With the deepening understanding of health risks, health risk assessment models have been increasingly applied in residential area planning and design. These models typically take into account multiple environmental factors (such as temperature, humidity, wind speed, pollutant concentrations, etc.) as well as population characteristics (such as age, gender, health status, etc.), quantitatively assessing their impact on health to provide scientific evidence for residential planning [27].

In terms of high-temperature health risk assessment, the climate risk assessment framework (Hazard × Exposure × Vulnerability) proposed by the IPCC has been widely applied. This framework evaluates the potential health risks of high temperature by quantifying hazard (e.g., high-temperature exposure), exposure (e.g., the time populations are exposed to high-temperature environments), and vulnerability (e.g., sensitivity of populations to high temperature). The Beijing Center for Disease Control and Prevention in China adopted a high-temperature health risk index (HRI) = heatwave intensity × population density × (1 - air-conditioning penetration rate) to identify high-risk communities. In addition, some studies have integrated meteorological data, health data, and spatial data to construct more refined health risk assessment models, improving the accuracy and reliability of the assessments [10].

In terms of airborne pollutant health risk assessment, the AQI has been widely used as an assessment indicator. However, a single AQI indicator is insufficient to fully reflect the composite health impacts of pollutants. Therefore, some studies have begun to explore the combination of AQI with other health risk indicators (such as HRI) to construct composite exposure health risk quantitative assessment models. These models assess the potential health risks of airborne pollutants more accurately by comprehensively considering the concentrations and toxicity of various pollutants, as well as the exposure levels and vulnerabilities of the population.

2.5 Limitations of existing research and innovations of this study

Although existing research has made significant progress in areas such as heat hazard, airborne pollutants and health risks, and residential morphology and wind environment health, there are still some limitations. First, existing studies mostly focus on the impact of a single factor (e.g., high temperature or pollutants) on health, with relatively little attention to the synergistic effects of multiple factors. However, in real environments, high temperature and air pollution often coexist and interact, jointly affecting residents' health. Therefore, this study will couple high-temperature and airborne pollutant health risk assessment models to more comprehensively reflect the potential threats of the residential environment to health. Second, the quantitative relationship between residential morphological parameters and health risks has not been sufficiently and systematically explored in existing research. Although some studies have investigated the impact of morphological parameters such as building height and plot ratio on ventilation performance, systematic quantitative relationships have not yet been formed. This study will employ CFD numerical simulations and field investigations to quantitatively analyze the impact of key morphological parameters such as building height difference on residential ventilation performance and health risks, and propose morphology control thresholds based on health risk. Finally, existing studies are relatively weak in proposing planning control indicators. Based on the research results, this study will propose to incorporate building height difference into the mandatory contents of regulatory planning, providing scientific basis for urban planning and management.

3. RESEARCH METHODS

3.1 Research data

This study selects typical residential areas in the Yangtze River Delta region as the research object. Economic integration in the Yangtze River Delta has led to significant urban cluster growth. In recent years, the Yangtze River Delta region experiences more than 20 days of high temperature (above 35℃) each summer. High population density, high building density, and high summer heat have led to typical health problems in residential areas caused by high temperatures and air stagnation. Meteorological data in this study comes from the China National Meteorological Data Center's China Surface Climate Data Daily Dataset (V3.0) and measured microclimate data of residential areas; spatial data is mainly obtained through remote sensing images, GIS data, and field surveys, including residential morphological parameters (plot ratio, building density, average building height, spatial openness, building height difference, etc.) and environmental data (air temperature, wind speed, pollutant concentration). Meanwhile, residential health data (such as heatstroke cases and incidence of respiratory diseases) was collected to verify the accuracy of the health risk assessment model [28].

3.2 Health risk assessment model for residential areas

High temperature and air pollution have synergistic effects. This study establishes a compound exposure health risk quantitative assessment model for high temperature and airborne pollutants. WHO (2021) points out that for every 1℃ increase in temperature, the mortality rate related to $PM_{2.5}$ increases by 2.1%; when O_3 concentration exceeds 30℃, the daily value exceedance rate increases by 40%. Existing studies mostly adopt a linear addition of high-temperature HRI and AQI, but when HRI > 3.0 and AQI > 150, the number of outpatient visits for respiratory diseases increases exponentially, verifying the necessity of nonlinear coupling [10]. Therefore, this study constructs a coupling index HRI-AQI, with the formula as follows:

$$HRI - AQI_{coupled} = \left(\frac{HRI - \mu_{HRI}}{\sigma_{HRI}}\right) \times \left(\frac{AQI - \mu_{AQI}}{\sigma_{AQI}}\right) \times \text{Weight Coefficient}$$

- $\frac{HRI - \mu_{HRI}}{\sigma_{HRI}}$ Standardized HRI
- $\frac{AQI - \mu_{AQI}}{\sigma_{AQI}}$ Standardized AQI

The HRI adopts the climate risk assessment framework (hazard × exposure × vulnerability) proposed by IPCC, and the formula is: HRI = f(H, E, V) = HHI × HEI × HVI, where HHI, HEI, and HVI represent high-temperature hazard index (heat intensity), high-temperature exposure index (population density, proportion of vulnerable population), and high-temperature vulnerability index (air conditioner penetration rate, distribution of medical resources), respectively. AQI adopts the Chinese standard (GB3095-2012), including weighted calculation of concentrations of six pollutants: PM2.5, PM10, O_3, NO_2, SO_2, and CO. Weight coefficients are determined using the entropy weight method to determine the relative contribution of HRI and AQI, or expert scoring method to set initial values (e.g., under extreme climate scenarios, HRI weight = 0.6, AQI = 0.4).

The HRI-AQI assessment model adopts a multiplicative form to amplify the health risk when high temperature and pollution co-occur (such as intensified O_3 generation during heatwaves), to better capture the coupling effect. At the same time, standardization is used to eliminate dimension differences and describe spatial heterogeneity, making it applicable to comparison across different cities.

Table 1. Key variables and indicators table of the influence of residential morphological parameters

Level	Variable	Quantitative Indicator	Data Source/Selection Basis
Morphological Parameters	Floor Area Ratio (FAR)	Total building base area / total land area	Regulatory planning data + remote sensing interpretation; reflects construction intensity
	Building Height Standard Deviation (HSD)	Standard deviation of height differences between adjacent buildings	Point cloud data + GIS analysis; airflow disturbance effect
	Adjacent Building Height Difference (ABHD)	Height difference between adjacent buildings	Point cloud data + GIS analysis; airflow disturbance effect
	Average Building Height (ABH)/m	Total building height in residential area / number of buildings	Point cloud data + GIS analysis; impact on horizontal and vertical distribution of airflow and pollutants
	Spatial Openness (SO)	Area of unbuilt space / building area per block unit	Regulatory planning data + remote sensing interpretation; reflects construction intensity and ventilation capacity
	Mean Building Volume (MBV/m^3)	Total volume of all buildings in the residential area / number of buildings	Point cloud data + GIS analysis; impacts aerodynamics
	Degree of Enclosure (DE)	Sum of building perimeters / total block perimeter	Regulatory planning data + GIS analysis; reflects block enclosure and pollutant dispersion
Environmental Parameters	Ventilation Performance	Average wind speed (m/s), effective ventilation duration (h)	CFD simulation + field measurement
	Thermal Comfort	HTCI (℃), PET (℃)	ENVI-met and other simulations
Health Performance	Heat-related Disease Risk	Heatstroke consultation rate (‰), cardiovascular disease incidence rate	Hospital data + epidemiology
	Pollutant-related Respiratory Disease Risk	Emergency visits for asthma/COPD (‰)	Hospital Information System (HIS)

3.3 Analysis of the influence of residential morphological parameters

Many studies have proven that residential morphological parameters have environmental effects [29-31]. For every 1m increase in building height difference, pedestrian-level wind speed increases by 0.3–0.5 m/s; when plot ratio > 2.5, surface temperature increases by 1.2–1.8℃. Meanwhile, there also exists a transmission mechanism between environment and health. Lai et al. through 10 years of tracking data, confirmed that for every 10 μg/m³ increase in $PM_{2.5}$ concentration, emergency visits for childhood asthma increased by 3.2%, but this effect weakened by 47% in well-ventilated areas (wind speed > 1.5 m/s) [32]. A "morphology–environment–health" three-level transmission path framework can be formed (Table 1):

Morphological Parameters $\xrightarrow[\text{Wind Speed/Turbulence Intensity}]{\text{Impact}}$ Environmental Performance $\xrightarrow[\text{Pollutant Dispersion/Thermal Comfort}]{\text{Improvement}}$ Health Effects

The analysis of the influence of residential morphological parameters was conducted through pollutant detection in typical residential areas, collection and processing of health variable data, combined with CFD numerical simulation. Statistical research methods such as correlation analysis and sensitivity analysis were used to identify key residential morphological parameters affecting residential health and to propose optimization suggestions.

3.4 Quantitative experiment on building height difference in residential areas

Building height difference is the most influential metric among residential morphological parameters regarding ventilation performance. The current research method that combines residential morphology and wind environment performance with the early design process mainly uses CFD software to simulate, compare, and optimize the finalized design schemes [33]. However, because the initial design does not reflect the performance characteristics of the wind environment, it is sometimes difficult to make effective adjustments after the scheme is finalized. The purpose of this experiment is to establish a set of quantitative ventilation control methods for building height difference in residential areas. The final form will be a quantitative guideline similar to the daylight spacing regulations. With the help of this guideline method, designers can have control over the wind environment performance of the design without having to conduct full-scheme CFD simulations or wind tunnel tests, simply by referring to the guideline table. By following this quantitative guideline, relatively ideal wind environment performance and health performance can be achieved. At the same time, urban planning and management departments can also use this method and the health risk assessment model to control the wind-thermal health performance of residential areas. For example, it can be stipulated that for newly built residential communities of different health risk levels, the proportion of buildings meeting the quantitative guideline control requirements must not be lower than a certain percentage [34].

Experiment Design:

Includes determining experimental objects, controlling experimental indicators, experimental tools, airflow parameter settings, and establishing a digital model of the experiment. Among them, the experimental objects are mainly typical slab-type residential buildings in the Yangtze River Delta region. The comfort indicator control for the experiment sets the lower limit of outdoor wind speed in summer at 3 m/s. The evaluation standard of experimental results is defined as the simultaneous satisfaction of the following two conditions: (1) On the ground-level plane, the wind speed zone above 3 m/s between front and rear buildings must be continuous; (2) On the cross-section of the building's central axis, the wind speed zone above 3 m/s between front and rear buildings must be continuous from the upper air to the ground.

The experiment uses Virtualwind 2.1 software for simulation. The software was developed by the wind engineering company RWDI and is capable of simulating and demonstrating indoor and outdoor airflow fields dynamically and statically. In the experiment, the wind direction selected is the most frequent wind direction in summer—S (due south), the wind speed is the average outdoor wind speed in summer—3.4 m/s, and the environmental roughness type is set as Urban [34] (Figure 1).

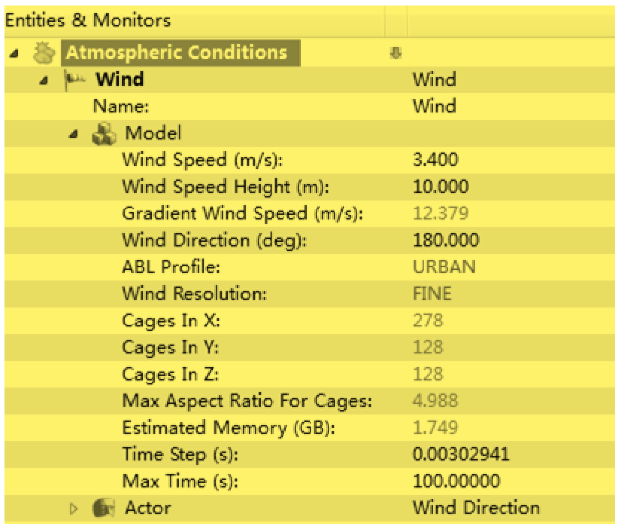

Figure 1. Virtualwind parameter settings

Experimental Grouping:

The experiment was grouped based on variables such as building width, front-row building height, and buildingdistance, and corresponding constant values were set. The digital model of the experiment only considered an ideal determinant layout and includes variables such as building width, front-row building height, and building distance, establishing multiple experimental groups composed of combinations of constants and variables (Table 2). In the experiment, building width was set at four values: 15 meters, 30 meters, 45 meters, and 60 meters. Front-row building height ranged from 10 meters to 100 meters, increasing by 10-meter modules. Building distance ranged from 10 meters to 50 meters, increasing by 5-meter modules. The experimental groups were divided into four main groups according to different building widths, and each group was further divided into several subgroups based on different front-row building heights and building distance (Table 3). As shown in Table 2, the dimensional settings of the experimental model include the following two constants and three variables [34]:

Table 2. Rules for setting building model dimensions

Constant I	Constant II	Variable I	Variable II	Variable III	Target Quantity
Angle Between Wind Direction and Building Normal	Building Depth (Unit: meters)	Building Width (Unit: meters)	Front Row Building Height (Unit: meters)	Building Distance (Unit: meters)	Height Difference (Unit: Floors)
0°	15	15, 30, 45, 60	10, 20, 30, 40, 50, 60, 70, 80, 90, 100	10, 15, 20, 25, 30, 35, 40, 45, 50	

Table 3. Dimension settings of four groups of building models

Constant I	Constant II	Constant III	Constant IV	Variable	Target Quantity
Angle Between Wind Direction and Building Normal	Building Depth (Unit: meters)	Building Width (Unit: meters)	Front Row Building Height (Unit: meters)	Building Distance (Unit: meters)	Height Difference (Unit: Floors)
0°	15	15/30/45/60 Four Groups	10	10, 15, 20, 25, 30, 35, 40, 45, 50	

Experimental Grouping: D0-W30-H30 (0-degree wind direction incident angle, the left side of the figure is the inflow direction, the south-side building is 30 meters wide and 30 meters high)

Code	Height Difference	Distance	Plan Diagram	Section Diagram	Meets 3m/s or Not
2-30-1	6m	25m			No
2-30-2	9m	25m			Yes
2-30-3	6m	30m			No
2-30-4	9m	30m			Yes
2-30-5	3m	35m			Yes
2-30-6	6m	35m			Yes
2-30-7	6m	40m			Yes
2-30-8	0m	45m			Yes
2-30-9	0m	50m			No
2-30-10	3m	50m			Yes

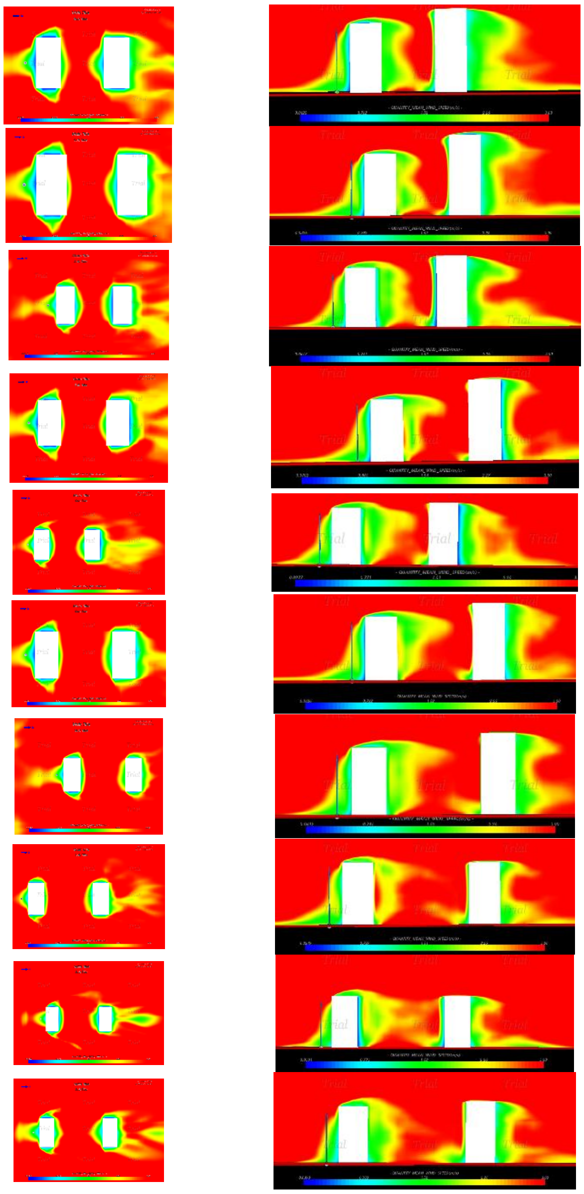

Figure 2. Simulation images with building width of 30 meters, front-row building height of 30 meters, and building distance of 25/30/35/40/45/50 meters

Simulation:

CFD software was used to perform simulation calculations to obtain the distribution of inter-building wind speeds under different height difference layers. The experimental results are presented in the form of color maps. The maximum value of the color map was set to a wind speed of 3 m/s. Red indicates areas with wind speed greater than or equal to 3 m/s, and other colors indicate areas with wind speed less than 3 m/s. The evaluation standard is defined as the simultaneous presence of connected 3 m/s wind speed zones in both the plan and section view. Through simulation calculation, the critical height difference values under different combinations of building width, front-row building height, and building distance are obtained [34].

During the experiment, it can be observed that as the north-south building height difference increases, the wind speed between buildings tends to increase. When it reaches or exceeds a certain critical value, the inter-building wind speed can meet the experimental index of 3 m/s.

Taking the simulation case with a building width of 30 meters, front-row building height of 30 meters, and building distance of 25 meters as an example, as shown in the figure below: when the height difference between front and rear buildings is 0 or 2 floors, it fails to meet the requirement of a connected 3 m/s wind speed zone in both the plan and section view; when the height difference is 3 floors, the requirement is met. Therefore, the experimental result for this group is 3 (floors) (Figure 2).

4. RESULTS AND DISCUSSION

4.1 High temperature health risk assessment

In the Yangtze River Delta region, HRI is mainly dominated by Hazard (H), with Exposure (E) mainly distributed in the central cities of Shanghai and Zhejiang, and in the downtown areas of prefecture-level cities in Jiangsu and Anhui. The main pattern is H-E-V. In city centers, HHI and HEI values are higher, while HVI values are lower (Figure 3). EFAST sensitivity analysis shows the relative contribution of each factor to HRI. Population density (E-01), vegetation coverage rate (E-02), and daytime near-surface maximum temperature (H-01) have the greatest impact on HRI variance (Figure 4). It can be seen that during high-temperature heatwave periods, residential morphology parameters have a significant impact on health risks. In particular, for building height difference, for every 1-meter increase in building height difference, the surface temperature can be reduced by 0.32-0.51℃, significantly lowering heat exposure risk [10]. Meanwhile, reasonable layout of building height can promote airflow circulation, reduce pollutant concentration, and further reduce health risks.

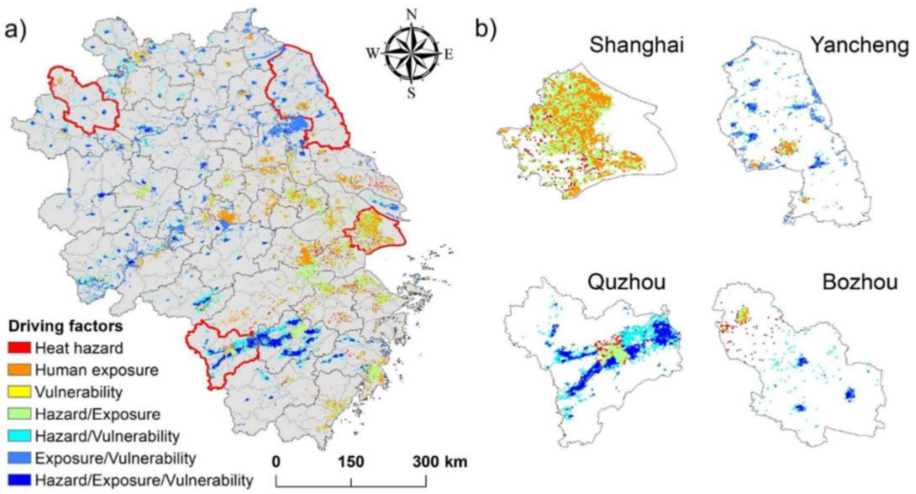

Figure 3. Map of the dominant factors in the high-risk areas in the YRD [10]

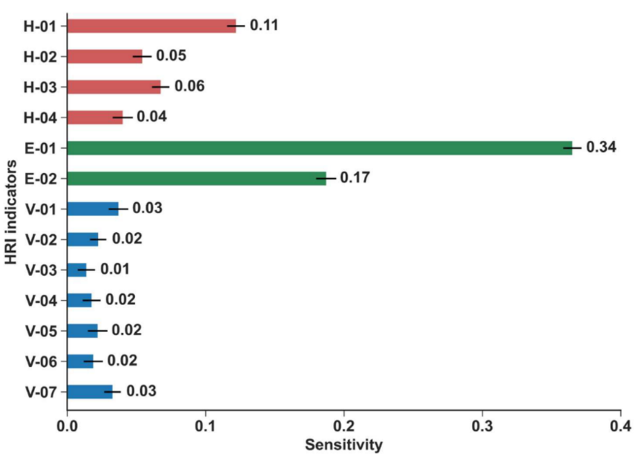

Figure 4. Bar plot of the global sensitivity of the HRI indicators [10]

4.2 Dominant role of building height difference in ventilation performance and atmospheric pollutant dispersion

This study finds that building height difference is a key morphological parameter to improve the ventilation performance of residential areas. By reasonably setting the building height difference, airflow circulation can be effectively promoted, reducing the accumulation of pollutants and the risk of heat exposure. This finding is consistent with previous research (wind speed is negatively correlated with pollutant concentration, and has the highest correlation with building height difference among residential morphology parameters) (Table 4 and Figure 5) [22], but this study further quantifies the specific impact degree of building height difference on ventilation performance, providing more precise guidance for the optimization of residential morphology.

Table 4. Correlation analysis results between pollutant mass concentration and meteorological elements [22]

Meteorological Elements	Pollutants	Summer		Autumn		Winter	
		Correlation Coefficient	*p*	Correlation Coefficient	*p*	Correlation Coefficient	*p*
Wind Speed	$PM_{2.5}$	-0.308**	<0.01	-0.461**	<0.01	-0.512**	<0.01
	CO	-0.133**	<0.01	-0.394**	<0.01	-0.312**	<0.01
Temperature	$PM_{2.5}$	0.174**	<0.01	-0.041	<0.01	0.191**	<0.01
	CO	0.203**	<0.01	-0.030	<0.01	-0.016	<0.01
Relative Humidity	$PM_{2.5}$	0.272**	<0.01	0.419**	<0.01	0.299**	<0.01
	CO	-0.061	<0.01	0.660**	<0.01	0.202	<0.01

Note: ** Correlation is significant at the 99% confidence level

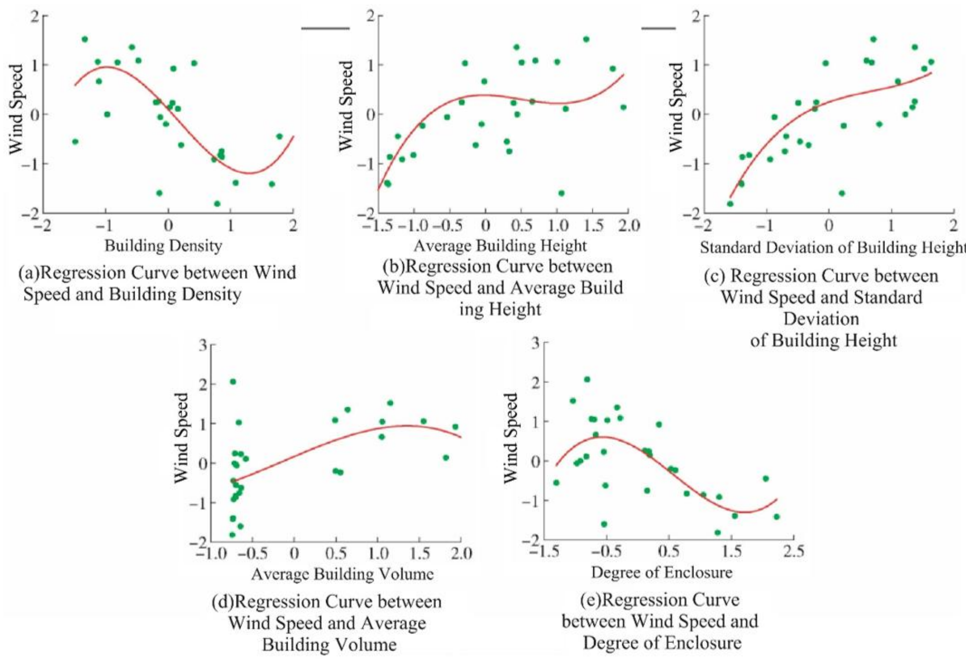

Figure 5. Unary regression graph [22]

Table 5. Minimum height difference in floors to meet the 3 m/s ventilation requirement when the southern building width is 15 meters (south lower, north higher)

Building Distance / Southern Building Height	10m	15m	20m	25m	30m	35m	40m	45m	50m
10m	3	2	2	1	1	1	0	0	0
20m	--	--	3	2	2	0	0	0	0
30m	--	--	--	3	2	0	1	0	0
40m	--	--	--	3	1	1	0	0	0
50m	--	--	--	3	3	1	0	0	0
60m	--	--	--	--	0	0	0	0	0
70m	--	--	--	--	--	0	0	0	0
80m	--	--	--	--	--	--	0	0	0
90m	--	--	--	--	--	--	--	0	0
100m	--	--	--	--	--	--	--	--	0

Note: The "--" in the Tables 5-8 indicates that the building distance at this time does not meet the relevant residential distance regulations based on sunlight and ventilation requirements; therefore, no CFD simulation experiment was conducted; To appropriately simplify experimental conditions, this experiment only roughly controlled the exclusion of residential distance and did not exclude all distance conditions that fail to meet the sunlight spacing requirements according to detailed sunlight spacing and strict sunlight analysis simulation results.

4.3 Recommendations for planning control indicators

Through the ventilation simulation experiment on height difference, we obtained a series of quantitative control indicators for ventilation height difference in the row-layout of residential buildings. These indicators include the minimum height difference in floors required to meet the 3m/s wind speed under different building widths, front-row building heights, and building distance. The experimental results show that with the increase of building width, the minimum height difference in floors also increases accordingly; while the changes in front-row building height and building distance have a certain impact on the minimum height difference in floors. Through the analysis of the experimental results, we found a clear corresponding change relationship between the height difference in floors and building width [34]. In addition, we also discovered some interesting phenomena. For example, under certain specific conditions, although the building width increases, the minimum height difference in floors decreases. This may be related to the combined effects of building layout, wind direction, and other factors.

The quantitative experiment of height difference in residential areas studied the ideal ventilation height difference condition when residential buildings are arranged in parallel and the wind direction incident angle is zero degrees. The results show that as the north-south building height difference increases, the wind speed between buildings tends to rise. When a certain critical value is reached or exceeded, the inter-building wind speed can meet the 3 m/s experimental index requirement. The table shows the minimum height difference in floors between adjacent front and back buildings on the windward side where the southern buildings have different widths and heights, which meet the 3m/s ventilation requirement [34]. The following are the experimental image data matrices (the values in the height difference column in the tables represent the height of the north-side building minus the height of the south-side building) (Tables 5-8).

Table 6. Minimum height difference in floors to meet the 3 m/s ventilation requirement when the southern building width is 30 meters (south lower, north higher)

Building Distance / Southern Building Height	10 m	15 m	20 m	25 m	30 m	35 m	40 m	45 m	50 m
10m	3	2	3	1	2	1	1	1	0
20m	--	--	3	2	3	3	4	1	0
30m	--	--	--	3	3	1	2	0	1
40m	--	--	--	3	3	1	0	0	1
50m	--	--	--	3	3	2	0	0	0
60m	--	--	--	--	3	1	1	0	0
70m	--	--	--	--	--	0	0	0	0
80m	--	--	--	--	--	--	0	0	0
90m	--	--	--	--	--	--	--	0	0
100m	--	--	--	--	--	--	--	--	0

Table 7. Minimum height difference in floors to meet the 3 m/s ventilation requirement when the southern building width is 45 meters (south lower, north higher)

Building Distance / Southern Building Height	10 m	15 m	20 m	25 m	30 m	35 m	40 m	45 m	50 m
10m	4	3	3	3	2	2	2	2	1
20m	--	--	4	3	3	1	0	0	0
30m	--	--	--	6	5	4	2	2	0
40m	--	--	--	11	11	11	10	7	0
50m	--	--	--	9	10	11	9	5	0
60m	--	--	--	--	11	11	6	5	0
70m	--	--	--	--	--	8	6	2	2
80m	--	--	--	--	--	--	5	3	0
90m	--	--	--	--	--	--	--	0	0
100m	--	--	--	--	--	--	--	--	0

Table 8. Minimum height difference in floors to meet the 3 m/s ventilation requirement when the southern building width is 60 meters (south lower, north higher)

Building Distance / Southern Building Height	10 m	15 m	20 m	25 m	30 m	35 m	40 m	45 m	50 m
10m	5	4	4	4	3	3	1	1	1
20m	--	--	4	4	3	1	0	0	0
30m	--	--	--	5	5	4	5	4	0
40m	--	--	--	9	6	6	7	0	0
50m	--	--	--	11	9	8	9	8	8
60m	--	--	--	--	9	8	9	8	8
70m	--	--	--	--	--	10	8	5	3
80m	--	--	--	--	--	--	exceeding height	exceeding height	2
90m	--	--	--	--	--	--	--	exceeding height	0
100m	--	--	--	--	--	--	--	--	0

Note: In Table 8, “exceeding height” indicates that the height requirement for the rear (north-side) building exceeds 100 meters. Under this condition, the quantitative guidelines no longer provide specific values for the minimum height difference layers but require conducting CFD numerical simulations or wind tunnel physical experiments on the residential wind environment according to the specific design scheme. This combination of quantitative guidelines with specialized simulation analysis refers to the current regulatory approach for sunlight spacing in China. Generally, sunlight spacing regulations impose quantitative distance requirements based on sunlight coefficients for low- and mid-rise buildings, while for high-rise residential buildings, one-to-one specialized sunlight analysis simulations are required according to the specific design scheme.

Based on the research results, this study proposes, according to the health risk assessment model, a hierarchical control of residential building height difference, and recommends including building height difference as a mandatory content in regulatory planning (Table 9). By pre-controlling a certain proportion of building height differences, the ventilation and thermal environment of residential areas can be effectively improved, reducing health risks. Meanwhile, it is suggested that planning authorities strengthen the review and supervision of morphological parameters when approving residential planning schemes to ensure the effective implementation of residential form optimization measures.

Table 9. Example table of hierarchical control indicators for residential height difference based on the HRI-AQI assessment model

HRI-AQI Control Zone Type \ Building Width	15 m	30 m	45 m	60 m	Applicable Scenarios
Level 1 Control Zone	3*λ	3*λ	4*λ	5*λ	High-density core areas, old community renovation, elderly residential areas
Level 2 Control Zone	3	3	4	5	New commercial housing, mixed-use areas
Level 3 Control Zone	-	-	3	4	Ordinary residences, low-density communities

Note: λ is the height difference threshold (number of floors) adjustment coefficient, $\lambda > 1$; The numbers in the table are height difference thresholds (number of floors), determined according to the row-column height difference ventilation quantification experiments.

5. CONCLUSIONS AND OUTLOOK

5.1 Main conclusions

This study systematically analyzed the impact mechanism of controlling residential morphological parameters (especially building height difference) on wind-heat coupled health risks through quantitative regulation. The study found: (1) Building height difference (and the resultant standard deviation of building heights) is significantly positively correlated with ventilation efficiency and is a key regulatory variable to improve microclimate; it can effectively control high-temperature health risks and air quality risks; (2) There is a synergistic effect between high temperature and air pollution; when constructing health assessment models, the nonlinear coupling relationship between the two must be considered; (3) By establishing a "height difference - wind speed - health assessment" three-stage response path, an example of residential form control thresholds based on health risks was proposed.

5.2 Policy recommendations

Based on the research results, the following policy recommendations are proposed: (1) Include building height difference in regulatory planning mandatory content, pre-control building height difference to improve residential ventilation and health performance; (2) Strengthen the planning department’s review and supervision of residential morphological parameters to ensure the effective implementation of morphological optimization measures; (3) Promote the concept of healthy cities and incorporate health risk assessment into the entire residential planning process.

5.3 Future research directions

Future research may further explore the following directions: (1) Consider more morphological parameters (such as building orientation, green coverage ratio, etc.) on wind-heat coupled health risks; (2) Combine climate change projection data to assess the trend of future high-temperature weather impact on residential health risks; (3) Conduct comparative studies in multiple cities and regions to verify the universality and promotion value of this study.

Furthermore, the impact of residential morphological parameters on health risks does not exist in isolation but involves complex multi-parameter coupling effects. For example, increased plot ratio and building density exacerbate ventilation problems, but reasonable building height layout can alleviate this effect to some extent. Therefore, in the optimization process of residential morphology, it is necessary to comprehensively consider the interactions among multiple parameters to achieve the best health benefits.

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