

Article

High-Resolution Urban Wind Risk Assessment for Emergency Management Using UAV–CFD Integrated Modeling

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Abstract

Coastal cities exposed to extreme wind events are facing increasing challenges in emergency management under climate change. Accurate and high-resolution wind environment information over complex urban terrain is essential for disaster risk assessment and evidence-based emergency planning; however, such information is often unavailable in conventional management practices. This study proposes an integrated UAV–CFD framework to support urban wind risk assessment by combining multi-source geospatial data and high-resolution numerical simulation. A refined urban terrain model with a spatial resolution of 0.5 m was constructed through the fusion of Google Earth data and UAV oblique photogrammetry, and subsequently coupled with a computational fluid dynamics (CFD) model to analyze the urban wind environment. Field measurements obtained from a 50 m wind observation tower were used to validate the simulation results. The results reveal significant wind speed amplification caused by complex terrain and building configurations, with a maximum amplification factor of 1.95 due to the canyon effect. The relative errors between simulated and measured wind speeds and turbulence intensity were generally within 15%, demonstrating the reliability of the proposed framework. By providing high-resolution and spatially explicit wind risk information, this study offers practical decision-support for emergency management, urban planning, and resilience-oriented disaster mitigation in coastal cities.

Keywords: urban wind risk; emergency management; UAV–CFD integration; disaster risk assessment; urban resilience



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1. Introduction

Coastal cities are increasingly exposed to extreme wind events such as typhoons under the influence of climate change, posing growing challenges for urban safety and emergency management [1]. Accurate assessment of the urban wind environment is essential for disaster risk analysis, infrastructure safety evaluation, and evidence-based emergency planning [2]. In coastal regions with complex terrain and dense building configurations, wind flow patterns can vary significantly over short spatial scales [3]. However, conventional wind hazard assessments often rely on regional meteorological station data or simplified terrain models, which cannot adequately capture localized wind

amplification and turbulence characteristics in complex urban environments [4]. As a result, emergency management decisions—such as evacuation route planning, temporary shelter allocation, and infrastructure resilience design—may be based on incomplete wind risk information [5].

In recent years, researchers have increasingly applied computational fluid dynamics (CFD) to investigate urban wind environments due to its capability to simulate complex airflow patterns around buildings and terrain [6]. At the same time, advances in unmanned aerial vehicle (UAV) photogrammetry have enabled high-resolution terrain modeling, providing new opportunities for improving the accuracy of urban wind simulations [7]. Several studies have attempted to combine UAV-based terrain reconstruction with CFD modeling to analyze wind environments in complex urban areas [8]. These approaches demonstrate that UAV-derived point cloud data can significantly improve the representation of urban morphology in numerical simulations. Taken together, these studies highlight the importance of integrating high-resolution terrain data with numerical simulation for urban wind analysis [9]. However, existing research tends to treat terrain reconstruction and wind simulation as relatively independent processes, with limited emphasis on multi-source data integration within a unified analytical framework [10]. Moreover, the application of such high-resolution modeling approaches to practical emergency management and resilience-oriented decision-making remains insufficiently developed.

Nevertheless, several limitations remain in existing research. Many studies rely primarily on single-source UAV data for terrain reconstruction, which may lead to spatial inconsistencies when integrating geographic information, building morphology, and simulation models [11]. In addition, relatively limited attention has been paid to the systematic integration of multi-source geospatial datasets and their application in urban emergency management contexts [12]. Consequently, the potential of high-resolution wind environment modeling to support resilience-oriented urban governance remains insufficiently explored [13].

In response to these limitations, this study addresses the following research question: How can multi-source geospatial data and UAV-based terrain modeling be integrated with CFD simulations to generate high-resolution wind risk information that supports emergency management and urban resilience planning in coastal cities with complex terrain?

To answer this question, this study develops a multi-source data collaborative UAV–CFD framework for high-resolution urban wind risk assessment [14]. The main contributions of this study are threefold. First, a multi-source data fusion approach is proposed to integrate UAV oblique photogrammetry with geographic information for high-precision urban terrain reconstruction [15]. Second, an integrated UAV–CFD modeling framework is established to simulate spatially explicit wind environments in complex coastal urban areas [16]. Third, the study demonstrates how high-resolution wind risk information can support evidence-based emergency management and resilience-oriented urban planning [17]. By bridging high-resolution environmental modeling with emergency management applications, this research contributes to the development of more sustainable and resilient coastal cities [18]. In this study, urban wind risk is defined as the potential hazard arising from spatial variability in wind velocity and turbulence within complex urban environments, which may affect infrastructure safety, pedestrian exposure, and emergency response effectiveness [19].

2. Methodological Framework for Urban Wind Risk Assessment

Guided by the concept of urban wind risk and resilience-oriented emergency management, this study integrates high-resolution terrain modeling with CFD-based wind simulation to analyze spatial wind hazards in complex urban environments [20]. The

methodological framework is therefore designed to link theoretical considerations of urban environmental risk with practical modeling approaches for decision-support [21,22].

2.1. Field Measurement of Wind Field

Field measurement is uniquely positioned to deliver first-hand data, making it the most direct and reliable approach available [23]. In wind environment studies, measured wind velocity data serves dual purposes: It is directly applicable for analyzing wind characteristics and serves as a benchmark to validate other research methods. This study utilized a 50 m wind observation tower, installed on the northern coastline of Hainan Island along the Qiongzhou Strait, to collect wind field data. The tower site is surrounded by high-rise buildings on its western and northern sides, with the coastline located approximately 200 m to the south. The terrain is basically the same as the C-type surface in the current specification, as shown in Figure 1. The tower was instrumented with three-dimensional ultrasonic anemometers at three levels: 20 m, 35 m, and 50 m above ground. The ultrasonic anemometers were configured with a 1 Hz sampling frequency to synchronously capture wind velocity and direction within the near-ground turbulent boundary layer (see Figure 2). The field measurement data provides an essential empirical basis for validating high-resolution wind risk information used in emergency management and urban safety planning.

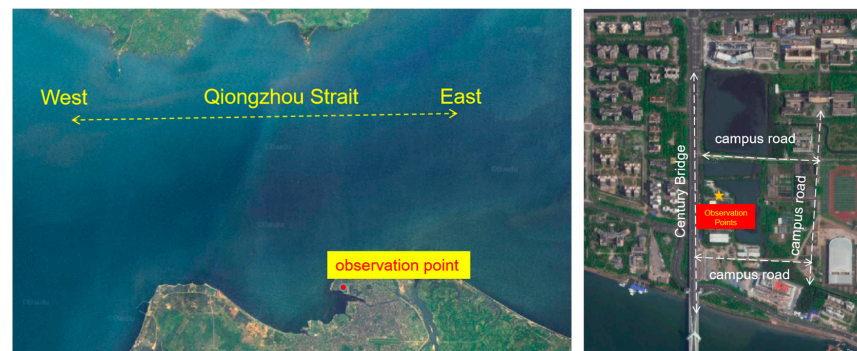


Figure 1. Installation position of wind observation tower.

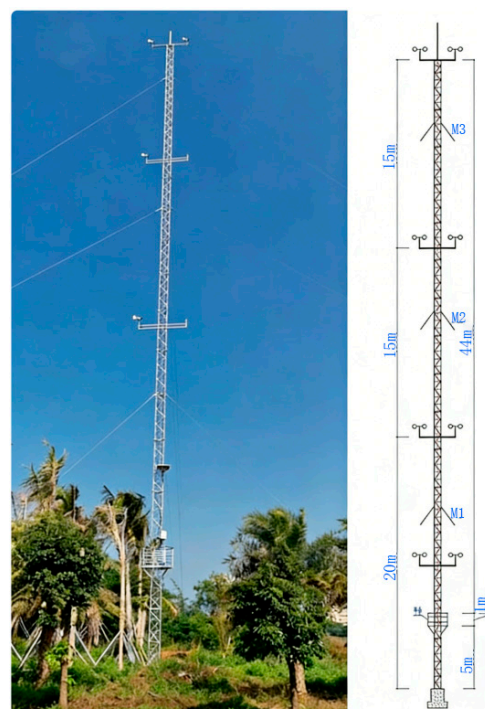


Figure 2. Photos of wind observation tower and layout of measuring points.

The methodological framework of this study consists of three main components. First, field measurements from a wind observation tower are used to obtain empirical wind data and provide validation for the numerical simulation. Second, high-resolution urban terrain modeling is conducted using UAV oblique photogrammetry combined with multi-source geospatial data. Third, CFD numerical simulations are performed based on the reconstructed terrain model to analyze the spatial distribution of the urban wind environment.

2.2. Complex Terrain Modeling Method Based on UAV

A target area (1000 m × 1000 m) was delineated within the Google Earth framework, with the core modeling domain defined around the location of the wind observation tower. A standard multi-rotor UAV was deployed for the mission. The flight plan was designed with a heading overlap of 80%, a side lap of 60%, an altitude of 80–110 m, and a camera tilt angle of 30~60°. This configuration ensured comprehensive coverage of building facades and surface details through multi-angle imagery. To ensure data quality, aerial imaging was conducted during sunny weather to avoid cloud obscuration. The acquisition frequency was set to 1 Hz, enabling synchronous recording of GPS positioning and IMU attitude data. For complex terrain areas, a block-based flight strategy was implemented. Each flight block covered an area of $\leq 0.25 \text{ km}^2$ with a single flight duration of 30 min. Five sets of backup batteries were deployed to ensure uninterrupted operations and data integrity. The division of these regional blocks is illustrated in Figure 3.



Figure 3. Regional block division.

A detailed digital model of the coastal urban terrain was created from UAV oblique imagery through a workflow comprising multi-view image matching and point cloud reconstruction. The oblique photography point cloud was generated primarily using the Structure from Motion (SM) algorithm. Initially, a sparse point cloud was created through multi-view image feature point matching (e.g., using the SIFT algorithm). This was subsequently processed with Multi-View Stereo (MVS) technology to produce a dense point cloud, effectively capturing details of building facades and terrain variations. To improve terrain spatial reliability for decision-making, the least squares method was employed to optimize the image exterior orientation elements, thereby compensating for camera distortion and positioning errors and thus enhancing the final model's fidelity. The

surface morphology was dynamically fitted based on a triangulated irregular network (TIN), followed by point cloud classification and filtering. The vegetation and building point clouds were separated by Global Mapper, and the bare surface data was retained to generate a digital elevation model (DEM). Combined with NURBS surface reconstruction technology, the discrete point cloud was transformed into a continuous terrain surface, and the STL format structured grid was output for CFD simulation calculation. The process of phased reverse modeling technology is shown in Figure 4.

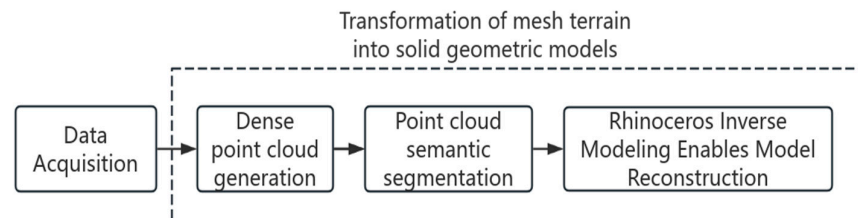


Figure 4. Flowchart of reverse modeling technique.

2.3. CFD Numerical Method

In this study, CFD is employed as an analytical tool to generate spatially explicit wind risk information rather than for turbulence model development. With the completion of the fine terrain modeling, a numerical model is built using the exported mesh, which serves as the foundation for all subsequent CFD simulations. To achieve a balance between simulation accuracy and computational efficiency, key parameters, including the computational domain size, model position, and mesh size, are determined [24]. A full-scale (1:1) numerical model is developed. The computational domain, illustrated in Figure 5, is defined with respect to the maximum building height (H) with the following extents: $5H$ at the inlet and lateral sides, $15H$ at the outlet, and $6H$ in height. The front of the calculation domain is set as the velocity inlet, the rear is the pressure outlet, and the model surface is a non-slip boundary condition.

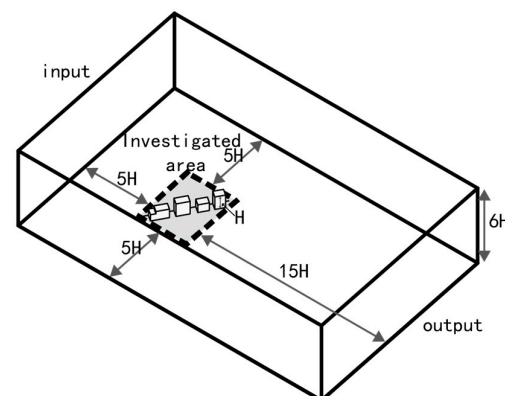


Figure 5. Numerical model calculation domain setting.

The flow field was discretized using a hybrid mesh comprising both structured and unstructured grids. A body-fitted grid with a minimum thickness of 0.01 m was employed near the walls, in conjunction with a wall function to account for viscous effects. A grid independence study was conducted to ensure a target $y^+ < 5$ for satisfactory near-wall resolution. Five mesh schemes, ranging from 3 million to 16 million elements, were tested. Results indicated that solution accuracy converged when the grid count reached 13 million elements, as shown in Figure 6.

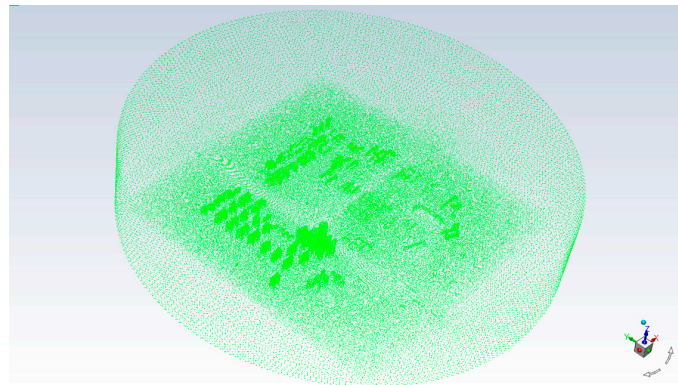


Figure 6. Computational mesh of the domain.

The simulations employed a second-order discretization scheme under steady-state conditions. The governing equations were discretized using the finite volume method. A second-order central difference scheme was applied to the diffusion terms, while a second-order upwind scheme was used for the convection terms. Pressure–velocity coupling was achieved using the SIMPLE algorithm. The Reynolds-averaged Navier–Stokes (RANS) equations served as the governing equations. The inlet wind profile was defined based on field measurements obtained from a wind observation tower and UAV-based measurements [25], and turbulence at the inlet was generated using a User-Defined Function (UDF).

For turbulence modeling, the standard $k-\epsilon$ model was adopted due to its robustness and computational efficiency in simulating mean wind flow over complex urban terrains [26]. Although more advanced turbulence models, such as the $k-\omega$ SST and Realizable $k-\epsilon$ models, can provide improved predictions for near-wall flow separation and recirculation, their advantages are more significant in studies focusing on detailed local flow structures. In contrast, the present study aims to capture the overall spatial distribution of wind velocity at the urban scale. Previous studies have shown that the standard $k-\epsilon$ model can provide sufficiently accurate predictions for mean wind characteristics in urban environments while maintaining high computational efficiency and numerical stability (e.g., [27–29]). Considering the large computational domain and high grid resolution used in this study, the increased computational cost of higher-order models is not expected to yield proportionally significant improvements in prediction accuracy. Therefore, the standard $k-\epsilon$ model was selected as an appropriate compromise between computational efficiency and predictive performance. Nevertheless, it is acknowledged that this model may have limitations in resolving near-wall effects and complex recirculation regions, which will be further explored in future studies.

The simulations were conducted in a transient formulation to ensure numerical stability and adequate resolution of flow evolution. The dimensionless time step was defined as $\Delta t^* = U\Delta t/L$, where U is the characteristic inlet wind velocity, Δt is the physical time step, and L represents the characteristic length scale. Based on a three-dimensional time-step independence analysis, Δt^* was set to 0.01, ensuring stable convergence and sufficient temporal resolution.

This study is based on several assumptions. First, the urban terrain and building geometry are treated as static during the simulation period, neglecting dynamic changes such as vegetation movement or temporary structures. Second, the inflow boundary conditions are assumed to represent steady-state wind conditions derived from field measurements. Third, the standard $k-\epsilon$ model is assumed to provide sufficiently accurate predictions of mean wind characteristics at the urban scale.

3. Results and Discussion

3.1. Spatial Reliability for Decision-Making Based on UAV

In UAV low-altitude photogrammetry systems, image quality is a fundamental determinant of the accuracy in 3D geometric reconstruction. Following image acquisition, a rapid image stitching preprocessing step is initiated, conducted in parallel with an assessment of the geometric integrity and radiometric quality of the data. If data quality issues are identified, a supplementary aerial photography or a partial re-flight contingency plan should be implemented promptly. For image sequences exhibiting color deviation, abnormal exposure, or contrast imbalance, digital enhancement tools can be employed to perform full-gamut equalization, optimize spectral consistency, and ensure that the engineering requirements for 3D point cloud reconstruction are met. Ultra-dense 3D point clouds were first rendered into multi-perspective, two-dimensional images. These images then served as the basis for reconstructing a high-resolution, photorealistic 3D model, which accurately recreates the original scene with its full geometric detail and native image resolution. The digital orthophoto map and digital surface model resulting from the digital modeling are shown in Figure 7.

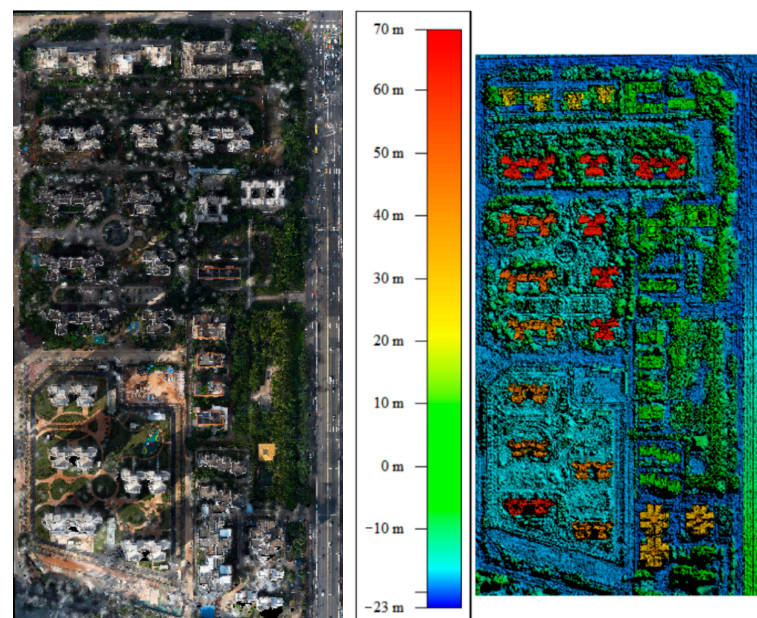


Figure 7. The digital orthophoto map and digital surface model.

The point cloud data is exported from the digital surface model (DSM), which captures elevation information of the Earth's surface, including buildings and vegetation. As the DSM incorporates above-ground features, it cannot be directly used as a terrain analysis model and requires further optimization. For classifying the derived layer point cloud data in the digital orthophoto map, LiDAR point cloud data can be used as a reference, serving both automated and visual classification workflows. Guided by the orthophoto map, point clouds are processed through a combination of automatic classification and manual editing. This facilitates the optimization and simplification of the terrain model by filling gaps in the LAS data and selectively modifying details. The LAS layer is shown in Figure 8, which displays a diversity of point cloud types. At this stage, ground points are isolated through filtering, and the remaining task is to extract vegetation and buildings from the above-ground features. The extracted point cloud data can be utilized for further analysis and modeling, such as wind field simulation and urban planning, serving as a foundation for 3D modeling of complex terrain.

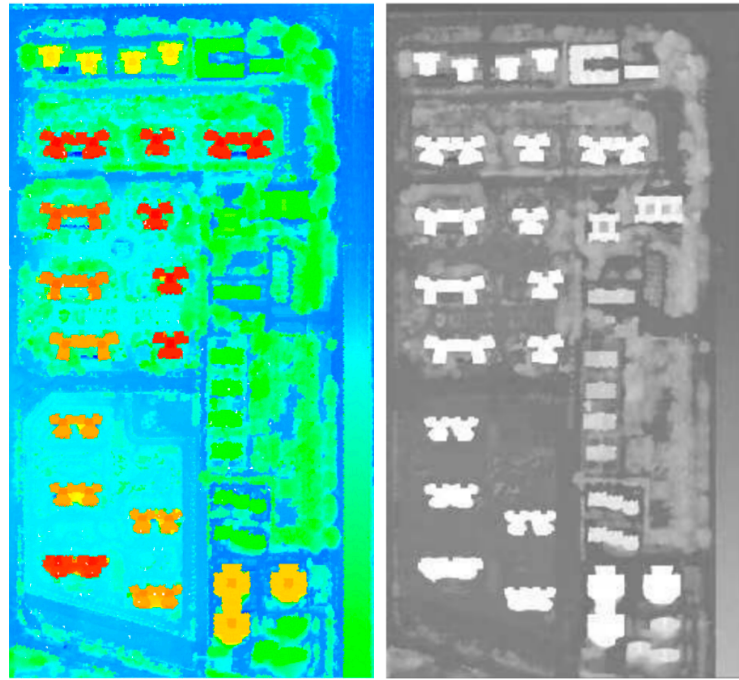


Figure 8. LAS layer point cloud map and building classification map.

The generated digital orthophoto map and digital terrain model were used to create a high-precision DEM of the target area. This DEM was then processed to generate a terrain file interpretable by CFD software. The process of establishing the terrain model is given in Figure 4. Through data processing, the digital file generated from terrain modeling can be converted into georeferenced data containing latitude, longitude, and elevation values. By applying a coordinate transformation, the latitude and longitude coordinates were converted to rectangular coordinates within a plane coordinate system. The resulting rectangular coordinate data was used to generate a corresponding 3D terrain model, which accurately captures the topographic undulations and characteristic details of the landscape, as shown in Figure 9.

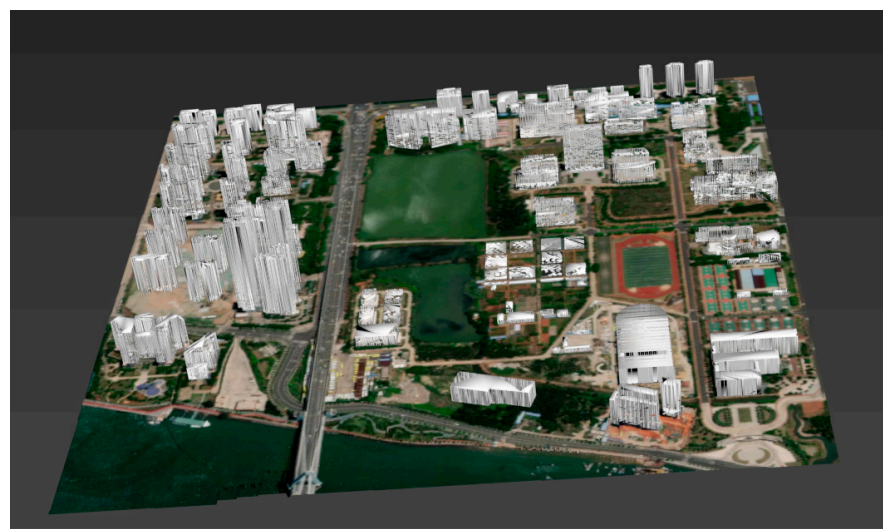


Figure 9. Illustration of urban terrain model.

Based on a comparative analysis with existing traditional modeling methods, the proposed approach demonstrates significant improvements in key performance metrics. Under the same modeling area, this method reduces manual intervention by 60%. When

compared with traditional GIS modeling, the point cloud density reaches up to 600:1, representing a 33% increase in density. Furthermore, the average elevation error (RMSE) is reduced by 20% in comparison with conventional UAV-based modeling techniques. The resulting high-resolution terrain model enables detailed identification of wind-sensitive urban areas, which is critical for spatial risk screening in emergency management.

3.2. Numerical Analysis and Verification of Wind Environment

The urban terrain model developed in the previous section is imported, after which grid generation and computational parameter setup are performed to analyze the wind environment across the terrain. Simultaneously, near-ground wind field data is measured by a wind observation tower installed in the area of interest. The statistically analyzed wind parameters from this tower then serve as the benchmark for verifying the accuracy of the numerical simulation. Figure 10 presents the average velocity cloud diagram of the computational domain obtained from the numerical simulation. Significant interference from urban buildings on the wind environment is observed in the above figure, with notable phenomena including airflow occlusion and local acceleration. The vertical wind velocity distribution is topographically influenced but is found to be essentially consistent with the inlet wind profile conditions. Figure 11 presents the wind velocity distribution at heights of 20 m, 35 m and 50 m under the same incoming wind direction.

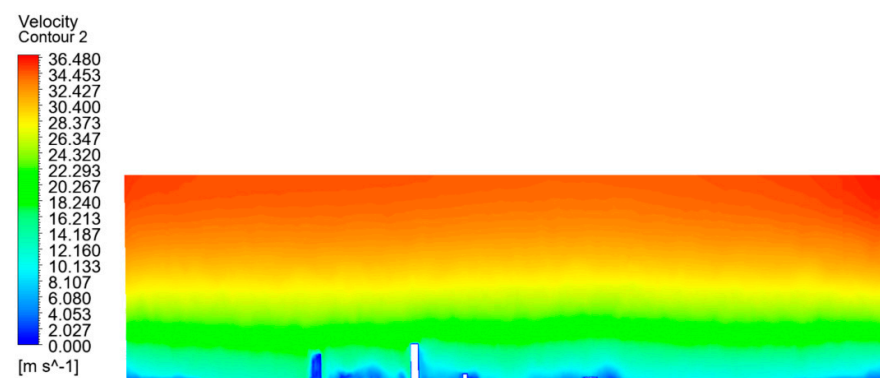


Figure 10. Distribution of the overall average wind speed in the computational domain.

The figure reveals how architectural forms and complex terrain create spatial disparities in the wind environment, which directly influence risk prevention/control and the development of emergency strategies in intelligent emergency management. This phenomenon can be explained by the interaction between airflow and urban morphology. Dense building clusters and irregular terrain surfaces modify the local pressure distribution, leading to flow acceleration in constricted passages (canyon effect) and flow separation in wake regions. These processes generate spatial heterogeneity in wind velocity and turbulence intensity, which in turn contribute to the formation of localized high-risk wind zones. Under this wind direction, the urban buildings and terrain exert a substantial influence, causing significant changes in both wind velocity and direction. This interference effect is more pronounced at lower heights. The observed vertical variation is structurally driven by the combined effects of surface roughness, building density, and terrain elevation. Near the ground, increased surface roughness and obstacle density enhance frictional resistance and turbulence generation, whereas at higher elevations, reduced obstruction leads to more stable flow conditions. This is primarily because, in proximity to the ground, surface obstacles generate considerable frictional drag, while the canyon effect leads to localized wind speed amplification, forming high-risk wind zones that require priority consideration in emergency planning. In particular, the “gorge effect” created by building groupings can

multiply the local wind velocity, producing a maximum amplification factor of 1.95 in this study. Such wind speed amplification represents a critical threshold for pedestrian safety and emergency operations in dense urban environments. This phenomenon can significantly impact pedestrian comfort, structural wind resistance, and emergency management. The findings from the wind environment analysis can inform urban planning decisions to help mitigate these adverse effects. Figure 12 shows the turbulent kinetic energy intensity at the three aforementioned heights, depicting fluctuations in the wind field.

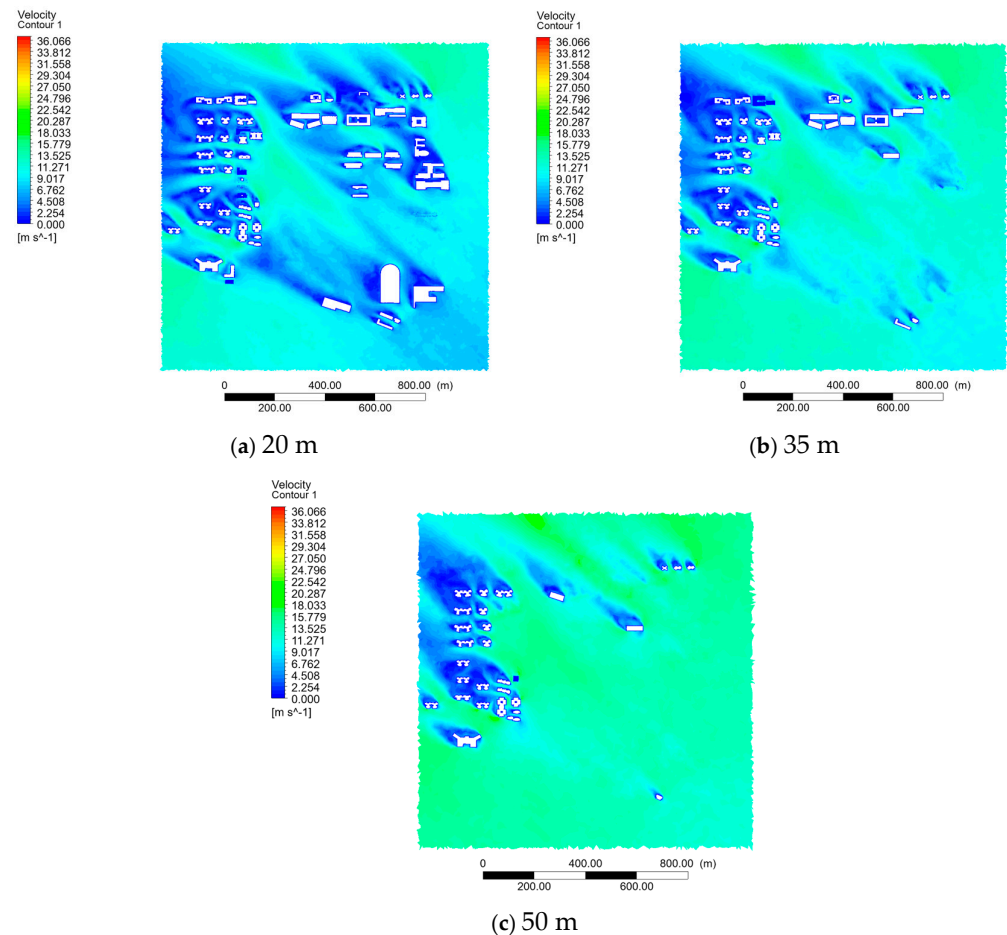


Figure 11. The average wind velocity distribution at different heights.

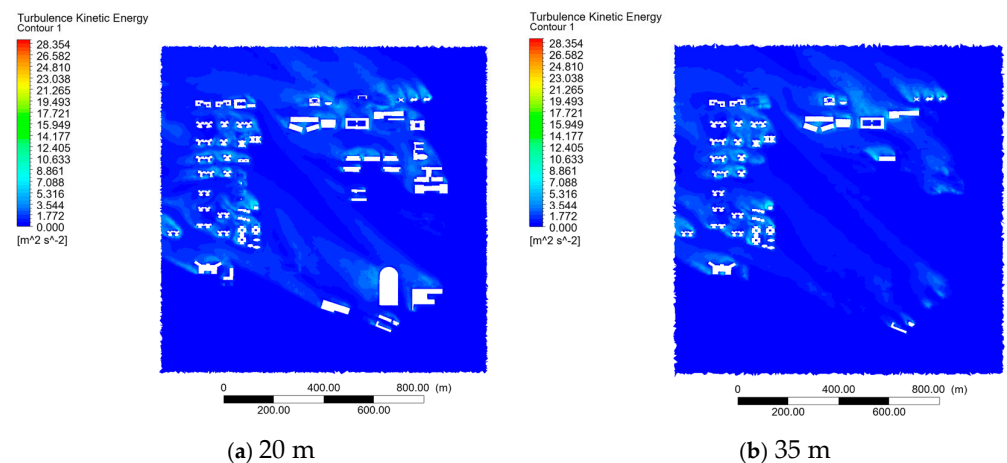


Figure 12. Cont.

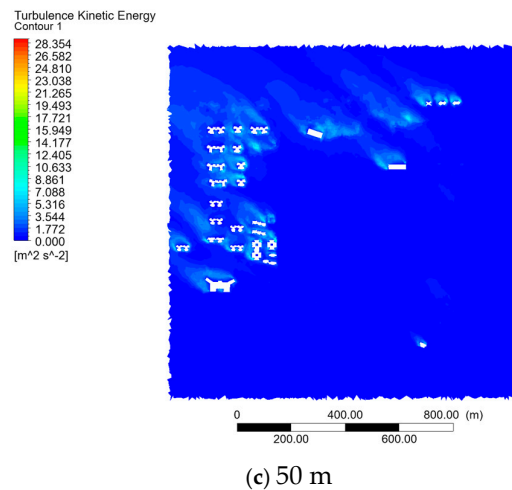


Figure 12. The turbulent kinetic energy intensity cloud diagram at different heights.

Turbulent kinetic energy intensity is defined as the intensity of wind velocity fluctuations relative to the average velocity. It is thus a direct measure of the flow disturbance induced by terrain features and the resulting turbulence. As shown in Figure 13, at the 20 m height, the incoming flow undergoes vortex shedding, flow separation and reattachment, and coherent interference due to the disturbance from the dense building group. Consequently, a distinct turbulent structure forms in the building wake, with the maximum turbulent kinetic energy intensity reaching nearly 30%. This region is characterized by intense flow fluctuations and high vortices, indicating the most active zone for energy exchange and mixing. This should be highly noticed for the structural design that is controlled by fluctuating wind velocity. The turbulent kinetic energy intensity decreases with height due to the reduced interference from the terrain and buildings. Figure 13 presents the vortices map for the analysis area, clearly illustrating the vortices, shear layers, and rotational motion within the flow field. The vortices map clearly reveals that the flow separation point and separation zone, located along the building group edges and in the wake area, correspond well with the regions of high turbulent kinetic energy intensity mentioned earlier.

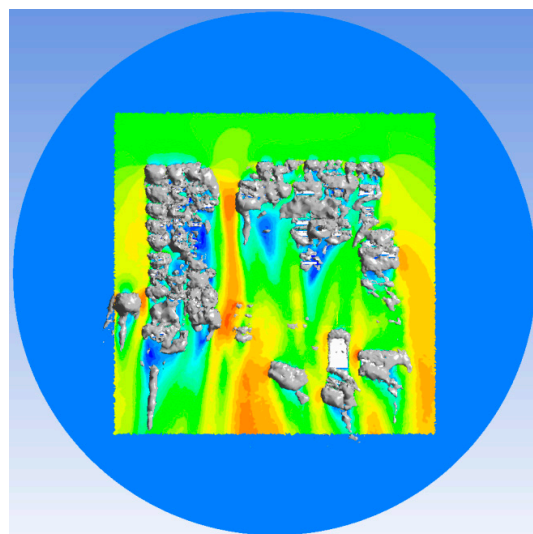


Figure 13. The vortices map of the target area.

In order to further explore the characteristics of the near-ground wind field in the target area and verify the effectiveness of CFD numerical simulation, the real-time wind

velocity data measured by the wind observation tower is also analyzed. To illustrate the variation in wind velocity and direction across seasons and times of day, Figure 14 presents the wind rose diagram for the area, a tool widely applicable in urban planning, architectural design, and environmental assessment. In this system, the wind direction is defined with 0° at true north (perpendicular to the Qiongzhou Strait) and 180° at south.

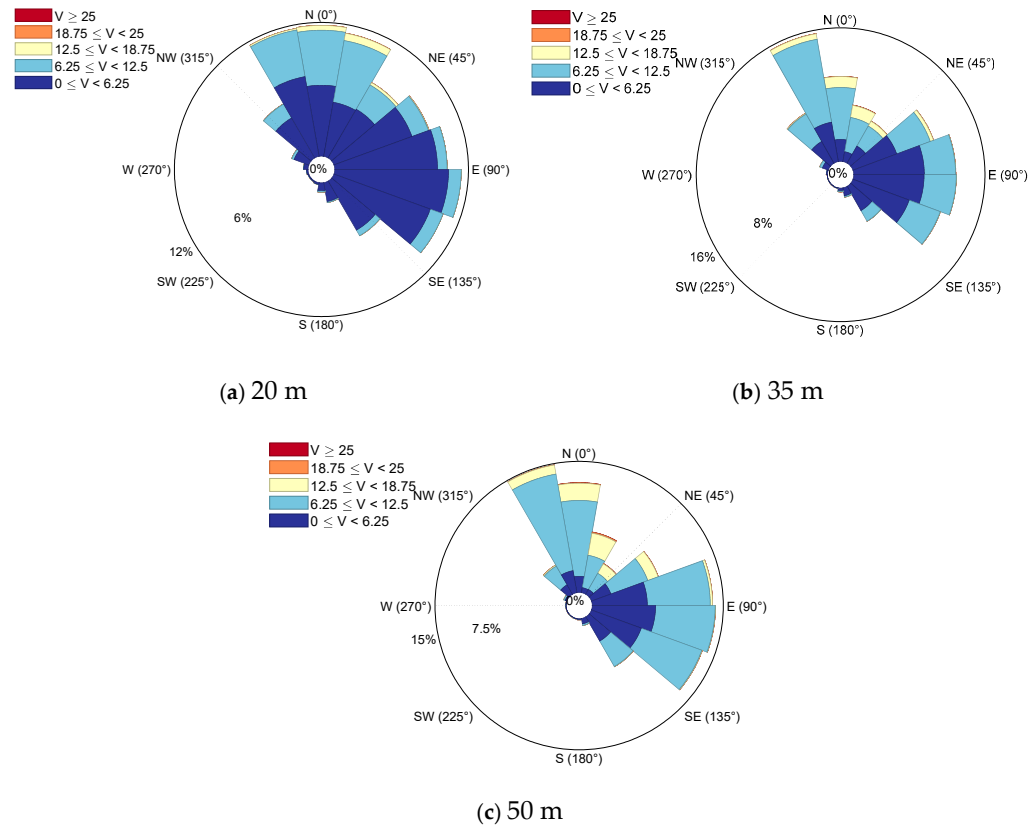


Figure 14. Field-measured wind rose diagram.

The figure above shows that winds during the observation period were predominantly from the north and east, with a maximum instantaneous speed of 24.6 m/s recorded at the 50 m height. The wind direction during the daytime shows distinct variations. In the morning (8:00~11:00), it remains relatively stable, predominantly from 330° to 360° , which aligns with the prevailing wind direction. Around noon, however, it becomes more variable, shifting through a wider range of 30° to 120° . The analysis confirms that the study area exhibits a typical island climate, characterized by distinct morning and evening wind direction shifts associated with sea–land breezes.

For validation, wind velocity data from the meteorological tower, specifically during periods of prevailing northerly winds, was selected and benchmarked against the corresponding CFD simulation results. To manage the extensive dataset, the data was filtered based on two principles: first, to select records with coherent wind velocity and direction for reliable comparison; and second, to ensure that all selected measured data samples were temporally aligned and of equal duration. To evaluate the simulation accuracy, two key parameters at 20 m, 35 m, and 50 m heights were compared: the 10-minute average wind velocity (U_z), and the turbulence intensity (I_u) based on the along-wind fluctuation component. The discrepancy between the measured and simulated values was evaluated using the relative error, calculated as follows: $\text{relative error} = (\text{CFD value} - \text{measured value}) / \text{measured value}$. The comparison results are shown in Table 1. The observed agreement between sim-

ulated and measured results indicates that the proposed framework can provide sufficiently reliable wind risk information for emergency management applications.

Table 1. The comparison results.

	Method Type	20 m	35 m	50 m
U_z (m/s)	Measured	9.01	9.81	11.12
	CFD	10.13	10.96	12.21
Relative Error		12.43%	11.72%	9.80%
I_u (%)	Measured	0.38	0.34	0.26
	CFD	0.33	0.29	0.23
Relative Error		−13.16%	−14.71%	−11.53%

Despite the overall agreement between simulation and measurement results, several limitations should be noted. First, the grid resolution may not fully capture small-scale turbulent structures near the ground, which could contribute to the observed discrepancies. Second, the use of steady inflow conditions may not fully represent the temporal variability of real wind fields. Third, the simplification of surface features, such as vegetation dynamics, may introduce additional uncertainties.

To ensure the robustness of the simulation results, a grid independence test and time-step sensitivity analysis were conducted. The results indicate that the selected grid size and time-step configuration provide stable and convergent solutions, supporting the reliability of the proposed modeling framework.

The comparison demonstrates good overall agreement between the field measurements and the CFD results, with relative errors generally within 15%. These findings are consistent with previous studies on urban wind environment simulation, which have reported similar levels of agreement between CFD predictions and field measurements when using RANS-based turbulence models [30]. For example, prior research has shown that relative errors within 10–20% are generally acceptable for engineering-scale wind environment assessment, indicating that the accuracy achieved in this study is within a reasonable and reliable range. Regarding the average wind velocity, the CFD results generally overestimate the measurements. The overestimation error is inversely proportional to height, reaching a maximum of 12.43% closest to the ground. Proximity to the ground increases surface-induced disturbance to the wind field and leads to greater wind speed fluctuations. This limitation necessitates further improvement in the numerical method's accuracy for simulating the near-surface wind environment. The turbulence intensity results also show a similar trend, but the numerical simulation results are smaller than the measured values. Despite the good accuracy of the CFD simulations, discrepancies persist and are more pronounced near the ground. It should be noted that potential error sources include the grid resolution's limited ability to resolve partial-scale vortices, the inability to simulate the motion of surface vegetation, interference from the surrounding wind field on the target area, and so on.

Addressing the pressing need for wind disaster prevention and mitigation in coastal cities, this study develops an integrated approach that combines UAV-based high-resolution urban terrain modeling with CFD simulations of the wind environment. The method's effectiveness is validated against field measurements, demonstrating its practical value for engineering applications. The proposed method accurately acquires essential wind environment data for the area of interest. This data facilitates effective structural safety analysis and supports the formulation of evidence-based emergency strategies. Consequently, the present study provides a valuable reference for enhancing coastal city resilience and advancing comprehensive emergency management capabilities.

3.3. Implications for Emergency Management and Urban Resilience

Overall, the results demonstrate that urban wind risk is strongly influenced by the interaction between terrain complexity and building morphology, highlighting the importance of high-resolution modeling for capturing these localized effects.

Urban wind disasters pose significant challenges to emergency management in coastal cities, particularly in areas characterized by complex terrain and dense building configurations [31]. The high-resolution wind environment information generated in this study provides actionable insights for risk-informed emergency planning. The identified high-risk wind zones associated with the canyon effect and local wind speed amplification highlight areas where emergency response operations, evacuation routes, and temporary shelters may be exposed to elevated safety risks. These findings also highlight the importance of incorporating high-resolution wind environment data into existing emergency management protocols, which currently rely largely on regional meteorological observations and may not sufficiently capture localized wind hazards in dense urban environments.

From an emergency management perspective, the spatially explicit wind risk information derived from the UAV-CFD framework enables the prioritization of critical urban zones requiring targeted mitigation measures. For example, regions exhibiting persistent wind speed amplification can be considered in advance when designing emergency access routes, allocating emergency resources, and planning crowd evacuation strategies during extreme wind events [32]. This approach supports a shift from reactive response to proactive risk mitigation.

Furthermore, the proposed framework facilitates cross-sectoral collaboration among emergency management agencies, urban planners, and meteorological services. By integrating high-resolution wind risk data into urban resilience planning and emergency decision-support systems, city authorities can enhance their capacity to anticipate wind-related hazards and reduce potential cascading impacts on urban infrastructure and public safety. Although this study focuses on a coastal city case, the methodological framework is transferable to other urban environments exposed to extreme wind hazards. For instance, the approach can be applied to high-density metropolitan areas characterized by complex building clusters and street canyons, where localized wind acceleration may pose risks to pedestrians and emergency operations. It is also relevant for medium-density urban districts or rapidly expanding coastal cities, where ongoing urban development continuously alters the wind environment and associated risk patterns. By integrating high-resolution terrain modeling with CFD simulations, the framework can support wind risk assessment across diverse urban morphologies and planning contexts.

In addition, the framework has important temporal relevance for emergency planning. Urban wind environments are not static and may change significantly following major urban redevelopment projects, new high-rise construction, or large-scale infrastructure development. Therefore, periodic reassessment of urban wind risk using updated terrain data is recommended. For rapidly developing urban areas, such assessments could be conducted after major planning revisions or every several years as part of routine urban resilience monitoring. This dynamic assessment capability enhances the practical value of the proposed framework for long-term emergency management and resilience-oriented urban governance. These findings demonstrate how high-resolution wind risk modeling can support sustainability-oriented urban governance by providing scientific evidence for emergency preparedness, urban planning, and resilience-building strategies [33]. From a sustainability perspective, the proposed framework contributes to multiple dimensions of sustainable urban development. Environmentally, it improves the accuracy of wind environment assessment, supporting a better understanding of urban microclimate and hazard distribution. Socially, it enhances public safety by identifying high-risk wind zones

that may affect pedestrian exposure and emergency evacuation. Economically, it supports cost-effective disaster risk mitigation by enabling more targeted infrastructure design and resource allocation. In terms of long-term resilience, the framework facilitates proactive risk management and adaptive urban planning by providing high-resolution data for continuous monitoring and decision-making. Therefore, this study contributes to the integration of high-resolution environmental modeling into sustainability-oriented urban governance systems. These findings demonstrate that high-resolution wind environment modeling can significantly improve the spatial accuracy of urban wind risk assessment and provide scientific support for integrating environmental simulation data into emergency management decision-making systems.

4. Limitations and Scope Conditions

Despite the promising results, several limitations and scope conditions of this study should be acknowledged.

First, regarding boundary conditions, the CFD simulations are based on steady-state inflow conditions derived from field measurements, which may not fully capture the temporal variability of real wind environments under rapidly changing weather conditions such as typhoons.

Second, in terms of generalizability, the study focuses on a specific coastal urban area with complex terrain. While the proposed framework is transferable in principle, its direct applicability to other cities with different climatic conditions, urban morphologies, or terrain characteristics may require further validation and calibration.

Third, several methodological constraints should be noted. The use of the standard $k-\epsilon$ turbulence model, although computationally efficient, may have limitations in capturing small-scale turbulence structures and near-wall flow separation. In addition, the resolution of the terrain model and grid discretization may influence simulation accuracy, particularly in near-ground regions.

Fourth, potential sources of bias may arise from data acquisition and modeling processes. For example, UAV-based terrain reconstruction may be affected by image quality, occlusions, and processing algorithms, while the simplification of vegetation and surface dynamics may introduce uncertainties in wind field simulation.

Despite these limitations, the proposed framework provides a reliable and practical approach for high-resolution urban wind risk assessment. Future research should focus on improving model accuracy under transient wind conditions, expanding validation across diverse urban contexts, and integrating dynamic environmental factors into the simulation framework.

5. Conclusions

This study developed an integrated UAV-CFD framework for high-resolution urban wind risk assessment in coastal cities with complex terrain. By combining multi-source geospatial data with refined numerical simulation, a detailed urban terrain model was constructed to support accurate wind environment analysis.

The results show that complex terrain and building configurations significantly influence local wind patterns, with a maximum wind speed amplification factor of 1.95 caused by the canyon effect. Validation against field measurements indicates that the simulation results are reliable, with relative errors generally within 15%, demonstrating the applicability of the proposed framework for practical urban wind risk assessment.

From a sustainability perspective, the proposed framework supports environmental risk assessment, enhances public safety, and enables more efficient allocation of emergency resources. By providing high-resolution wind risk information, it contributes to proactive

emergency management and resilience-oriented urban planning. Future research will focus on extending the framework to diverse urban contexts and incorporating dynamic environmental conditions to further improve model applicability.

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References

1. Duarte, C.M.; Ferreira, J.C.; Fortes, J. Risk Modelling in Urban Coastal Areas to Support Adaptation to Climate Change and Extreme Weather Events: Early Warning, Emergency Planning and Risk Management Systems. *J. Coast. Res.* **2020**, *95*, 785–789. [\[CrossRef\]](#)
2. Renault, M.A.; Bailey, B.N.; Stoll, R.; Pardyjak, E.R. A rapid method for computing 3-D high-resolution vegetative canopy winds in weakly complex terrain. *Front. Earth Sci.* **2023**, *11*, 1251056. [\[CrossRef\]](#)
3. Rakib, M.I.; Nay, S.; Evans, S.; Clausen, P. Wind Regimes in Urban Environments: Experimental Comparison with the IEC 61400.2-2013 Open Terrain Wind Model. In *Wind Energy Exploitation in Urban Environment*; Research Topics in Wind Energy; Springer: Cham, Switzerland, 2019; Volume 8, pp. 201–204.
4. Tabrizi, A.B.; Whale, J.; Lyons, T.; Urmee, T.; Peinke, J. Modelling the structural loading of a small wind turbine at a highly turbulent site via modifications to the Kaimal turbulence spectra. *Renew. Energy* **2017**, *105*, 288–300. [\[CrossRef\]](#)
5. Mei, S.; Hang, J.; Fan, Y.; Yuan, C.; Xue, Y. CFD simulations on the wind and thermal environment in urban areas with complex terrain under calm conditions. *Sustain. Cities Soc.* **2025**, *118*, 113611. [\[CrossRef\]](#)
6. Xie, M.; Chen, J.; Zhang, Q.; Li, H.; Fu, M.; Breuste, J. Dominant landscape indicators and their dominant areas influencing urban thermal environment based on structural equation model. *Ecol. Indic.* **2019**, *111*, 105992. [\[CrossRef\]](#)
7. Hang, J.; Luo, Z.; Sandberg, M.; Gong, J. Natural ventilation assessment in typical open and semi-open urban environments under various wind directions. *Build. Environ.* **2013**, *70*, 318–333. [\[CrossRef\]](#)
8. Singh, C.H.; Mishra, V.; Jain, K. High-resolution mapping of forested hills using real-time UAV terrain following. *ISPRS Ann. Photogramm. Remote Sens. Spat. Inf. Sci.* **2023**, *10*, 665–671. [\[CrossRef\]](#)
9. Ju, P.; Li, M.; Wang, J. Review of research advances in cfd techniques for the simulation of urban wind environments. *Fluid Dyn. Mater. Process.* **2022**, *18*, 449–462. [\[CrossRef\]](#)
10. Shukla, D.; Azad, H.K.; Abhishek, K.; Shitharth, S. Disaster management ontology—An ontological approach to disaster management automation. *Sci. Rep.* **2023**, *13*, 8091. [\[CrossRef\]](#)
11. Shi, H.; Chen, Y.; Gao, H.; Zhao, H. Effects of typhoon and upwelling on Chlorophyll-a distribution in the northeastern coast of Hainan during Summer. *PLoS ONE* **2023**, *17*, 1371. [\[CrossRef\]](#)
12. Tse, K.T.; Zhang, X.; Weerasuriya, A.U.; Li, S.W.; Kwok, K.C.S.; Mak, C.M.; Niu, J. Adopting ‘lift-up’ building design to improve the surrounding pedestrian-level wind environment. *Build. Environ.* **2017**, *117*, 154–165. [\[CrossRef\]](#)

13. Kuo, C.-Y.; Tzeng, C.-T.; Ho, M.-C.; Lai, C.-M. Wind Tunnel Studies of a Pedestrian-Level Wind Environment in a Street Canyon between a High-Rise Building with a Podium and Low-Level Attached Houses. *Energies* **2015**, *8*, 10942–10957. [\[CrossRef\]](#)
14. Xu, X.; Yang, Q.; Yoshida, A.; Tamura, Y. Characteristics of pedestrian-level wind around super-tall buildings with various configurations. *J. Wind Eng. Ind. Aerodyn.* **2017**, *166*, 61–73. [\[CrossRef\]](#)
15. Yu, J.; Stathopoulos, T.; Li, M. Discussion of “wind-tunnel testing of low- and midrise buildings under heterogeneous upwind terrains”. *J. Struct. Eng.* **2025**, *151*, 07025001. [\[CrossRef\]](#)
16. Yang, J.; Shi, B.; Shi, Y.; Marvin, S.; Zheng, Y.; Xia, G. Air pollution dispersal in high density urban areas: Research on the triadic relation of wind, air pollution, and urban form. *Sustain. Cities Soc.* **2019**, *54*, 101941. [\[CrossRef\]](#)
17. Harding, C.; Hasiuk, F.; Wood, A. Touchterrain—3d printable terrain models. *ISPRS Int. J. Geo Inf.* **2021**, *10*, 108. [\[CrossRef\]](#)
18. Hruby, F.; Ressler, R.; de la Borbolla del Valle, G. Geovisualization with immersive virtual environments in theory and practice. *Int. J. Digit. Earth* **2018**, *12*, 123–136. [\[CrossRef\]](#)
19. Sameer, M.A.; Mohammed, A.A. A study on seismic performance of tall buildings with transfer plate. *Int. J. Appl. Eng. Res.* **2019**, *14*, 1849–1859.
20. Potsis, T.; Stathopoulos, T. Wind induced peak pressures on low-rise building roofs via dynamic terrain computational methodology. *J. Wind Eng. Ind. Aerodyn. J. Int. Assoc. Wind Eng.* **2024**, *245*, 105630. [\[CrossRef\]](#)
21. Kim, Y.C.; Tamura, Y.; Yoon, S.-W. Proximity effect on low-rise building surrounded by similar-sized buildings. *J. Wind. Eng. Ind. Aerodyn.* **2015**, *146*, 150–162. [\[CrossRef\]](#)
22. Ahmad, F.; Majumder, D.; Ranjit, R.; Gupta, A.; Manhart, M. Preliminary study on the spread of air-borne pollutants in urban environment: A cfd simulation approach. *Sci. Rep.* **2025**, *15*, 18836. [\[CrossRef\]](#)
23. Liu, S.; Pan, W.; Zhang, H.; Cheng, X.; Long, Z.; Chen, Q. CFD simulations of wind distribution in an urban community with a full-scale geometrical model. *Build. Environ.* **2017**, *117*, 11–23. [\[CrossRef\]](#)
24. Nakamura, M.; Hamba, F. A rans model for shock/turbulence interaction. *Seisan Kenkyu* **2023**, *75*, 19–23.
25. Yu, J.; Stathopoulos, T.; Li, M. Estimating exposure roughness based on google earth. *J. Struct. Eng.* **2021**, *147*, 04020353. [\[CrossRef\]](#)
26. Rajasekarababu, K.B.; Vinayagamurthy, G.; Selvi Rajan, S. Evaluation of CFD URANS turbulence models for the building under environmental wind flow with experimental validation. *J. Appl. Fluid Mech.* **2022**, *15*, 1387–1401. [\[CrossRef\]](#)
27. Hedlund, A. Evaluation of rans turbulence models for the simulation of channel flow. *Dep. Inf. Technol.* **2014**, 202–205.
28. Shirzadi, M.; Mirzaei, P.A.; Naghashzadegan, M. Improvement of k-epsilon turbulence model for cfd simulation of atmospheric boundary layer around a high-rise building using stochastic optimization and monte carlo sampling technique. *J. Wind Eng. Ind. Aerodyn.* **2017**, *171*, 366–379. [\[CrossRef\]](#)
29. Guilmineau, E.; Deng, G.B.; Queutey, P.; Visonneau, M.; Wackers, J. Assessment of turbulence models for flow around three-dimensional geometries. In *Proceedings of the Notes on Numerical Fluid Mechanics and Multidisciplinary Design*; Springer: Cham, Switzerland, 2018; pp. 255–264.
30. Li, J.; You, W.; Ding, W. Evaluation of the CFD simulation method for wind prediction in complex urban spatial forms. *Int. J. Environ. Sci. Technol.* **2025**, *22*, 11319–11344. [\[CrossRef\]](#)
31. Kim, B.; Kim, H.S.; Suh, J.; Kwak, H.D. Prediction of lateral and angular eccentricity effects on plain annular seal performance using transient 3d CFD. *J. Mech. Sci. Technol.* **2025**, *39*, 3039–3048. [\[CrossRef\]](#)
32. Huang, M.; Liao, S.; Lou, W.; Lin, W.; Kareem, A. Multi-scale simulation of typhoon wind field at building scale utilizing mesoscale model with nested large eddy simulation. *J. Wind Eng. Ind. Aerodyn.* **2024**, *249*, 105733. [\[CrossRef\]](#)
33. Cui, Y.; Liu, Z.; Wu, H.; Sun, P.; Zhou, F. Evaluation of urban transportation resilience under extreme weather events. *Appl. Sci.* **2024**, *14*, 2076–3417. [\[CrossRef\]](#)

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