Assessment of Pedestrian-Level Wind Environment in Traffic-Oriented Pocket Parks Based on Coupled WRF-ENVI-met Modeling

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Abstract: Environmental problems driven by urbanization threaten public health and urban vitality. Improving urban wind environments helps regulate local climate, disperse air pollutants, and enhance quality. Traffic-oriented pocket parks support daily public activities, yet their wind environments are affected by vehicle emissions and complex airflow. However, studies on pedestrian-level wind environments in pocket parks are limited, and integrated analyses linking environmental performance with human activity are insufficient. This study proposes a downscaling simulation framework coupling the mesoscale Weather Research and Forecasting (WRF) model with the microscale ENVI-met model to simulate pedestrian-level wind environments under a unified meteorological background. Typical traffic-oriented pocket parks in Nanjing were selected as case studies. Wind conditions in winter and summer were evaluated, and simulation results were overlaid with the spatial distribution of crowd concentration to identify three spatial types: core conflict zones, seasonally adaptive zones, and stable low-response zones. Results show that the coupled WRF-ENVI-met approach overcomes limitations of traditional field measurements and enables comparative wind environment assessment across multiple pocket parks. Seasonal differences in wind conditions were observed, and pavilion and corridor structures influenced local airflow. Spatial correspondence was identified between wind environment quality and crowd concentration, though this relationship is affected by multiple factors and requires further validation. This study supports climate-adaptive green space design in high-density urban areas.

Keywords: Transit-oriented pocket parks, wind environment, simulation

1 Introduction

Rapid urbanization has led to a range of environmental problems, including urban heat islands and air pollution, posing serious challenges to public health and urban vitality. As a key natural driving force, the urban wind environment provides a direct and effective means to regulate local climate, disperse pollutants, and improve thermal comfort (REN et al. 2018). In the context of urban development shifting toward quality-oriented renewal of existing spaces, pocket parks – characterized by small size and flexible layouts – have become important components for strengthening public space networks and improving residents' quality of life. Among them, traffic-oriented pocket parks located along major urban roads function as highly accessible nodes of public activity, but their wind environments are simultaneously affected by vehicular emissions and complex airflow associated with urban ventilation corridors. This results in a dual condition of high public use and elevated environmental exposure risk. However, current pocket park design practices largely rely on landscape aesthetics and empirical experience, with limited consideration of microclimate performance. In particular, quantitative studies on pedestrian-level wind environments remain insufficient to support human-centered and climate-adaptive spatial optimization. Consequently, the application of digital simulation techniques for accurate and efficient diagnosis of wind environment quality has become a critical issue for sustainable development in high-density urban areas.

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Within landscape architecture research, studies on wind environments are fewer than in architecture and urban planning, although they span macro-, meso-, and micro-scale analyses. Existing studies have focused primarily on block-scale green spaces (ZHANG et al. 2017), residential areas (HONG & LIN 2014), and street canyons (PENG et al. 2021), with limited attention to urban park green spaces (HOU et al. 2018, SHI et al. 2015). Research on pedestrian-level wind environments has mainly examined streets (CHEN et al. 2023), open roads (ABHIJITH et al. 2017), and residential areas (ZHEN et al. 2019), emphasizing the effects of vegetation structure and green space layout (STOJANOVIC et al. 2020, ZHANG et al. 2025). In recent years, research emphasis has shifted from vegetation and green space form toward microclimate regulation related to human health and thermal comfort, promoting the widespread use of the ENVI-met model (HAMI et al. 2019, LIN et al. 2023). Nevertheless, most studies assess wind environments under isolated conditions and rarely integrate spatial use patterns, limiting their ability to characterize site-specific wind quality or support practical design decisions.

Although ENVI-met has advantages in simulating vegetation-related microclimates, its application is constrained by computational demands and limited coverage, making it difficult to support systematic analysis of multiple small urban green spaces. Moreover, its reliance on station-based observations or short-term field measurements as boundary conditions often fails to represent realistic inflow wind fields under complex urban morphology, reducing the reliability of cross-site comparisons. To address these limitations, this study develops a multi-scale downscaling framework that couples the Weather Research and Forecasting (WRF) and ENVI-met models. City-scale meteorological conditions are simulated using WRF to establish a unified atmospheric background, which is then used as dynamically stable boundary conditions for ENVI-met. This approach enables simulation of pedestrian-level wind fields in multiple pocket parks under consistent meteorological conditions and supports the identification of site-specific wind patterns and potential risk areas relevant to planning and design.

Based on multi-dimensional assessment at the urban scale, this study selects representative traffic-oriented pocket parks as empirical cases and develops a framework that integrates refined wind simulation, evaluation of pedestrian-level (1.5 m) wind environment, and overlay analysis with spatial use patterns. A coupled simulation approach is adopted to link WRF at the urban scale with ENVI-met at the site scale, and the results are validated using field measurements. Wind environment characteristics and seasonal quality are evaluated for both summer and winter, and their spatial correspondence with patterns of park use is examined. The study aims to: (1) develop and validate a WRF-ENVI-met downscaling framework for fine-scale simulation of pedestrian-level wind environments; (2) establish wind environment evaluation criteria and identify seasonal problem areas; and (3) explore the relationship between wind environment quality and spatial use to inform the optimization of traffic-oriented pocket parks. Ultimately, the goal is to improve environmental quality, promote public health, and enhance spatial vitality in high-density historic urban areas.

2 Method

2.1 Study Object

This study focuses on traffic-oriented pocket parks along urban roads in the old city of Nanjing. Traffic-oriented pocket parks are a clearly defined functional category in the Nanjing

Pocket Park Construction Guidelines (Trial). They are small open green spaces, usually less than 1 hectare, developed in underutilized areas near transportation facilities such as bus stops, roads, intersections, and underpasses. These parks primarily serve pedestrians for transit gathering, short-term stops, and leisure activities.

2.2 Selection of Typical Meteorological Days

To reduce the influence of incidental weather, this study selected "typical days" in winter and summer as the reference for meteorological simulations. Based on nearly 20 years of wind speed and direction data from the Nanjing station of the U.S. National Oceanic and Atmospheric Administration (NOAA), the average wind speed and prevailing wind direction for each season were calculated. Actual dates with the smallest deviations from the seasonal averages were then chosen as the typical days. The final selected dates were June 24, 2023, for summer (average wind speed 2.826 m/s, prevailing wind direction 110°) and February 23, 2023, for winter (average wind speed 2.368 m/s, prevailing wind direction 90°).

2.3 Mesoscale Wind Environment Simulation

This study employed the WRF version 4.5.0, incorporating the fifth-generation reanalysis product (ERA5) data, static geographical datasets, and local climate zone (LCZ) data. A four-level nested domain approach was used to simulate the wind, thermal, and humidity environment on typical summer and winter days within the study area. Detailed model configuration parameters are listed in Table 3. The WRF simulation results were validated against hourly observations from the Nanjing National Meteorological Station provided by the China Meteorological Data Service Centre. Validation metrics included bias, root mean square error (RMSE), and correlation coefficient (R).

Table 1: Summary of WRF model configuration.

	D01	**D02**	**D03**	**D04**
Horizontal resolution	9 km	3 km	1 km	333.33m
Microphysics	WRF Single-Moment 5-class scheme			
Cumulus scheme	Kain-Fritsch (new Eta) scheme			
Land surface scheme	Noah Land Surface Model			
Surface layer scheme	Revised MM5 Monin-Obukhov scheme			
Planetary boundary layer scheme	Yonsei University scheme			
Longwave radiation scheme	RRTMG scheme			
Shortwave radiation scheme	RRTMG scheme			
Surface urban physics scheme	BEP scheme			

2.4 Selection of Representative Traffic-Oriented Pocket Parks

This study applied a three-stage screening approach based on wind environment, air pollution, and traffic location to identify representative traffic-oriented pocket parks. First, poorly ventilated areas were identified based on the spatial distribution of average wind speed on the typical summer meteorological day simulated by WRF for the old city of Nanjing, with a focus on zones characterized by the lowest wind speed levels. Second, areas with high air pollution were delineated within the influence ranges of air quality monitoring stations in the old city of Nanjing that recorded the highest ten-year average PM2.5 concentrations during winter. Third, among candidate green spaces meeting the criteria of low wind speed and high pollution, sites adjacent to high-grade roads and located close to schools were prioritized to facilitate long-term field investigation. Based on this screening process, the green space along Beijing East Road and Heping Park in Nanjing were ultimately selected as the study sites.

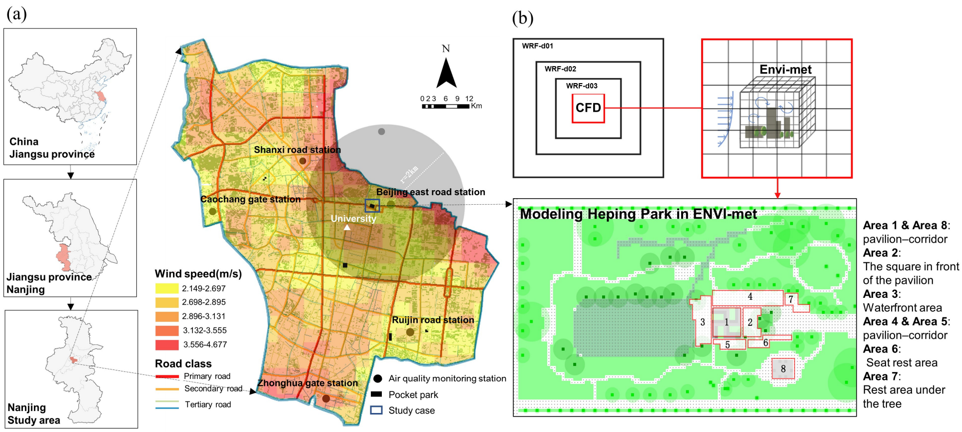

Fig. 1: (a) Study area and sample selection, (b) Schematic diagram illustrating the principle of WRF-ENVI-met wind environment simulation

2.5 Coupled WRF-NVI-met Downscaling Simulation

This study develops a coupled downscaling framework to simulate pedestrian-level wind environments in urban pocket parks under a unified atmospheric background and to reduce uncertainty associated with limited on-site data and scale mismatch in conventional meteorological forcing. The proposed workflow couples WRF and ENVI-met models. Based on the location of Heping Park, hourly meteorological variables were extracted from the corresponding WRF grid cells, including 10 m wind speed, 2 m air temperature, and 2 m relative humidity. These data were then used as boundary conditions to generate a high-resolution and dynamically stable initial meteorological field in ENVI-met using the Full Forcing mode. The pedestrian-level wind environment within the pocket parks was simulated at a height of 1.5 m through the coordinated operation of multiple ENVI-met modules. Within the ENVI-met domain, a horizontal resolution of 1 m × 1 m was adopted to accurately represent landscape elements such as water bodies, vegetation, and pavilion-corridor structures. To verify the reliability of the proposed approach, simulated wind speeds were validated against field measurements collected at boundary monitoring points of Heping Park.

2.6 Data Collection of Crowd Concentration Intensity

Crowd concentration intensity was used to represent spatial use within pocket parks and was quantified as the hourly number of people staying in each activity space. Visitor spatiotemporal behavior was captured using a combination of Wi-Fi probe sensing and on-site observation to characterize within-park crowd distribution. Field surveys were conducted during peak periods on one day in both summer and winter (08:00-11:00 and 14:00-17:00). Three Wi-Fi probes were deployed in each park, each with an approximate 40 m coverage radius. Mobile device signals were recorded at 30-minute intervals, including MAC addresses, received signal strength, and timestamps. Visitor locations were estimated using triangulation, achieving meter-level accuracy. To compensate for the undercounting of individuals without mobile phones (e. g., children and older adults), panoramic cameras were used to record on-site scenes, and image recognition identified and counted visitors, ensuring completeness.

3 Results and Discussion

3.1 Validation of Wind Environment Simulation Data

Using the summer period as an example, WRF outputs were validated against meteorological station observations. The model slightly overestimated wind speed (Bias = +0.93 m/s; RMSE = 1.62 m/s; R = 0.66) and air temperature (Bias = +1.50 °C; RMSE = 1.93 °C; R = 0.96), while relative humidity was underestimated (Bias = −16.19%; RMSE = 18.52%; R = 0.91). WRF-simulated wind, temperature, and humidity for the Heping Park grid cell were then used to drive ENVI-met for pedestrian-level wind environment simulation. ENVI-met wind speeds showed a small positive bias (Bias = +0.21 m/s; RMSE = 0.24 m/s; R = 0.77) when validated against in-park measurements. Overall, errors were within acceptable ranges, supporting the feasibility of the coupled framework.

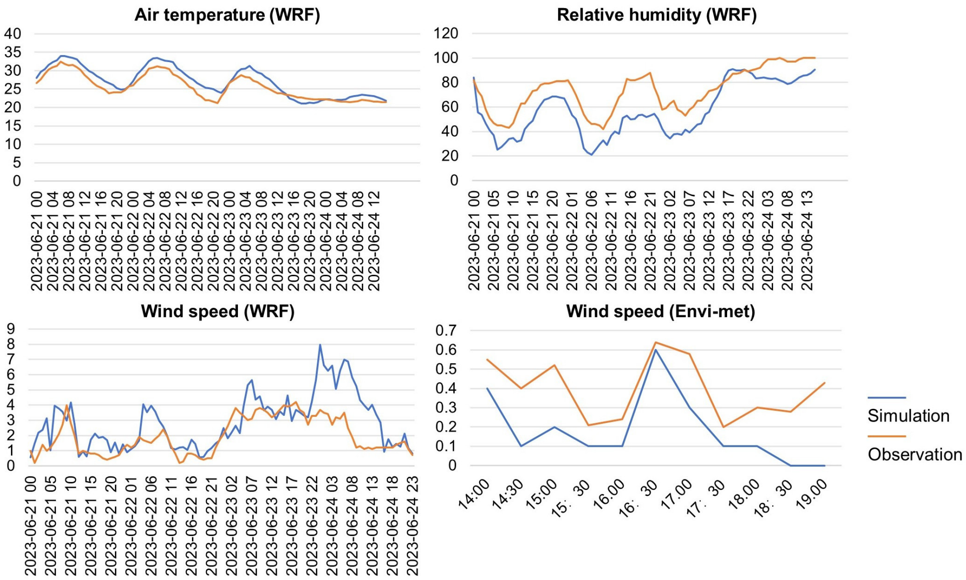

Fig. 2: Comparison between simulated and observed values

3.2 Wind Environment Evaluation Criteria

A wind speed evaluation framework for the pedestrian-level wind environment was established based on the Green Building Evaluation Standard (GB/T 50378-2019), the Shenzhen Green Building Evaluation Specification (SZJG30-2009), and the Hong Kong Planning Department's Air Ventilation Assessment Technical Guidelines. The framework includes two components: (1) wind-induced comfort and safety thresholds and (2) ventilation performance. Wind speeds below 1.0 m/s were classified as calm wind, which may contribute to thermal discomfort and pollutant accumulation, whereas wind speeds above 5.0 m/s were considered to involve potential pedestrian safety risks. Ventilation performance was assessed using a wind speed amplification factor ≥ 0.3, following SZJG30-2009. Using seasonal background wind speeds, the corresponding lower limits were 0.975 m/s in summer and 0.525 m/s in winter. The detailed criteria are provided in Table 2.

Table 2: Pedestrian-level wind speed zoning evaluation

Primary Category	Secondary Zone	Wind Speed Range (m/s)	Wind Environment Characteristics
Calm-wind Zone	Extremely Calm-wind Zone	Summer: < 0.975 Winter: < 0.525	Summer: Insufficient ventilation for convective cooling; Winter: Stagnant air; poor pollutant dispersion
Calm-wind Zone	Moderately Calm-wind Zone	Summer: 0.975-1.0 Winter: 0.525-1.0	Summer: Meets minimum ventilation, but below comfort range; Winter: Insufficient for comfort and pollutant dispersion
Suitable Wind Speed Zone	–	Summer/Winter: 1.0-5.0	Moderate wind speed balances comfort and pollutant dispersion
High Wind Speed Zone	–	Summer/Winter: > 5.0	Wind speed is too high, posing potential safety hazards

3.3 Results of Wind Environment Evaluation

(1) Seasonal Wind Environment Evaluation Results

In summer, suitable wind speeds (1.0-5.0 m/s) dominated the park (97.66%), with no high wind speed zones (> 5.0 m/s). Extremely calm (< 0.975 m/s) and sub-calm (0.975-1.0 m/s) areas accounted for 1.92% and 0.42%, respectively. Wind speeds in the central pavilion-corridor, and roadside pavilions, major resting spaces, were below 1.0 m/s, highlighting areas for wind environment optimization. In winter, calm wind areas increased to 67.85%, including 2.73% extremely calm, which hinders pollutant dispersion, such as PM2.5. Suitable wind speeds (1.0-5.0 m/s) accounted for 32.15%, mainly over water surfaces and scattered green spaces, with no high wind speed zones. Within the suitable range, usable activity areas were limited and concentrated over water, indicating suboptimal winter wind environments for accessible spaces.

(2) Spatial Correspondence Between Wind Environment and Crowd Concentration

Overlaying wind environment maps with crowd concentration revealed consistent spatial differentiation across seasons. In summer, the waterfront activity area (Area 3) benefited from an open water surface to the east and its location in a wind acceleration zone, showing the best ventilation and relatively high activity. The area north of the central pavilion-corridor (Area 4) was sheltered by vegetation, with stable airflow and moderate activity. In contrast, the southern and southeastern areas (Areas 5 and 6) were in wind shadow zones, with reduced wind speeds and sparse activity. Notably, the central pavilion-corridor (Area 1) had the highest crowd concentration (up to 74 people) but low wind speeds. In winter, key functional areas showed a stronger mismatch. Area 1 remained the most used space but had the lowest wind speeds, dropping below 0.5 m/s under the structure, forming a "high crowd density-low wind speed" conflict. Area 3 had higher wind speeds near open water but attracted fewer visitors. Area 4, in wind speed increase zones, showed higher wind speeds and activity. In contrast, Area 5 remained in a wind shadow zone, with poor ventilation and low activity.

Table 3: Number of people and activity types by area, across seasons

Area ID	Activity types	Total count (Winter)	Total count (Summer)
Area 1	Resting, board games	55	74
Area 2	Dancing, fitness activities	13	15
Area 3	Resting	6	21
Area 4	Fitness activities, board games	35	41
Area 5	Resting, board games	5	4
Area 6	Resting	10	6
Area 7	Resting	16	16
Area 8	Resting	12	18

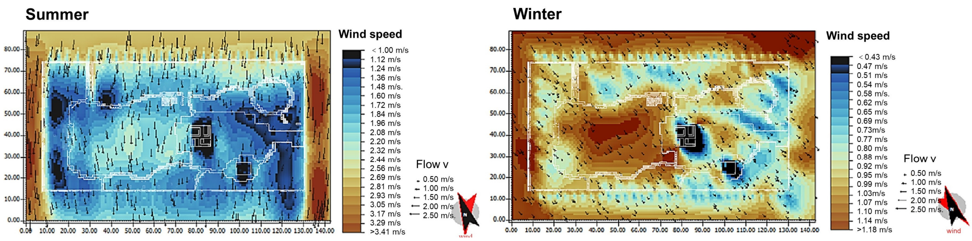

Fig. 3: Spatial distribution of wind speed on typical weather days in different seasons

3.4 Discussion

(1) Seasonal Differences and Landscape Effects on Wind Environment

The results show a seasonal contrast: ventilation is favourable in summer, while winter is dominated by calm conditions, implying weaker dilution of traffic-related pollutants. This gap is amplified by built elements. Compared to vegetation, pavilion-corridor structures exert stronger wind-blocking effects, creating persistent low-speed zones and reorganizing airflow into wind shadow and acceleration zones. These effects explain why the same functional space can remain under-ventilated across seasons, even with different background winds. For traffic-oriented pocket parks, pavilion-corridor design should be a primary control variable for wind environments. Early-stage seasonal simulations can test the placement, orientation, and opening strategy of such structures to avoid creating under-ventilated resting spaces.

(2) Classification of Wind-Crowd Spatial Relationships

Overlaying wind environment results with crowd concentration spatial data reveals a spatial correspondence, classified into three types. Core conflict zones are characterized by persistent low wind speed and high crowd concentration in both summer and winter, as seen in Area 1. Seasonally adaptive zones show a favourable match between suitable wind conditions and high activity in summer (Areas 3 and 4), while in winter, Areas 4 and 7 serve as main comfortable activity spaces, and Area 3 experiences a marked decline in crowd presence under higher wind speeds. Stable low-response zones, represented by Areas 5 and 6, consistently exhibit low wind speed and low crowd concentration across seasons. Crowd concentration intensity is influenced by multiple factors, including landscape, thermal conditions, and individual preferences. The classification aims to describe the spatial co-occurrence of wind environment quality and activity intensity to support design diagnosis and prioritization, rather than establishing a one-to-one causal relationship. Any causal link between wind environment quality and crowd concentration requires further quantitative testing. Incorporating crowd vitality into wind environment evaluation, this study aims to guide localized wind optimization to enhance pollutant dispersion and better serve park users.

(3) Implications for Pocket Park Planning and Renovation

Based on the above findings, implications for the planning and renovation of pocket parks can be identified. Multi-season wind environment simulations should be conducted prior to construction to avoid seasonal imbalances in spatial use caused by conflicting summer and winter wind conditions, which may lead to inefficient use of public resources. In the renewal of existing parks, pedestrian flow monitoring can be combined with adjustments to landscape nodes and pathways to guide activities toward areas with more favorable wind conditions, while prioritizing microclimate improvement in areas with consistently high crowd concentration. Vegetation configuration should be adapted to seasonal wind characteristics through an appropriate combination of evergreen and deciduous species, providing wind protection while maintaining ventilation and avoiding the formation of calm wind zones.

(4) Methodological Innovation and Potential for Extension

The key methodological contribution is a reusable workflow that supports consistent cross-park comparison of pedestrian-level wind environments under a unified atmospheric background. By reducing reliance on extensive field measurements, it offers a time- and cost-efficient approach for multi-site assessments and enables synchronized evaluation across parks. Beyond wind environments, the workflow can be extended to simulate air temperature and humidity, thereby supporting thermal comfort assessment. As a digital workflow applicable at the design stage, it can inform microclimate-oriented decisions on node placement and landscape element configuration, offering practical value for climate-adaptive green space planning in high-density urban areas.

4 Conclusion and Outlook

This study focuses on traffic-oriented pocket parks, selecting representative cases through a multi-dimensional evaluation. A coupled WRF-ENVI-met simulation workflow was developed to model pedestrian-level wind environments, along with corresponding evaluation criteria. Based on simulation results, wind environment quality was overlaid with crowd spatial use patterns, identifying three typical spatial relationships. Due to limitations in experimental conditions and model accuracy, there are certain errors in crowd behavior tracking data and simulation models. Additionally, the current overlay classification primarily describes spatial co-occurrence patterns rather than causal relationships. Future research will further simulate the impact of landscape element characteristics on microclimate formation and conduct comparative studies across multiple scenarios, aiming to develop human-centered microclimate regulation strategies and health-oriented design approaches for pocket parks.

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