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Pedestrian-level wind speed analysis: a case study

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ABSTRACT
This study analyses wind speed and wind comfort at the Auckland University of Technology, addressing a research gap in how urban contexts influence wind comfort in Auckland. Field surveys assessed public perceptions of wind speed during summer and winter, while computational fluid dynamic (CFD) simulations used historical data to examine the effects of street orientations, aspect ratios and building arrangements. High-risk areas, defined by average wind speeds exceeding 3.3 m/s, were identified, and mitigation scenarios were proposed. The findings show that street orientation has the greatest impact on wind speed, with areas angled 45 degrees to the predominant wind direction facing the most significant challenges. This research offers insights into wind comfort from an architectural and design perspective.

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KEYWORDS
Wind speed; orientations; building arrangements; aspect ratio; wind comfort; human comfort

1. Introduction

In the process of urbanization, natural land covers give way to constructed materials, resulting in a substantial alteration of land surface roughness (Chew, Nazarian, and Norford 2017). The significance of urban morphology and architectural components on urban wind speed and thermal patterns cannot be denied (Banerjee et al. 2022). For example, the height-to-width ratio of a canyon, known as the canyon aspect ratio, stands out as a vital parameter when classifying wind speed within an urban street canyon (Rodríguez-Algeciras, Tablada, and Matzarakis 2018). The diversity in urban design elements, such as building arrangements and variations in street width, profoundly adjusts the local ventilation capacity (Rodríguez-Algeciras, Tablada, and Matzarakis 2018). Alongside the larger-scale urban morphology factors, the small-scale details of the street also play a role in shaping urban wind speed (Ishugah et al. 2014). The flow dynamics within an urban area is mainly determined by factors like aspect ratio, building forms and orientations, street alignments, and the presence of vegetation (Y. Huang et al. 2021; Xie et al. 2020).

In urban environments, wind speeds are lower compared to rural areas due to the obstruction caused by urban structures (Allegrini, Dorer, and Carmeliet 2015). While decreased wind speed can be beneficial in temperate climates during winter, the opposite holds true for tropical regions (Cheng et al. 2012). Both extremely high and low wind speeds at street level pose significant challenges to human comfort in urban areas (Gulyás, Unger, and Matzarakis 2006). Hence, it is crucial to evaluate methods for analysing wind speed in urban street canyons. Many previous studies have focused on the impact of wind speed in tropical and subtropical climates, particularly its effects on outdoor comfort in these areas. For instance, research conducted in Singapore concluded that enhancing wind speed is the most effective strategy for improving comfort in shaded outdoor spaces (Yang, Wong, and Jusuf 2013). Similarly, a field survey carried out in Hong Kong found that individuals feeling warm wished for stronger winds, aligning with expectations (Li et al. 2018). The presence of stagnant air in urban areas has led to outdoor thermal comfort issues during the hot and humid summer months in Hong Kong, among other challenges (Ng et al. 2011). In the temperate climate, a study in an inner-city neighbourhood (Oberhausen, Germany) showed that increasing wind speed in summer can reduce Physiological Equivalent Temperature (PET) by up to 1.5°C (Müller, Kuttler, and Barlag 2014). Research in the Netherlands also shows that urban geometry has significant impacts on wind speed (Taleghani et al. 2015).

For increasing liveability in urban contexts, providing an acceptable range of wind speed is necessary. For this aim, it is necessary to define a specific comfort wind range based on the location. This helps architects and urban designers assess the wind speed in designated areas and create outdoor areas as comfortable as possible, encouraging people to spend more time outdoors. In this research, a specific wind comfort criteria have been designed to analyse the results of simulated wind speed in selected locations based on the comfort range, serving as a guide for new design scenarios. After identifying areas at risk due to high wind speeds, we then analyse the impact of urban design elements, such as street orientation, aspect ratio, and building arrangements, on these conditions. These elements play a significant role in wind speed in various urban contexts. After analysing the impacts of these elements on wind speed at the selected location of this research, we compare these research

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results to the previous literature review in Section 8 (moving beyond the local context) to obtain a broader perspective on the impacts of different urban elements on wind speed in various climates.

1.1. The significance of this study

New Zealand is in the latitudes known as the 'Roaring Forties', which means it experiences relatively high average wind speeds. Auckland City, the largest city in New Zealand, is situated in a relatively windy area. Auckland is often referred to as the City of Sails (Richard Flay and Lockeb 2019). Based on Auckland, New Zealand's weather history, the average wind speed from 2000 to 2023 was 4.64 m/s. Additionally, the highest wind speed during these 23 years was recorded in October 2009, reaching a speed of 58.12 m/s (Figure 1 in supplementary material).

New Zealand has recognized the challenges associated with unpleasant or dangerous wind conditions particularly in cities (Richard Flay and Lockeb 2019). Auckland Council's Unitary Plan sets wind comfort criteria divided into four categories based on activities: Category A is suitable for prolonged sitting, Category B for brief sitting, Category C for slow walking, and Category D for fast walking. There is also a Category E, which indicates universally dangerous conditions. Each category is defined by the probability of hourly mean wind speeds exceeding specific thresholds. For example, Category A areas, intended for long-term public use, require wind speeds to remain below 4.3 m/s for 99% of the time, providing a calm environment for prolonged sitting. Category B, which supports brief sitting, has a higher wind speed threshold, permitting speeds up to 7 m/s. Category C, appropriate for slow walking, allows wind speeds of up to 9 m/s. Finally, Category D, suitable for areas with pedestrian passage but with less stringent comfort requirements, permits wind speeds up to 10.3 m/s, more than double the limit set for Category A (Richard Flay and Lockeb 2019; PCD 2016).

Many research studies conducted in Auckland have used wind performance categories to evaluate the impacts of buildings, especially high-rise buildings, on the wind speed in their surrounding areas through wind tunnel tests (RGJ Flay and Andrews 1995; Tominaga et al. 2008; Richard Flay and Lockeb 2019; Pirooz, Li, and Flay 2020; Richards et al. 2002). They utilized the wind comfort criteria set by Auckland Council, which defined an hourly mean wind speed of under 4.3 m/s as suitable for long-term public use as a reference for their analysis. However, significant research gaps in wind comfort criteria at the pedestrian level in Auckland still need addressing.

1. While there is some prior research on wind speed analysis at the pedestrian level in Auckland, the number of studies is limited. Most of these studies have focused solely on analysing the impact of building heights on wind speed. Neglected aspects such as the canyon aspect ratio, building arrangements, and building directions play a vital role in wind speed analysis at the pedestrian level and need to be addressed.
2. Wind tunnel analysis involves the use of physical facilities to test real airflow over physical models. In contrast, Computational Fluid Dynamics (CFD) simulations utilize computer algorithms to solve fluid dynamics equations, simulating fluid flow and its effects without relying on physical models. CFD simulations offer flexibility, enabling the study of flows at various scales, from macro to micro. They allow for easy parameter adjustments, condition changes, and analysis of multiple scenarios without the need for new physical models. CFD simulations are efficient for iterative design and rapid scenario evaluation. Therefore, it is essential to use CFD simulations alongside wind tunnel testing to analyse wind speeds in Auckland.
3. While the Auckland City Council has recommended a mean wind speed of under 4.3 m/s as a comfortable range for long-term public use based on the Beaufort scale (Bennett 2007), it is necessary to reconsider and modify this range. As indicated in Table 1, when wind speeds exceed 3.3 m/s, categorized as a gentle breeze, based on comfort criteria and safety, long-term sitting and standing become tolerable just once a week (Bennett 2007). Therefore, it is crucial to establish a more precise range of wind speeds for analysing pedestrian comfort in Auckland.

Table 1. Beaufort scale (Bennett 2007).

Beaufort scale	Description	Mean wind speed range (m/s) @ 10m	Effects
B0	Calm	0-0.2	
B1	Light Air	0.3-1.5	No noticeable wind.
B2	Light Breeze	1.6-3.3	Wind felt on face.
B3	Gentle Breeze	3.4-5.4	Wind extends light flag.
B4	Moderate Breeze	5.5-7.9	Raises dust and loose paper. Hair disarranged and clothing flaps.
B5	Fresh Breeze	8.0-10.7	Limit of agreeable wind on land.
B6	Strong Breeze	10.8-13.8	Umbrellas used with difficulty. Force of the wind felt on the body. Wind noisy and frequent blinking.
B7	Near Gale	13.9-17.1	Inconvenience felt when walking, difficult to walk steady. Hair blown straight.
B8	Gale	17.2-20.7	Generally, impedes pedestrians, walking difficult to control. Huge difficulty with balance in gusts.
B9	Strong Gale	20.8-24.4	People blown over by gusts. Impossible to face wind, earache, headache, breathing difficulty. Some structure damage occurs, failing of roof tiles, tree branches etc. Very hazardous for pedestrians.
B10	Storm	24.5 $<$	Seldom experienced inland. Trees uprooted; considerable structural damage occurs.

In this study, our objective is to analyse wind speeds based on different aspect ratios, building arrangements, and building directions in an urban area located within Auckland. The focal point of our investigation is the city campus of Auckland University of Technology. Aligned with our concerns, the primary aims of this study are as follows:

1. Evaluating public sensations of wind speeds during both summer and winter.

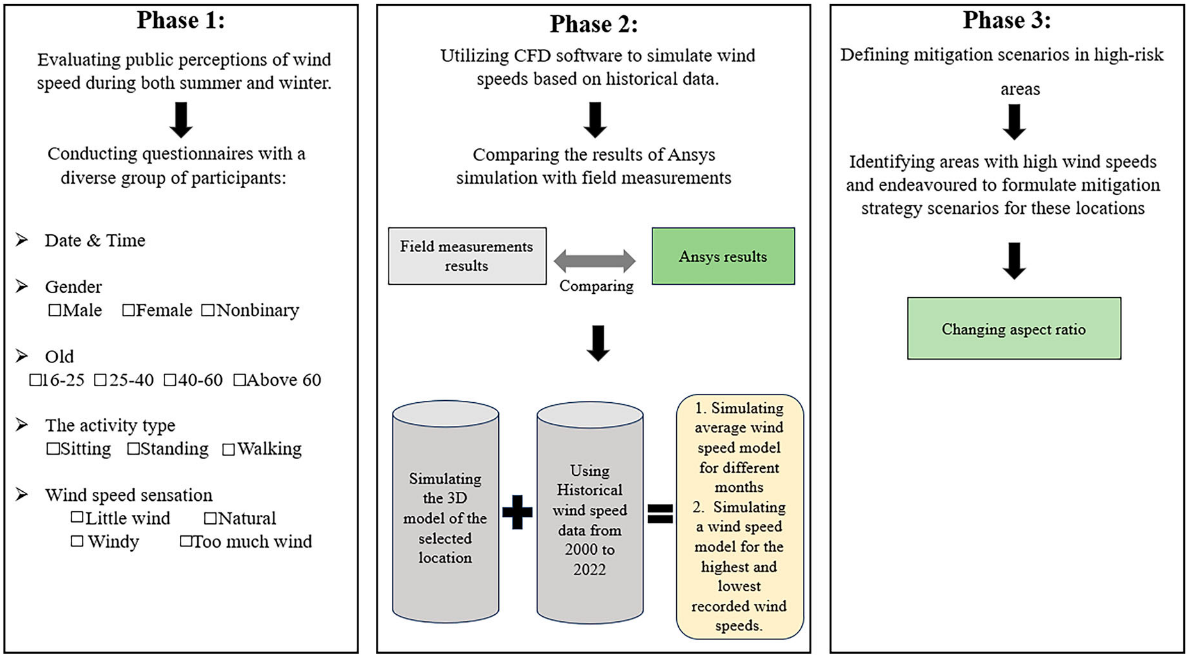


Figure 1. The structure of the research.

2. Utilizing CFD to simulate wind speeds based on historical data and analyse the impacts of street orientations, building arrangements, and various aspect ratios on wind speed.
3. Defining new scenarios for mitigation strategies in areas identified as high risk.

In this research, our goal is to extend methodologies and insights to provide applicable knowledge for optimizing urban environments across diverse cultural and geographical settings. While focusing on Auckland University of Technology, this study employs a methodology that can be replicated in various urban settings, allowing for the assessment of urban morphology and its impact on wind speed and outdoor thermal comfort in other contexts. The use of Computational Fluid Dynamics (CFD) simulations combined with historical wind data creates a flexible framework that can be adapted to different geographic locations and urban configurations. From an architectural and design perspective, we analyse the impacts of aspect ratios, building orientations, and arrangements on end users' comfort and perception, with the intention of incorporating these findings into future architectural and urban design processes. This repeatable methodology offers valuable insights beyond the specific case study, supporting broader efforts to enhance urban resilience and livability in areas with diverse climates and urban forms.

2. Method

This research comprises three distinct phases. In the first phase, we administered surveys to a diverse set of participants during both the summer and winter seasons, aiming to find out their sensations of wind speed in specific locations. We also recorded pertinent physical attributes such as age, gender, clothing type, and activity level. Moving to the second phase, we simulated wind speeds by CFD (Ansys Fluent) at the selected locations using historical wind speed data from 2000 to 2023. Proceeding to the third phase, with wind speed simulations finalized, we pinpointed areas with high wind speeds and endeavoured to formulate mitigation strategy scenarios for these locations. These new scenarios encompass adjustments to the new aspect ratios (Figure 1).

The research is conducted at the city campus of Auckland University of Technology (AUT), located at S-36° 51′, E174° 46′, with an approximate area of 38,000 m^2. The study area comprises 16 buildings ranging in height from 8 to 48 m. The orientations of these buildings vary, ranging from north–south and west–east to northwest-southeast and northeast-southwest, exhibiting diverse aspect ratios from shallow to deep. Vegetation cover, particularly trees, is sparse in the southern part of the location but becomes more abundant in the northern part (Figure 2 in supplementary material).

3. Evaluating public sensations of wind speed (Phase 1)

Wind speed at the pedestrian level is among the most critical environmental factors that influence user satisfaction in urban open spaces. Individuals have diverse sensations of wind speed, resulting in variations in their resilience and vulnerability. Before assessing the wind speed range based on software simulations and designed comfort criteria, our aim was to understand people's actual wind sensations at various times in selected locations. This approach gives architects and urban designers a more realistic sense for design by assessing real people's feelings in the initial stages of design. To assess people's sensations of wind speed, surveys were utilized. These surveys were conducted on various days during the summer and winter of 2023, between 8am and 4pm, at different locations within AUT. We aimed to administer questionnaires in all four main outdoor areas, which serve as primary gathering spots and leisure spaces.

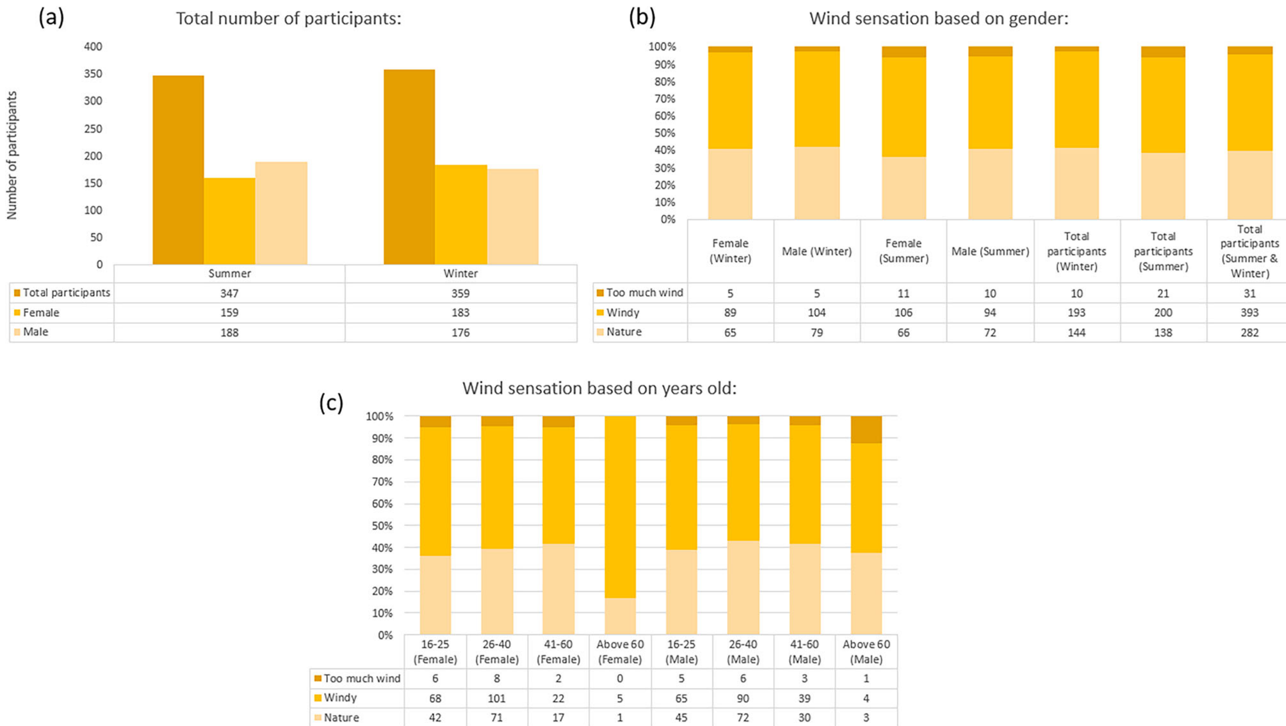


Figure 2. Wind sensation based on surveys.

Due to resource limitations, collecting data from every individual present at these locations was not feasible. However, efforts were made to distribute surveys to as many participants as possible. To ensure a representative sample, participants of different genders and ages were deliberately selected. The surveys included inquiries about participants' preferences concerning wind speed. Furthermore, relevant physical attributes, including age, gender, clothing type, and activity level, were recorded.

As a result, the study successfully included 706 participants – 342 females and 364 males (Figure 2(a)). Over half of the participants, namely 60%, reported feeling windy or experiencing excessive wind during both summer and winter seasons. To be more precise, during winter, 56% of all participants (94 females and 109 males out of 347 participants) reported feeling windy or experiencing too much wind. This percentage increased to 63% during the summer, with 117 females and 104 males out of 359 participants reporting the same sensation. Notably, the feeling of excessive wind was more prevalent among females, surpassing males by 61% compared to 58% (Figure 2(b)). These findings can be emphasized by previous studies, which indicate that women are more weather-sensitive than men (Graw, Sommer, and Matzarakis 2022; Zafarmandi, Matzarakis, and Norford 2024; Zafarmandi et al. 2022).

In terms of age distribution, half of the participants fell between the ages of 26 and 40. The highest frequency of perceiving strong winds was among participants above 60 years old, constituting 71% of this group. This was followed by participants aged between 16 and 25, with 58% reporting a similar sensation (Figure 2(c)).

The results of the questionnaires indicated that wind speed causes discomfort for a significant number of participants, who are considered a sample of end users utilizing outdoor spaces at Auckland University of Technology. This suggests the need for analysing wind conditions and their impacts on people's comfort in more detail.

4. Utilizing CFD to simulate wind speeds based on historical data (Phase 2)

In this study, we chose Ansys Fluent as our Computational Fluid Dynamics (CFD) simulation tool. CFD models offer an effective and potent approach to estimating wind speed in urban settings (Blocken 2015). They are crucial for comprehending and optimizing wind conditions in the design and development of urban places due to their adaptability, affordability, and capacity to handle complex scenarios (Mirzaei 2021). Ansys Fluent is a computational fluid dynamics (CFD) software suitable for modelling various fluid flow phenomena, including wind speed in urban areas (Mirzaei and Carmeliet 2013). In CFD simulation, a high-quality mesh is crucial for accurate simulations, allowing the capture of urban area details. The boundary conditions for simulation encompass specifying inflow conditions (wind speed, direction, turbulence properties), where turbulence significantly affects urban airflow (Pantusheva et al. 2022). In our research, the RANS model was utilized, specifically the shear stress transport model based on k-ω equations, which is a well-established computational fluid dynamics tool for simulating single-phase flows with high Reynolds numbers. This model was chosen due to its high accuracy near walls and its superior convergence compared to other models. It employs the Navier-Stokes Equations for momentum conservation and the continuity equation for mass conservation. Turbulent flow effects are incorporated through the modified Wilcox k-ω two-equation model, which accounts for realistic limitations in the equations used (Younis and Berger 2004).

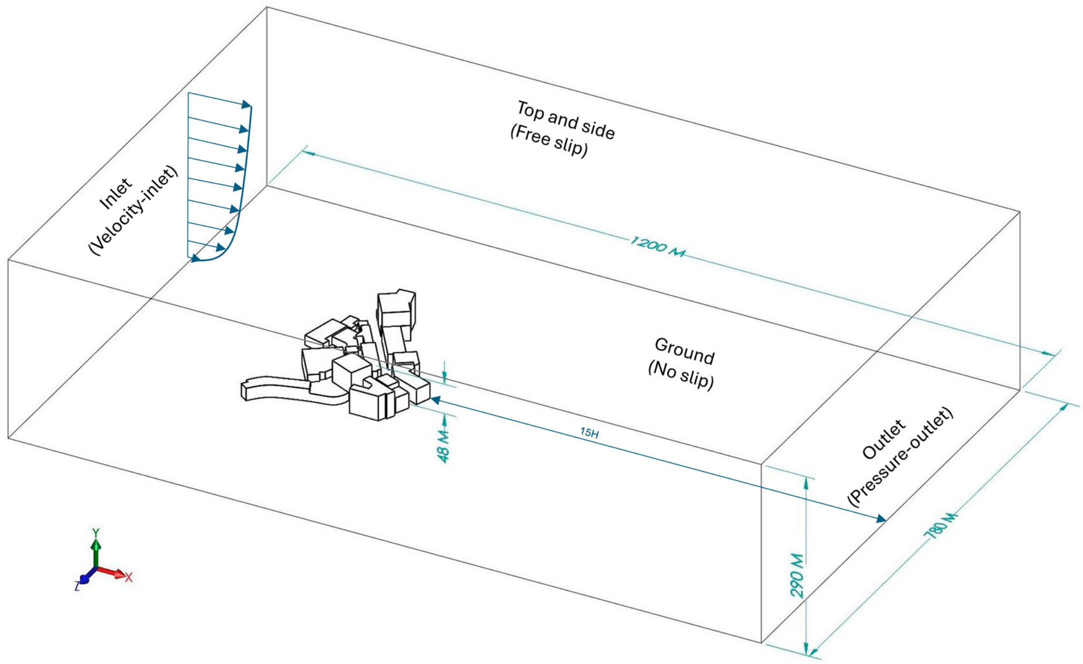


Figure 3. Details of the CFD simulations, (number of mesh elements: 7,260,609).

The validity of the simulated wind data was evaluated by comparing observed meteorological values. Field measurements were conducted using the Davis 6152 Wireless Vantage Pro2 weather stations. The Vantage Pro2 employs high-quality sensors designed to provide accurate and reliable measurements of wind speed and direction. The sensors utilized in the Vantage Pro2 maintain an accuracy of within ±2.2 km/h for wind speed. Four distinct locations were selected for field measurements based on their potential to provide varying aspect ratios. The sensors were positioned at pedestrian level with a height of 1.5 m during the measurement process. Meteorological conditions at these locations were monitored and recorded every 30 min from 8:30 to 16:30 on 14 March 2023 (Figure 3 of supplementary material).

Subsequently, the wind speed results obtained from field measurements were compared with the corresponding data simulated by CFD for a specific day in March 2023. To be more precise, weather stations recorded wind speed every 30 min at selected locations, totalling 18 wind speed measurements for each location. Afterward, we simulated the wind speed at these selected locations using CFD with 18 different wind speeds. The inlet wind speed and direction were obtained from the Auckland climate and weather website for the specific day and time. As depicted in Figure 3, we used the recorded wind speed from the meteorological data of Auckland as the inlet. Additionally, turbulence properties were set based on previous research (Shu, Wang, and Mortezazadeh 2020). In this study, the distance between the study area and the domain boundary is determined by previous research. Specifically, considering the highest building height as 48 m (H = 48), the upstream distance is set to 5H, the downstream distance to 15H, and the lateral distance to ±5H (Abu-Zidan, Mendis, and Gunawardena 2021; Janssen, Blocken, and van Hooff 2013). The details of the CFD simulation are illustrated in Figure 6, with the total number of mesh elements set at 7,260,609. A sensitivity analysis, involving the mesh density of the computational domain, was performed to investigate its impact on solution accuracy and convergence (Gilani, Montazeri, and Blocken 2016; Montazeri and Blocken 2013). Initially, the CFD analysis was run with a coarse mesh (2,052,649 number of mesh elements). Then, to determine the optimal mesh resolution, the number of mesh elements was increased to 7,260,609, which yielded the highest accuracy in the CFD results. More information about the simulation is provided in Appendix A.

4.1. Agreement between field measurements with CFD simulation data

R^2 is commonly used as a method to assess the agreement between measured data and simulated data (Heinzl and Mittlböck 2003). In this research, the R^2 metric was employed to assess the concordance between field measurements and the simulated data produced by Ansys for wind speed. The obtained R-squared values exceeded 0.99 for all four measurements, indicating a robust alignment between the measured and simulated data (Figure 4).

After comparing the results of field measurements using CFD simulation, we concluded that the simulation offers great accuracy in simulating wind speeds at the chosen location. Consequently, we used Ansys to simulate historical wind speeds at AUT for four distinct periods at a height of 1.80 m. The purpose was to analyse the effects of wind speed on people's comfort. We simulated the average wind speed during Summer, Spring, Fall, and Winter from 2000 to 2023. Information on the model settings and mesh configuration is provided in Table 2, while the simulation results are presented in Table 3. Turbulence properties were based on previous research (Shu, Wang, and Mortezazadeh 2020). Due to the limited number of young trees located away from the main areas, they were just represented as simple shapes with real height and width in the simulations.

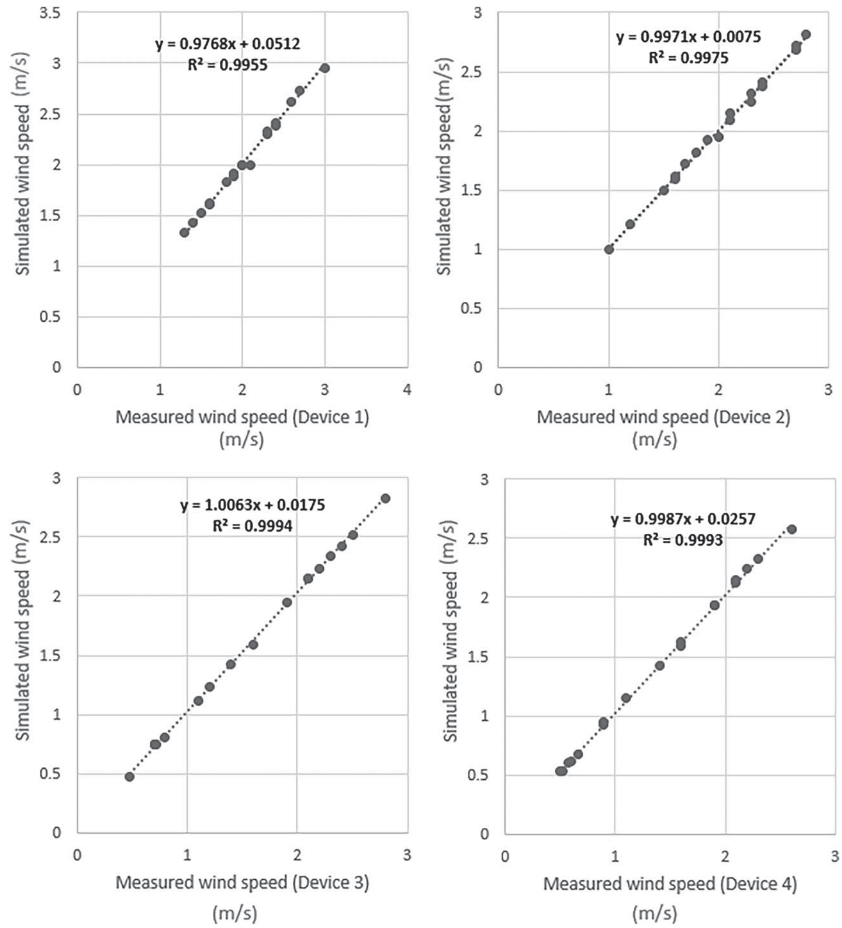


Figure 4. Scatter plot illustrating the measured and CFD simulated data points.

Table 2. Information on the model settings.

The inlet wind speed and direction	the recorded average wind speeds and directions for different seasons from the Auckland climate and weather website
The domain boundary conditions	(H = 48), the upstream distance: 5H, the downstream distance:15H, and the lateral distance: ±5H
Total number of mesh elements	7260609
Time for each simulation	2.30 h

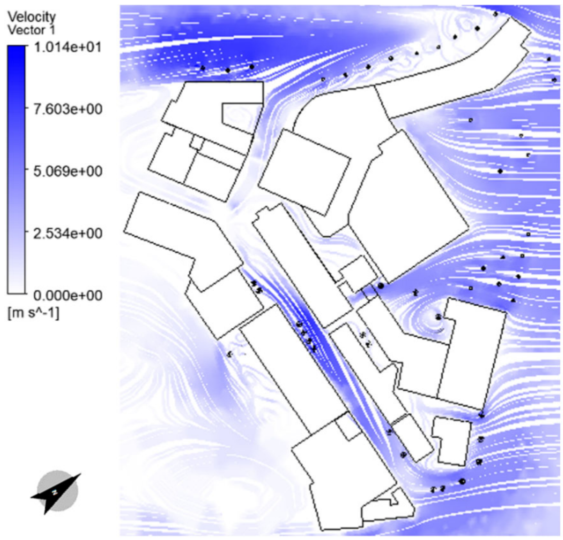
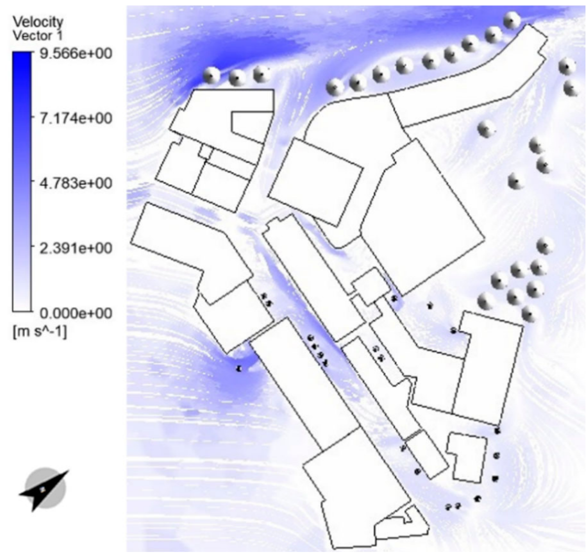
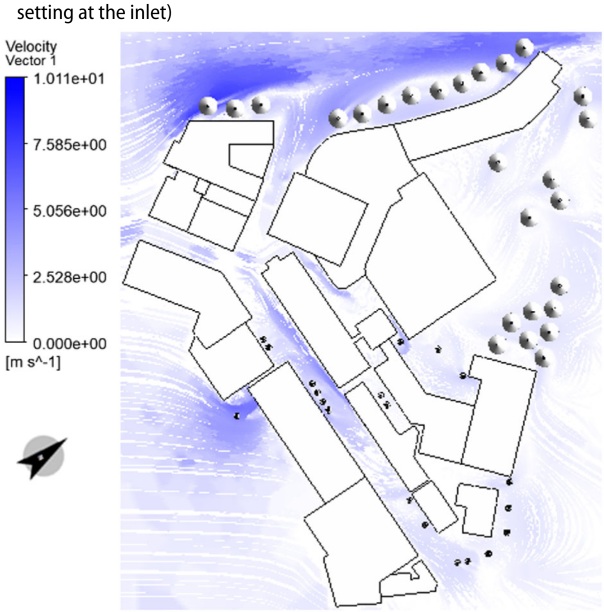
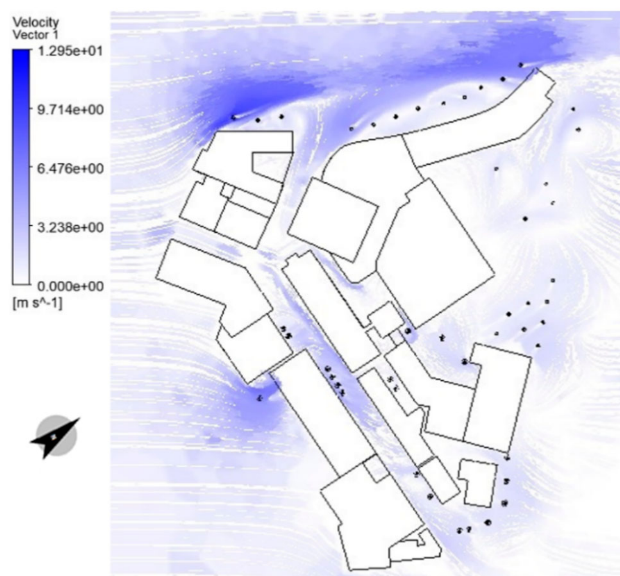
After simulating wind speeds based on historical data for four different seasons, we need to establish comfort criteria to analyse the effects of wind on people's comfort in selected locations and identify high-risk locations with high wind speeds. As explained in the introduction, the Auckland Council has a wind comfort criterion that requires modification, and a more accurate range based on other scales such as the Beaufort Scale. This range was developed by combining wind comfort criteria from the Auckland Council with the Beaufort Scale. According to the modified comfort criteria, areas with an average wind speed between 1.6 and 3.3 m/s are considered tolerable, areas with an average wind speed between 3.4 and 5.4 m/s are moderately unpleasant, and areas with an average wind speed between 5.5 and 7.9 m/s are significantly unpleasant (Figure 5).

Furthermore, to delve into wind speed details and identify potential risk areas, we subdivided the AUT campus into 4 distinct outdoor zones, which are the principal outdoor areas at AUT (Figure 4 of supplementary material). We conducted an analysis of the wind patterns within these areas and utilizing the Ansys results from Table 2. We consider the direction and aspect ratio of each location, which is the ratio between the average height (H) of the canyon and the width (W) of the canyon itself (Ali-Toudert and Mayer 2006; Gromke and Ruck 2012; Oke 1988). A canyon is considered uniform when its aspect ratio is approximately equal to 1 (with no noticeable openings on the walls), shallow when the aspect ratio is less than 0.5, and deep when the aspect ratio exceeds 2 (Ahmad, Khare, and Chaudhry 2005; Jamei et al. 2016).

4.2. Results of wind speed analysis location 1

Location 1 is a street that spans 200 m in length and 15 m in width, oriented in a west–east direction. This location has an orientation of approximately 45 degrees relative to both main wind directions in Auckland. The street consists of six different zones with varying aspect ratios. Based on the results obtained from Ansys simulations, it is evident that during the summer, the most challenging conditions in this location are posed by north-east winds. According to Figure 6, the zone with an aspect ratio of 1.3 experiences an average summer wind speed of 6.83 m/s, which is significantly uncomfortable, as shown in Figure 5. Three other zones with aspect ratios of

Table 3. The results of CFD simulation.

The average wind speed in Summer from 2000 to 2023: Average Wind Speed: 4.82 m/s, Wind Direction: North-east (the wind velocity setting at the inlet)	The average wind speed in Fall from 2000 to 2023: Average Wind Speed: 4.11 m/s, Wind Direction: South-West (the wind velocity setting at the inlet)
	
The average wind speed in Winter from 2000 to 2023: Average Wind Speed: 4.31 m/s, Wind Direction: South-West (the wind velocity setting at the inlet)	The average wind speed in Spring from 2000 to 2023: Average Wind Speed: 5.31 m/s, Wind Direction: South-West (the wind velocity setting at the inlet)
	

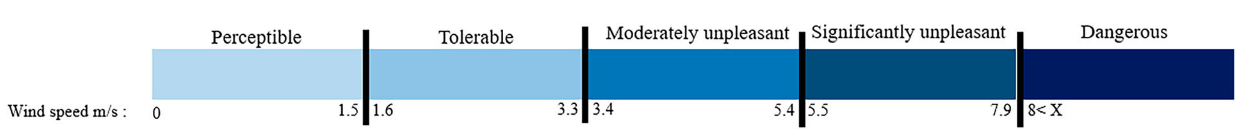


Figure 5. Modified comfort criteria based on wind speed.

1.8, 2.1, and 0.8 have moderately unpleasant conditions. These zones still experience moderately unpleasant conditions in winter.

Based on Figure 6, it is evident that while both predominant wind directions have a 45-degree angle with location one, winds from the north-east (summer winds) are more challenging than winds from the south-west (fall, winter, spring winds). This highlights the importance of building arrangements in the location, as the height of buildings facing north-east winds is lower than buildings facing south-west winds initially in this location (average 16 m to 38 m), and the wind speed in summer is higher than in other seasons. Furthermore, based on the results of analysing various aspect ratios, we can conclude that wider areas can have less unpleasant wind speed, especially when the heights of buildings on both sides are equal (aspect ratio: 0.3) in this location.

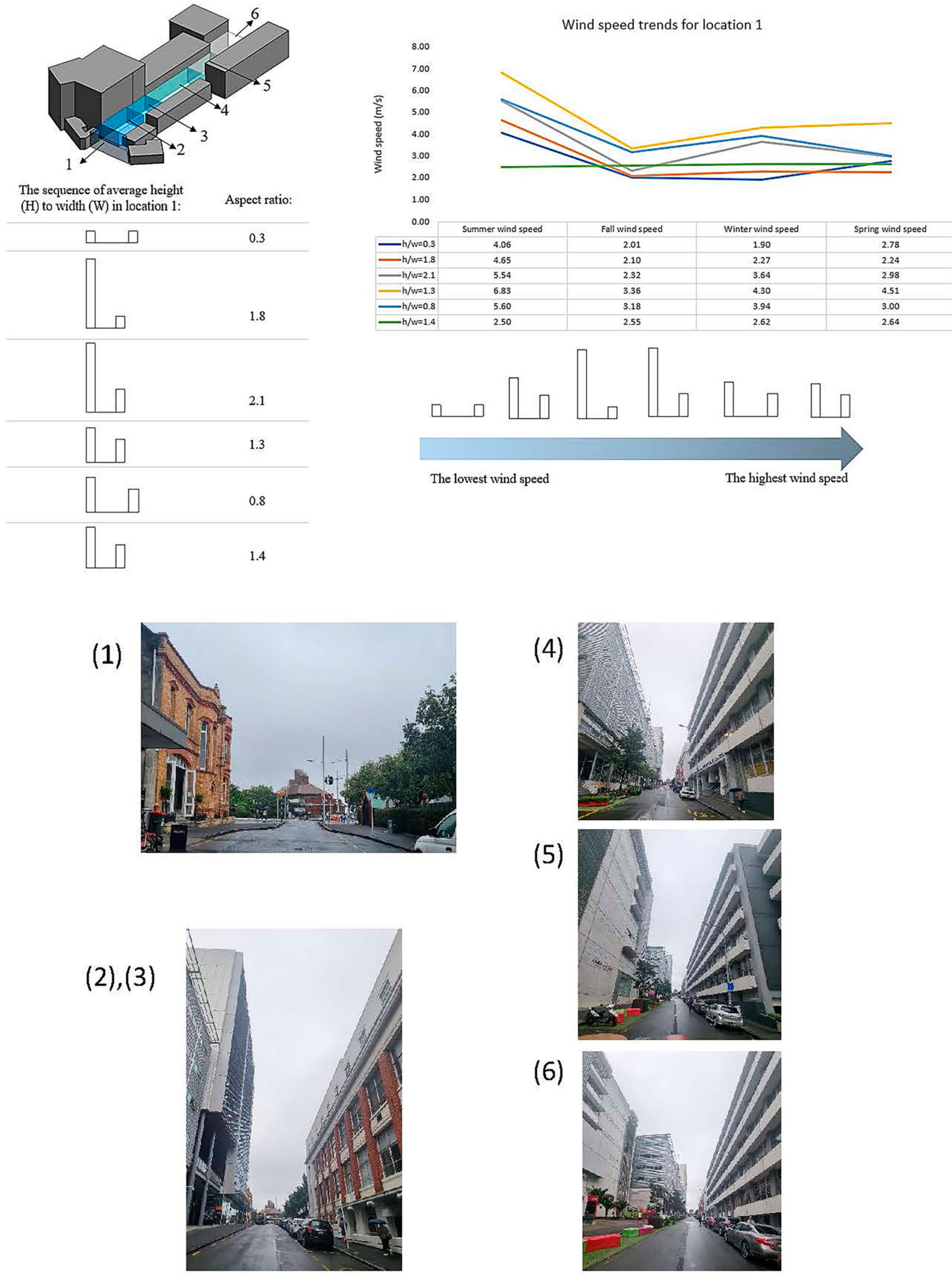


Figure 6. Results of wind speed analysis location 1.

4.3. Results of wind speed analysis location 2

Location 2 is a street that measures 60 m in length and 15 m in width, running in a northeast-southwest direction. This location aligns with both main wind directions in Auckland. The street comprises two distinct zones with relatively deep aspect ratios, specifically 2.0 and 1.6 (Figure 7). Based on the results obtained from Ansys simulations, it is evident that this location does not face wind comfort challenges from both predominant wind directions in all periods; the wind speed remains below 3.4 m/s. Moreover, the wind speed in this location has a direct correlation with the aspect ratio, indicating that the wind speed increases with a deeper aspect ratio.

4.4. Results of wind speed analysis location 3

Location 3 is a street that measures 60 m in length and 18 m in width, running in a northwest-southeast direction. This location has an orientation of approximately 90 degrees relative to both main wind directions in Auckland. This street comprises two distinct zones with relatively deep aspect ratios. Based on the results obtained from Ansys simulations, it is evident that in all periods, the wind speed remains below 3.3 m/s, indicating that Location 3 does not present any comfort challenges based on wind speed (Figure 8). Moreover, the wind speed in this location has a direct correlation with the aspect ratio, indicating that the wind speed increases with a deeper aspect ratio.

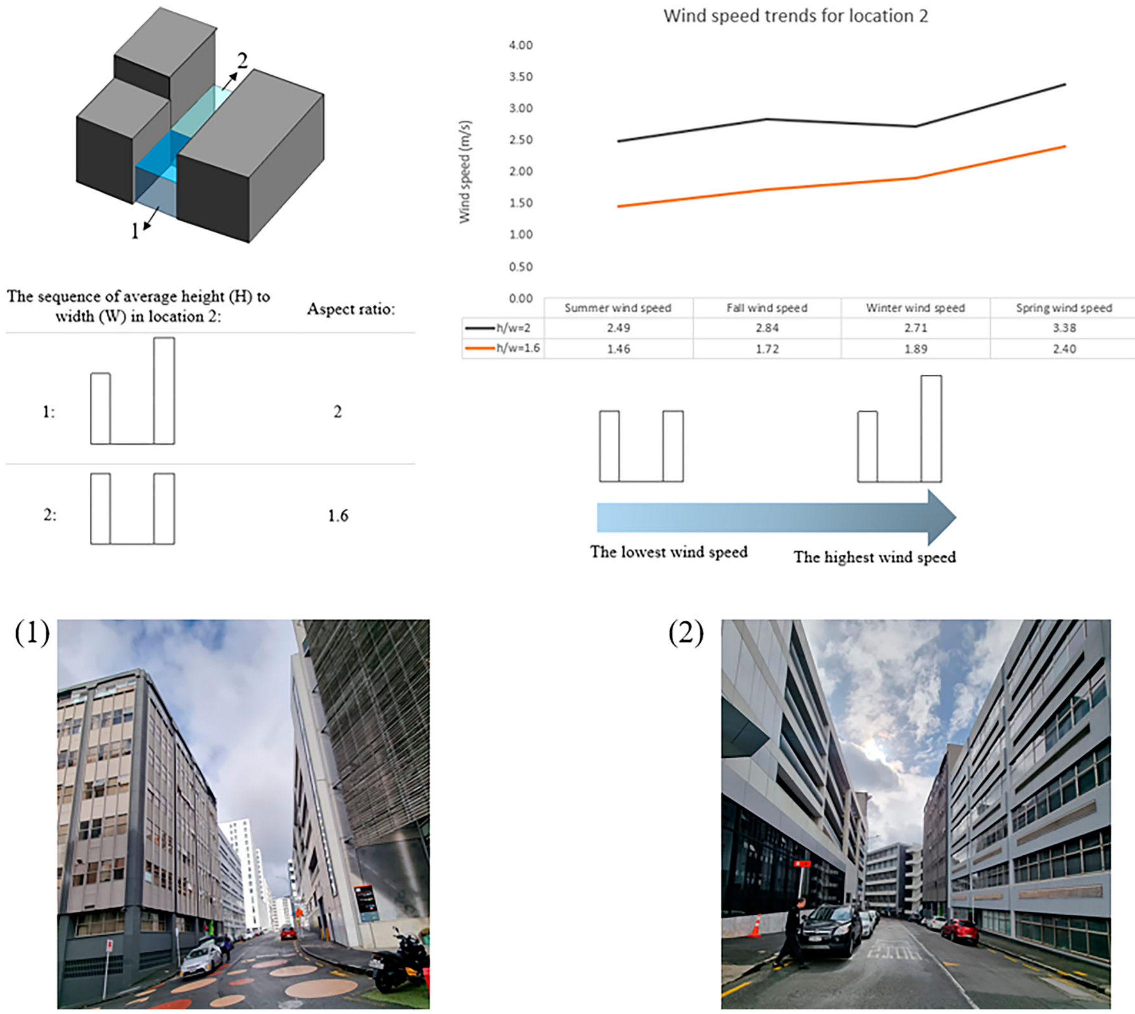


Figure 7. Results of wind speed analysis location 2.

4.5. Results of wind speed analysis location 4

Location 4 is a plaza with an area of 900 m^2, situated in a north–south direction. This location has an orientation of approximately 45 degrees relative to both main wind directions in Auckland. The plaza comprises two different aspect ratios, both of which are relatively shallow: 0.2 and 0.8. As illustrated in Figure 9, both areas exhibit unpleasant conditions during the summer, similar to location one, with average wind speeds of 4.32 and 3.53 m/s, respectively. This emphasizes the importance of building arrangements in the location, as the height of buildings facing north-east winds is lower than buildings facing south-west winds initially in this location (average 12 m to 24 m). Moreover, the wind speed in this location has a direct correlation with the aspect ratio, indicating that the wind speed increases with a deeper aspect ratio.

5. Defining mitigation scenarios in high-risk areas (Phase 3)

After analysing the wind speeds based on historical data in different locations at AUT, we have identified that the wind speed during summer presents a challenge in 7 different zones, and wind speed during winter is a challenge in 3 different zones. The highest risk areas that exposed risks for both summer and winters are in location 1, therefore location 1 is the high-risk area of AUT that needs mitigation scenario. The simulation results indicate that, the wind speed remains below 3.4 m/s in all periods and locations during fall and spring, which means within the tolerable and perceptible range based on comfort criteria.

Based on the simulation results, three different zones are exposed to moderate and significantly unpleasant wind speed conditions during both summer and winter, with speeds exceeding 3.4 m/s (Figure 10(e)). Consequently, we have worked to define new aspect ratios for these zones by adjusting the heights of buildings and establishing tolerable and perceptible wind speed ranges. The reason for defining a new aspect ratio as a mitigation scenario is to emphasize the importance of considering aspect ratios when designing new buildings in specific locations for future architectural and urban designs. Changing the orientations of street canyons is impossible as they are predetermined in urban design, but it is crucial to analyse and consider building heights in the initial stages of design and how different aspect ratios affect outdoor microclimate conditions in the location. Future designers should analyse the impacts of their design concepts not only on indoor conditions but also on outdoor conditions.

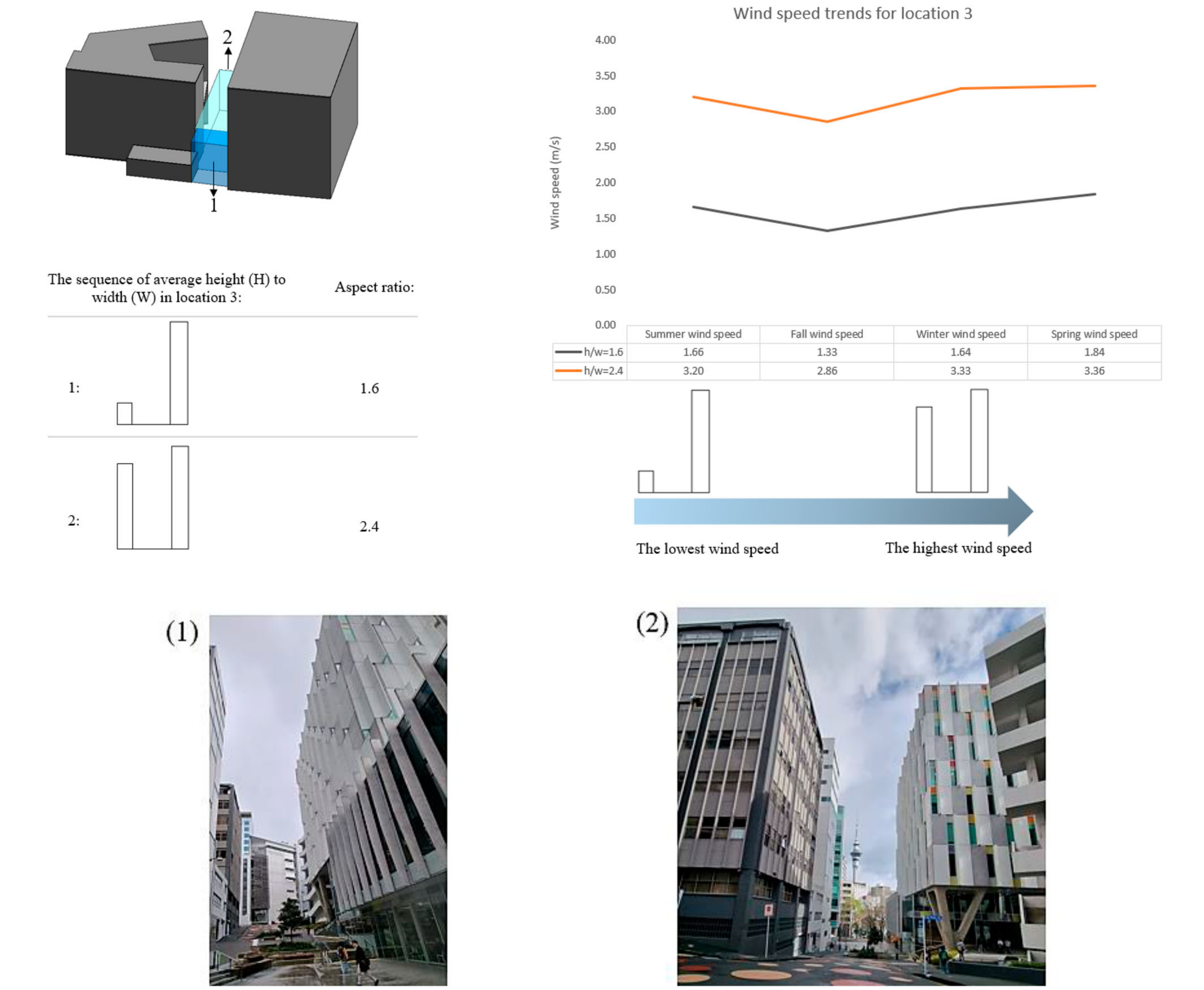


Figure 8. Results of wind speed analysis location 3.

The three high-risk areas are located adjacent to each other in Location One. The highest risk area is situated between two buildings with heights of 24 and 16 m, with a width between them measuring 15 m (aspect ratio: 1.3), specifically in zone two, as depicted in Figure 10(e). Based on Figure 10(a and b), the average wind speed in this area is 6.83 m/s in summer and 4.30 m/s in winter.

The second high-risk area is positioned between two buildings with heights of 24 and 16 m, and the width between them is 24 m (aspect ratio: 0.8), located in zone three according to Figure 10(e). According to Figure 10(a and b), the average wind speed in this area is 5.60 m/s in summer and 3.94 m/s in winter.

The last high-risk area is situated between two buildings with heights of 48 and 16 m, and the width between them measures 15 m (aspect ratio: 2.1), found in zone one as shown in Figure 10(e). Based on Figure 10(a and b), the average wind speed in this area is 5.54 m/s in summer and 3.64 m/s in winter.

To mitigate wind speed in both summer and winter in these areas, we defined new scenarios by altering the aspect ratios of each zone. Since these locations are adjacent to each other, we decided to implement a similar pattern for all of them.

5.1. First scenario: increasing aspect ratio (add a new level)

In the first scenario, we increased the aspect ratio in these zones by adding an additional level to buildings on both sides of the canyons (Figure 11(a)). As a result, the new aspect ratios were 2.4 for zone one, 1.6 for zone two, and 1 for zone three. After simulating wind speeds for both summer and winter with the new scenario, the comfort criteria worsened in these zones, with wind speeds increasing by approximately 0.5–1.5 m/s in high-risk areas. Therefore, increasing the aspect ratio is not a suitable scenario for these high-risk areas.

5.2. Second scenario: decreasing aspect ratio (remove an existing level)

In this scenario, we decreased one level of buildings on both sides of the canyons, resulting in new aspect ratios of 1.7 for zone 1, 1 for zone 2, and 0.6 for zone 3 (Figure 11(b)). After simulating wind speed for both summer and winter with this new scenario, the comfort criteria improved significantly in these

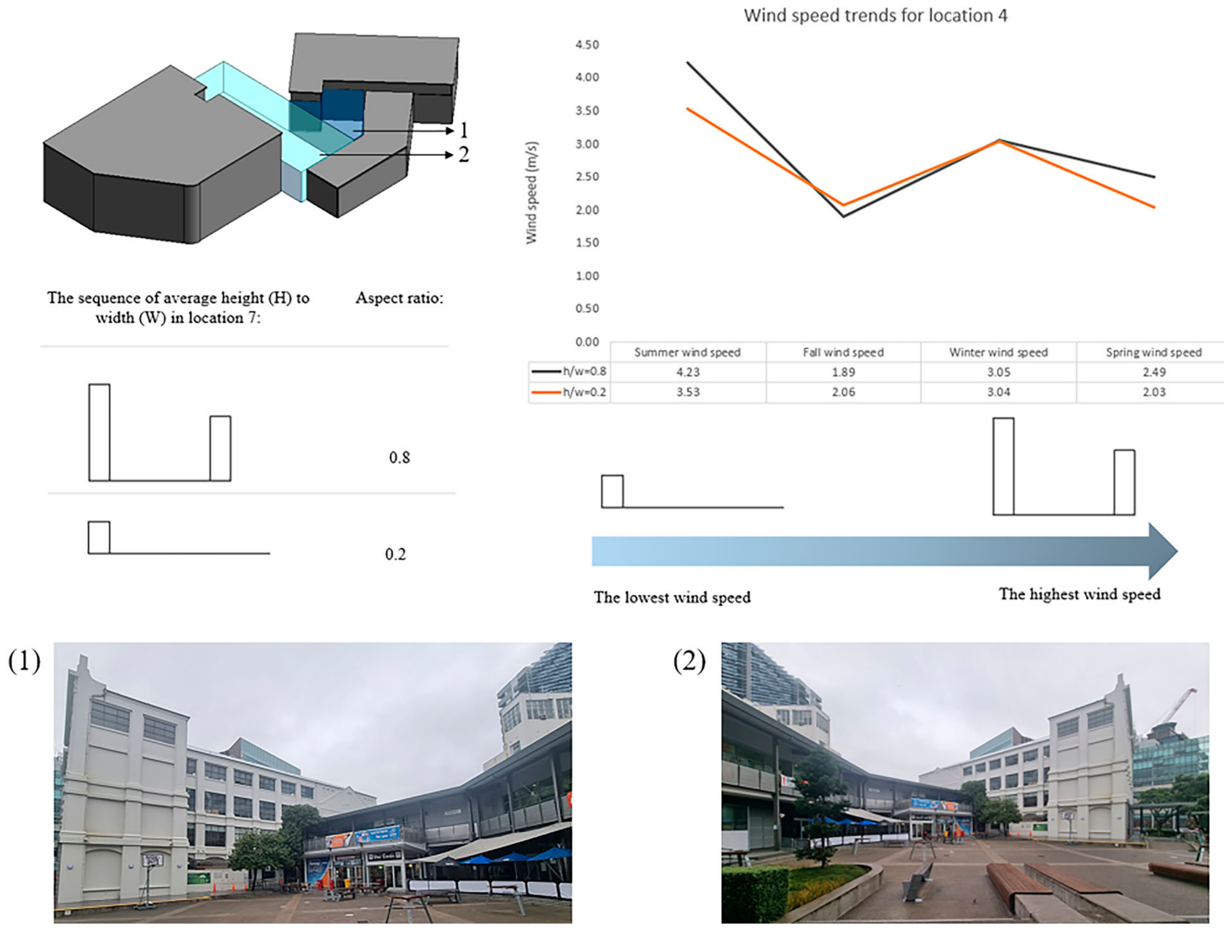


Figure 9. Results of wind speed analysis location 4.

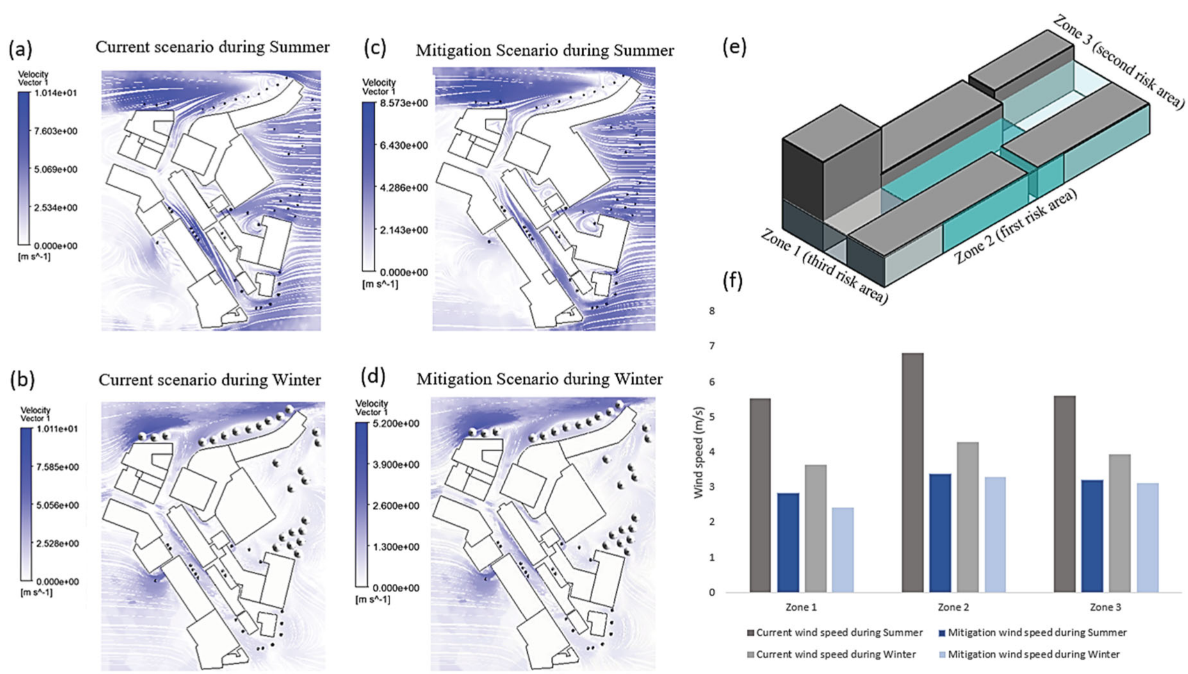


Figure 10. (a) current scenario during summer, (b): current scenario during winter, (c): mitigation scenario during summer, (d): mitigation scenario during winter, (e): risk areas, (f): current and mitigation wind speed in risk areas.

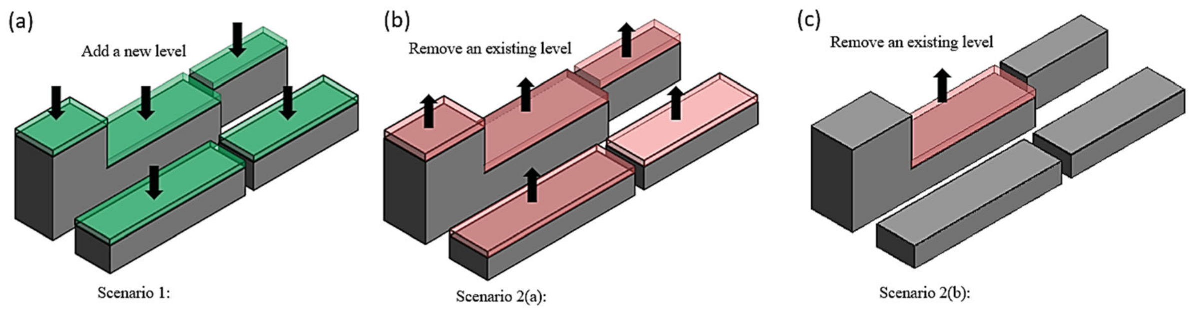


Figure 11. (a) first scenario (increasing aspect ratio) (b): second scennario (decreasing aspect ratio, part 1) (c): second scennario (decreasing aspect ratio, part 2).

zones. For zone 1 and 3, the new scenarios indicated a tolerable range of wind speed for both summer and winter, with wind speeds decreasing from 5.54 m/s to 2.85 m/s in summer and from 3.64 m/s to 2.42 m/s in winter for zone 1, and from 5.60 m/s to 3.20 m/s in summer and from 3.94 m/s to 3.12 m/s in winter for zone 3. For zone 2, although the new scenario led to a decrease in wind speed within an acceptable range for winter (from 4.30 m/s to 3.45 m/s), the wind speed in summer decreased to 4.5 m/s, which is still moderately unpleasant. Therefore, we defined another new scenario for zone 2 by decreasing the aspect ratio to 0.93 (Figure 11(c)), resulting in summer and winter wind speeds reaching 3.39 and 3.31 m/s, respectively, within a tolerable range (Figure 10(c and d)).

Based on the defined new scenarios and simulated results, decreasing aspect ratios in high-risk areas can mitigate wind speed in this study (Figure 10(f)).

6. Discussion

After simulating wind speeds for various time periods using historical data, we identified three zones with wind speeds falling into moderately or significantly unpleasant conditions during summer and winter. Consequently, we formulated various mitigation strategies.

From our analysis, the following key findings emerged:

- Orientations: According to the analysis results, it is evident that street orientations predominantly influenced by wind speed are the most critical factor in assessing wind comfort criteria, compared to building arrangements and aspect ratios. Streets oriented at a 45-degree angle to prevailing winds face the most significant wind challenges, followed by those at 90-degree angles. Conversely, streets parallel to predominant winds experience fewer challenges, even when they share the same aspect ratios as the most challenging areas. Therefore, it can be concluded that future designers should prioritize the consideration of street orientations when analyzing wind speed, ahead of other factors. Previous studies have also identified street orientation as a significant factor influencing wind speed.
- Arrangements: As locations parallel to wind speed or with 90-degree orientations to prevailing winds do not present wind challenges based on wind comfort criteria in this research, our analysis focused solely on building arrangements in challenging areas. From this, it can be concluded that, for mitigating wind speed in these areas, designing high-rise buildings at the street's edge facing the predominant winds should be prioritized. In this scenario, tall buildings can effectively block intense winds in these challenging locations, thereby reducing wind speed in those areas.
- Aspect Ratio: This study reveals distinct wind speed patterns influenced by aspect ratios in various directions and locations. Consequently, it becomes imperative to prioritize the analysis of diverse orientations before considering the impact of this factor in future studies. Nevertheless, our analysis indicates a clear correlation between wind speed and aspect ratio within the same location. Deeper aspect ratios correlate with increased wind speed, while wider areas tend to exhibit less unfavourable wind conditions, especially when the buildings' heights on both sides are equal. Additionally, within similar aspect ratios, the geometry of the ratio becomes a critical factor. Our analysis highlights that among areas sharing similar aspect ratios, those with greater width experience reduced wind speeds in comparison to areas with the same aspect ratio but different dimensions.

Our research reinforces the theory that urban morphology significantly impacts pedestrian wind comfort. This study builds on existing knowledge by offering a nuanced understanding of how various elements interact within different configurations. The observed correlation between aspect ratios and wind speeds across diverse orientations suggests that both micro – and macro-scale urban geometries should be jointly considered in wind comfort analysis, thus expanding the theoretical framework for urban climatology. Urban planners can apply these insights to other high-density cities with similar climates using our proposed methodology. Moreover, our findings are adaptable to cities with high wind conditions, contributing to more resilient urban designs. The framework employed in this study, which combines CFD simulations with field surveys, can serve as a replicable model for assessing pedestrian wind comfort in varied urban contexts. This approach facilitates the practical adjustment of designs based on real-time feedback and simulation data.

7. Limitations of the study

The high accuracy of CFD in simulating wind speeds has been validated for this location. For more comprehensive results, future research should consider employing Ansys in different urban contexts. However, Ansys Fluent is suitable for modelling various fluid flow phenomena, but it has limitations when

Table 4. Comparing the results of this study and previous studies.

Results of this research	Previous research results
Orientation:	
Streets oriented at a 45-degree angle to prevailing winds face the most significant wind challenges, followed by those at 90-degree angles (wind speed more than 3.4 m/s). Conversely, streets parallel to predominant winds experience fewer challenges(wind speed less than 3.4 m/s).	Streets oriented parallel to the prevailing wind has greater wind velocity than those oriented perpendicular to the wind (Jareemit and Srivanit 2019). Main streets should be arranged along the prevailing wind direction to face fewer wind challenges (Yuan and Ng 2012). The street orientation to the prevailing winds also is important: the highest reductions were observed for perpendicular directions and best penetrations are made for parallel directions (Kitous, Bensalem, and Adolphe 2012). The angle of the upwind has an important effect, when it is perpendicular to the canyon axis, resulting in wind speeds lower than 3 m/s at the pedestrian level. With an oblique upwind direction to the canyon axes, cross-type points play a role in enhancing the wind speed at the pedestrian level. When the wind flow is parallel to the canyon, the relation with the upwind and pedestrian wind has a relatively higher relationship (Arkon and Özkol 2014).
Arrangement:	
For mitigating wind speed in challenging areas(wind speed more than 3.4 m/s), designing high-rise buildings at the street's edge facing the predominant winds should be prioritized.	The uniformity of building heights has a negative effect on enhancing pedestrian-level wind speed (Arkon and Özkol 2014). Substituting low-rise structures with high-rise buildings may lead to a reduction in wind speed and the potential for natural ventilation in specific adjacent street canyons (T.-L. Huang et al. 2020). The effects of an urban high-rise building on its surrounding wind environment are case-specific(Kuo et al. 2020).
Aspect ratio:	
There is a clear correlation between wind speed and aspect ratio within the same location. Deeper aspect ratios correlate with increased wind speed, while wider areas tend to exhibit less unfavourable wind conditions, especially when the buildings' heights on both sides are equal.Among areas sharing similar aspect ratios, those with greater width experience reduced wind speeds in comparison to areas with the same aspect ratio but different dimensions.	The wind velocity in shallow canyon is mostly higher than those in the deep canyon. However, increasing the canyon length considerably improves the low wind speed in the deep canyon up to twice (Jareemit and Srivanit 2019). In streets with lower H/W ratios, when $0 < H/W \leq 1$, the canyon effect can be seen as lower pedestrian-level wind speeds (Arkon and Özkol 2014). In street canyons characterized by a unit aspect ratio, the experimental findings reveal that void decks can result in a twofold increase in pedestrian-level wind speed, in contrast to reference canyons lacking void decks(Chew and Norford 2018).

simulating vegetation, particularly trees. In this study, due to the limited number of young trees located away from the main areas, we have represented them as simple shapes with real height and width in simulations. Nevertheless, in locations with a significant number of trees, where factors like leaf properties, dynamic growth, and seasonal changes are important, Ansys may have limitations. The accuracy of wind speed simulations under these conditions should be validated in future research. Furthermore, the results regarding the impacts of orientations, building arrangements, and aspect ratios on wind speed are derived from the analysis of the AUT City Campus in Auckland. To gain a more comprehensive understanding, future researchers should analyse these factors in various urban contexts.

8. Moving beyond local context

While this research focused on pedestrian-level wind speed analysis in the context of Auckland, the results and achievements can be developed and extended to other parts of the world. In the initial stage of this study, we designed a modified comfort criteria range based on a combination of wind comfort criteria from the Auckland Council and the Beaufort Scale. This highlights the importance of designing wind comfort criteria based on the local conditions of various locations to achieve more accurate results in analysing wind comfort conditions in outdoor spaces based on wind speed.

Considering various urban design factors, such as aspect ratio, building arrangements, and orientations, this research can either support or challenge previous findings (Table 4). Defining the wind comfort range is linked to other weather conditions, like air temperature and humidity. For example, in tropical climates, the higher air temperature and humidity might expand the acceptable range of wind speed as a comfort criterion. This encourages designers to create areas with natural ventilation or increased wind velocity. These results emphasize the importance of analysing how different urban designs impact wind speed comfort criteria, considering location-specific weather conditions. While some previous research can guide future designs, it is crucial to recognize that certain factors' impact on wind comfort conditions may vary by location. Therefore, the analysis of different urban designs should consider the specific local conditions of the chosen location.

9. Conclusions

As wind speed plays a critical role in assessing human comfort in different urban areas, this research aimed to analyse the range of wind speeds for different time periods at Auckland University of Technology (AUT) based on various building aspect ratios. The study's objectives were to identify the most challenging time periods and high-risk areas within this location and to propose new scenarios for optimizing the area to maintain a tolerable range of wind speeds throughout the year. For this study, AUT was divided into 4 different locations, each further divided into different zones based on their aspect ratios, totalling 12 zones. We utilized both field surveys, including questionnaires, and software simulations using ANSYS to understand people's sensations and the range of wind speeds at AUT.

Based on our research findings, the following conclusions can be drawn:

- Among the 706 survey participants, over 60% reported experiencing windy conditions in both summer and winter in the selected location. These findings are consistent with Auckland's climate data, which shows that windy conditions are prevalent throughout most of the year (Lorrey et al. 2014).

- By correlating surveys results with the Beaufort Scale for wind intensity, areas with wind speeds below 3.3 m/s were considered comfortable (perceptible and tolerable ranges), while areas with wind speeds exceeding 3.4 m/s were categorized as high-risk areas (moderately/significantly unpleasant) based on ANSYS simulation maps for Auckland.
- The research indicates that the most challenging conditions are associated with north-east winds during the summer, affecting seven zones, which can be considered moderately/significantly unpleasant in selected location.
- In Location 1, the zone with an aspect ratio of 1.3 can be considered the area with the highest wind speed hazard at AUT, with an average wind speed of 6.8 m/s during the summer and an average wind speed of 4.3 m/s for winter.
- The optimal scenario for achieving tolerable wind speeds during both summer and winter involves reducing aspect ratios in high-risk zones in Location 1. This scenario has been examined in previous studies aimed at decreasing wind speeds in various urban contexts (Abdollahzadeh and Biloria 2021; Qaid and Ossen 2015).
- Ansys simulations showed that similar aspect ratios can result in varying wind speed patterns during comparable time periods. This highlights the significance of location orientation, wind directions, building arrangements and aspect ratio shapes in understanding the impact of urban designs on wind speeds, as also recommended in previous studies (Abd Razak et al. 2013; Ali-Toudert and Mayer 2006).

The methods and findings presented in this study are expected to provide valuable insights for urban planners and architects in assessing wind speed patterns in various urban contexts and implementing strategies to enhance human comfort. These efforts can contribute to improving the liveability of outdoor spaces in cities.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

Data availability statement

The authors confirm that the data supporting the findings of this study are available within the article.

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Appendix A

The computational domain size follows established guidelines based on the seminal works of Tominaga, Mochida et al. (Tominaga et al. 2008). It extends in various directions from the building model: horizontally, spanning 5 times the building height (H), and vertically, covering 5 times H. Upstream, it stretches 5 times H, and downstream, it extends 15 times H beyond the building model. Grid generation employs an expansion ratio ranging from 1.05

to 1.2, tailored to specific region needs within the domain. Grid construction exclusively utilizes hexahedral cells, as recommended by Tominaga, Mochida et al. (Tominaga et al. 2008). Mesh resolutions are determined through grid-sensitivity analysis.

The mean wind speed profile adheres to the logarithmic law. Profiles for wind speed, turbulent kinetic energy, and turbulent dissipation rate are employed, as described by Tanaka, Yoshie, and Hu (2006).

$$U(y) = \frac{u_*}{k} \times ln\left(\frac{y + y_0}{y_0}\right)$$

Where y represents the height coordinate, y0 $\approx$ 0.004 denotes the aerodynamic roughness assuming H $=$ 48 m. 'k' stands for the von Karman constant ($k = 0.42$), and 'u*' signifies the friction velocity. The aerodynamic roughness required to reconcile the two laws (logarithmic and power) can be determined using the following equation proposed by Holmes, Paton, and Kerwin (2007).

$$\alpha = \left(\frac{1}{\ln\left(\frac{y_{ref}}{y_0}\right)}\right)$$

The friction velocity is determined by the following equation:

$$u_* = k\frac{U_{ref}}{\ln\left(\frac{y+y_0}{y_0}\right)})$$

At a height equivalent to the building's height (H $=$ 0.2 m), the reference wind speed U_{ref} is recorded at 4.2 m/s, leading to a friction velocity of $u_* = 0.449$ m/s. The turbulent kinetic energy profile at the inlet was determined using wind tunnel measurements (Jiang et al. 2012) and adapted to the following structure:

$$k(y) = \gamma_1\, y^{\gamma_2} \exp\left(-\gamma_3 y\right)$$

The function adjusted with $\gamma_1 = 1.65$, $\gamma_2 = 0.27$, and $\gamma_3 = 3.05$ yielded the lowest mean squared error when compared to the wind tunnel data, as demonstrated by (Keshavarzian et al. 2021). The turbulence dissipation ratio (ε) profile is computed using the following equation:

$$\varepsilon = \frac{u_*^3}{k(y + y_0)}$$

And specific dissipation rate ω:

$$\omega = \frac{\varepsilon(\mathrm{y})}{C_\mu\, k(y)}$$

With a constant C μ of 0.09, as indicated by van Druenen et al. (2019).