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Developing Three-Dimensional CFD City Model Based on Public Accessible Information for Street-Level Wind Risk Assessment

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Abstract

A three-dimensional city model based on public accessible online information has been developed with success in this study. Detailed procedures on how to develop such model for computational fluid dynamics (CFD) simulation by using online maps, public accessible building information and online multimedia data will be reported in this paper. The city model developed in this study covers Marina Bay area of Singapore that includes highly developed urban region with many skyscrapers, greenery and water bodies, making it suitable for future urban heat island investigation. It can predict the street-level wind climate with a resolution of meters and has been validated by comparing with the measured wind data. We then conduct a risk assessment study of urban wind channels caused by a tropical typhoon, Vamei, which passed by Singapore on 27th Dec 2001. Furthermore, the application of the CFD city model in improving a real time wind prediction system for water quality control purpose is discussed.

Introduction

Understanding wind flow in a city is of great importance as it provides useful information on whether buildings ventilate well (relating directly to building energy efficiency), what pedestrians experience under different weather conditions, where wind channels are located and, furthermore, what the potential risks are of those wind channels under extreme weather conditions, such as typhoons [1-2].

Wind direction is also critical in pollution control as well as crisis management for instance when involving hazardous or toxic gas/liquid leakage [e.g. 3-4]. Beside wind related risk assessment for urban planning and city management, the street-level wind information serves as one of the key inputs when calculating thermal comfort of a city [5] as well as predicting water quality in reservoirs. [6]

A large number of computational fluid dynamics (CFD) city models have been developed for different cities in the world. However, most of those models were developed under non-disclosure agreement, meaning that once the project is finished, the models cannot be used anymore for research purposes.

As a result, most of newly developed turbulence models and heat transfer models were verified by using cuboids as buildings with simple building combination of 10~20 buildings within the area of 0.01 square kilometres, due to the lack of the 'real' city data. Given that a real life case is at much larger scale: usually several or tens of square kilometers including more complex building arrangements of hundreds of buildings, it is impossible to tell whether it is feasible to use those models in real life cases.

The aim of this work is to develop a city model based on public accessible online information so that it is possible to conduct urban wind as well as thermal comfort CFD simulation at the scale compatible to real life cases. Such model is free for academic usage without any constrains, yet provides the complicity that one usually faces in real life case studies. The methodology of developing CFD city model based on public accessible information makes it possible to evaluate the feasibility of different turbulence or heat transfer models before applying them in urban design and management related projects.

There are many challenges when developing such model, mainly because of the limited or uncompleted information about the buildings. In this paper, detailed procedures on how to develop a city model by using public accessible online information will be reported. A city model for the central business district (CBD) area of Singapore, has been developed purely based on public accessible online information. The model has been validated and CFD simulations were conducted to demonstrate how wind maps can be used for wind related risk assessment under tropical typhoon weather condition. Finally, the application of CFD simulation in real-time wind monitoring for urban water quality prediction is discussed.

3D CFD City Model Development

In order to simulate street level wind climate, the representation of the three-dimensional (3D) urban environment is essential. When developing a 3D city model for CFD simulation, detailed information of building shape, location and building height is required; usually only accessible by government agencies. In this study, we tried to develop a 3D city model based on online maps, public accessible building information as well as multimedia data such as images. The model can then be used in our future study on urban heat island and pollution research.

Figure 1 illustrates how to develop a city model based on public accessible online information, using a complex named Suntec City located in the CBD of Singapore as an example. First, the urban geometry, i.e. buildings shapes & location, was extracted from the Singapore street directory map [7]. The extracted building shapes were further treated using GIS into a hierarchical description of a landscape in different abstraction levels. Then the heights of the buildings were derived from the online accessible text. In the case when such information is unavailable, the building height was calculated based on how floors it has and floor to floor height, which is typically 5m for commercial buildings and 3.6m for HDB residential buildings in Singapore.

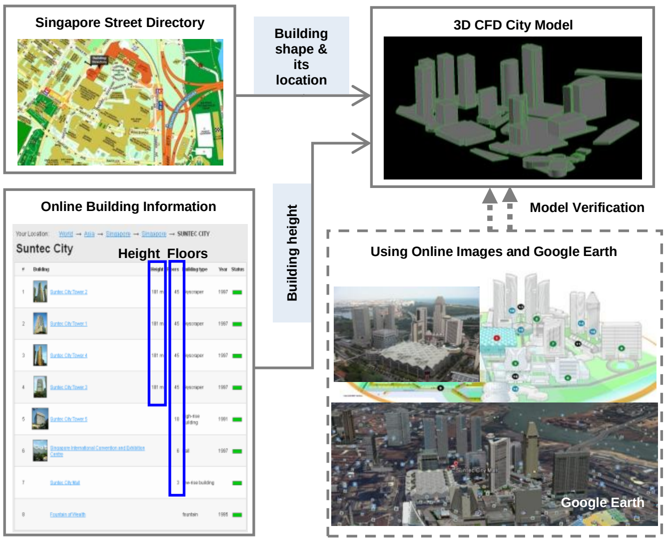


Figure 1. Developing three-dimensional city model based on public accessible online information, using Suntec City as an example.

The reconstruction of the 3D city model from GIS data is one of the key aspects for wind profile modeling in urban environments. The main body of buildings is reconstructed by extrusion according to their corresponding building heights. Both Google Earth [8] and online images or street views are used as reference to confirm the building reconstruction. Finally, the 3D model needs to be visually inspected to detect gaps so that the model will be water-proof and ready for meshing.

The city model developed in this study covers an area of around 3km*3km in the Marina Bay area of Singapore, including many high-rising buildings of 150~250 meters height. Located at the Southern tip of Singapore, Marina Bay is a 360 ha development designed to seamlessly extend Singapore's downtown district, CBD, and further support the city-state's continuing growth as a major business and financial hub in Asia. On top of highly developed urban regions, Marina Bay is planned with greenery all around – from the outdoors to tree-lined pedestrian malls, city rooms, sky terraces and roof gardens- Garden City by the Bay. The Marina Reservoir is located within the selected area, which catches freshwater and provides 10% of the island water needs. The developed city model together with satellite image from Google map is illustrated in Figure 2. Both the water-body and the greenery area can be identified on the ground by using satellite image.

CFD Simulation & Model Validation

The commercial CFD software FLUENT 13.0 [9] was used to calculate the three dimensional wind distributions over Marina Bay area. Mass conservation and momentum equations were solved. To capture the turbulent nature of the flow around buildings, the k-ε turbulence model is chosen because of its high computational efficiency [10].

The computational domain was built using tri elements to mesh the building and boundaries. The volume mesh was generated using Tgrid's automesh tool. The computational domain is 10km long, 10km wide and 0.8km high and the total number of computational cells is approximately 50 million. Velocity inlet, outflow, symmetry (for the sides and top surface) and wall (both building surfaces and ground) were used for the domain boundary conditions. Standard and second-order discretization schemes are adapted for pressure interpolation. Typically, it takes 2-3 days for one simulation case to be converged using a workstation of 12 cores (running 8 parallel-Fluent licenses) and 32GB memory.

(a) Satellite image from Google map

(b) 3D CFD model

Figure 2. The developed Marina Bay city model.

The model has been validated by comparing the simulation results with the measurement. The wind velocity and direction have been measured every minute by using two wind sensors, one of which locates in an open field. By analysing the measured wind data, we found that the wind flow inside the city changes periodically, which is a result of the changing atmospheric condition in the region and the turbulence. Therefore, it is important to simulate the transient wind flow when working on pollution or chemical dispersion. In this study, we used averaged wind data of the sensor in the open field (when the wind doesn't change vigorously) as inlet flow boundary condition. The comparison of CFD steady simulation with the measurement shows that there is less than 1% difference of wind direction, while the wind velocity is around 5% difference. Therefore the model developed by using online information is valid.

Wind Risk Assessment under Extreme Weather Condition: Using CFD Simulated Wind Results

In this section, the newly developed city model has been used to study the wind channels within the urbanized landscape around CBD area of the Marina Bay during the passage of the Typhoon Vamei, in particularly for the approaching and receding phases of the storm.

In Singapore, the first tropical cyclone formation, Typhoon Vamei, was recorded on 27 December 2001. In fact, the formation of Typhoon Vamei was the first-observed tropical cyclogenesis within 1.5 degrees of the equator, which was previously considered impossible due to the lack of Coriolis effect near the equator [11]. It was initially identified as a tropical storm and then upgraded to a typhoon by the Joint Typhoon Warning Center in Hawaii. The storm made landfall over southeast Johor at the southern tip of Peninsular Malaysia, about 50 km northeast of Singapore, at 0830 UTC 27 December 2001.

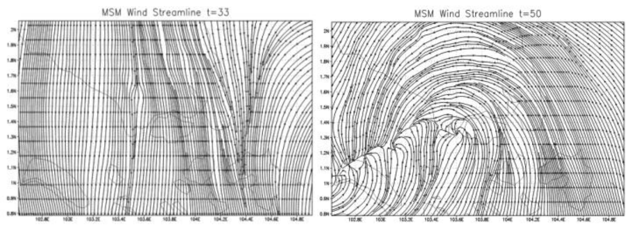
In our previous study, a very high resolution mesoscale spectral model (MSM), based on the National Centers for Environmental Predictions (NCEP) Regional Spectral Model, had been adapted and calibrated for Singapore. In particular it had been applied to the Marina Bay area, to downscale from the NCEP hourly weather fields, which is at 80km resolution, to a spatial resolution of 1km for Singapore as shown in Figure 3. For details about the MSM model please refer to [1-2].

To perform the wind risk assessment, the wind conditions in Singapore Marina Bay area during the period when the typhoon Vamei passed-by were reproduced by 3D CFD models. Two scenarios were simulated to illustrate how the wind direction change due to the passing typhoon affects the wind distribution in CBD area. One is at December 27th 2001 5 A.M. (during the approaching phase of the typhoon) and the other is at December 27th 2001 10 P.M. (during the receding phase of the typhoon). The inlet flow boundary conditions were provided by the downscaled wind flow at 1km resolution.

Figure 4 and Figure 5 illustrates the wind velocity contour in Singapore CBD area during the time when typhoon Vamei was approaching Singapore and receding from Singapore respectively. The wind distribution showed very different pattern at different phases of the typhoon Vamei. This is because the typhoon center was moving from southeast to the northwest in December 27th 2001. The wind direction in CBD area was changed by following the moving center of the typhoon Vamei.

In Figure 4 and 5, the locations of the channel flow can be identified clearly with the aid of the 3D CFD urban simulation. It can be seen that the maximum velocity during the receding phase (shown in Figure 5) is almost as twice as that during the approaching phase. The simulation results indicate that the wind condition during the receding phase might need special attention in terms of wind risk assessment.

As illustrated in Figure 6, CFD simulation provides the wind flow information at different height above the ground. The higher the location, the stronger the wind channel is. The information is particularly important for high-rising buildings with sky-gardens, where the maximum wind velocity of the wind channels among those buildings are almost doubled the value of incoming wind speed.



(a) Approaching Phases (b) Receding Phases

Figure 3. Typical surface wind flow of the Typhoon Vamei obtained by mesoscale spectral model. [1-2]

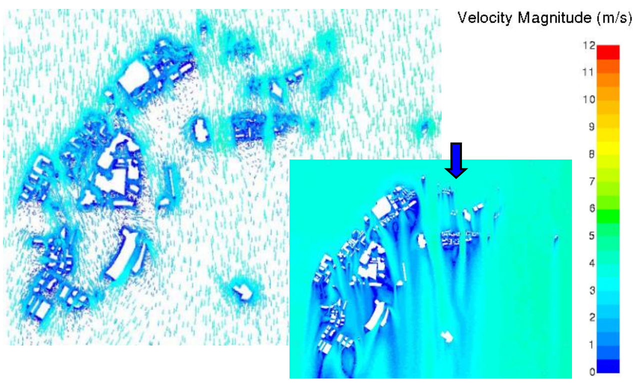


Figure 4. Wind distribution at 5 meter height during the approaching phase of typhoon Vamei, at T=33 hours (27 Dec 2001, 5am); representing a typical local wind pattern during Northeast monsoon season in Singapore.

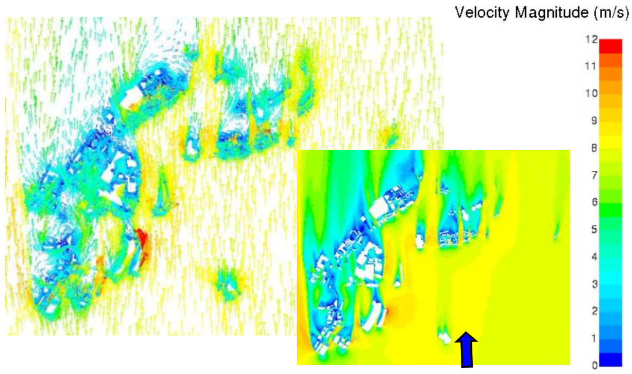


Figure 5. Wind distribution at 5 meter height during the receding phase of typhoon Vamei, at T=50 hours (27 Dec 2001, 10pm).

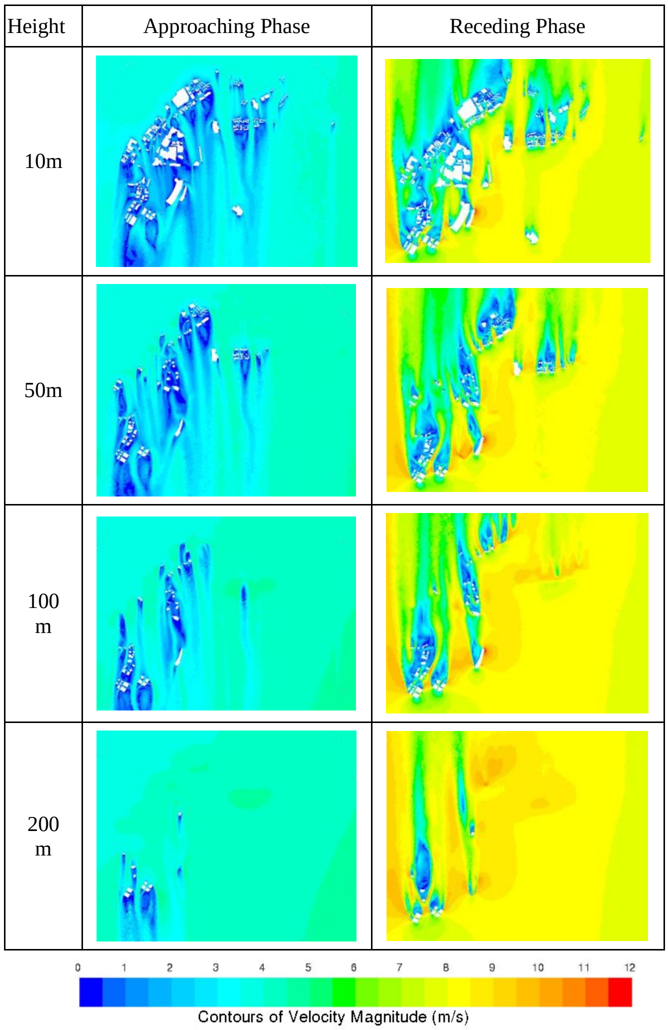


Figure 6.Comparison of wind flow at different height during different phases of the typhoon Vamei.

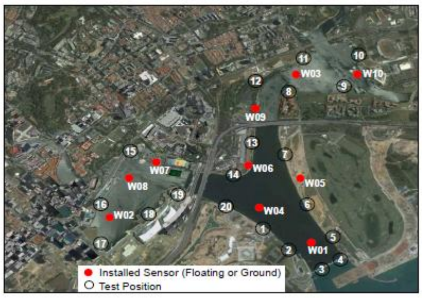
It is worth to mention that the landscape of Marina bay area has been changed greatly since 2001 when Typhoon Vamei passed by Singapore. Back then, many skyscrapers hadn't been built yet. We compared the wind channel distribution of 2001 landscape with current one by taking the newly developed high-rising buildings near Gardens by the Bay out from the city model and re-ran the CFD simulation. The results showed that those buildings have significant influence on the wind map and contribute greatly on the increased channel flow. Therefore, it is important to study the effect of new buildings on the surrounding environment (such as wind channels) before building them and CFD simulation provides a valid and useful tool for such evaluation purpose.

Discussion

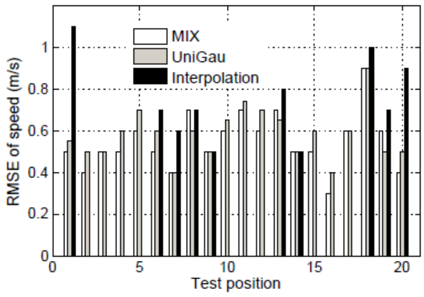
As mention in the section of Model Validation, the wind flow among buildings in CBD area is very complicated, constantly changing. [3-4] concluded that the turbulence must be simulated correctly before getting the right pollution dispersion pattern. However, a comprehensive turbulence model is computationally complex and time-consuming, making the instant CFD computation of large complex environment systems almost impossible. This significantly restricts its usage in urban design and urban planning as well as crisis management when real-time simulation results are needed.

One possible solution is to train a statistic model using CFD simulation results and then use the trained model to predict real time wind condition with the reading of sensors as input. A preliminary study has been conducted using CFD wind simulation results in two aspects: 1) to decide the locations of wind sensors; and 2) to train statistic models for real-time wind prediction. [12] To assess the spatial prediction effectiveness, both wind direction and speed were measured using the mobile wind sensor at 20 different locations (as shown in Fig. 7(a)). Fig. 7 (b) and Fig. 7 (c) compared the average RMSE of predicted direction and speed at each location from three different models: UniGau and interpolation (without CFD training), and MIX (trained by CFD wind pattern). MIX model performed the best with reduced errors.

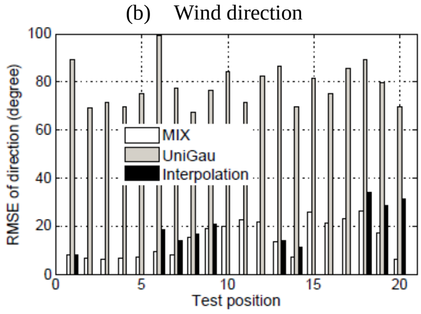
The positive results also indicate that the 3D city model developed in this study can reproduce the 'real' wind flow in Marina Bay reasonably well.



(a) Location of wind sensors



(b) Wind direction



(c) Wind speed

Figure 7. Assessment of the spatial prediction effectiveness. [12]

Conclusions

In this study, a three-dimensional city model has been developed based on public accessible online information. Building location and configuration was achieved from online map systems such as Google map, Street Directory etc, while building height was mainly obtained from online building information or estimated based on floor number and building type.

The CFD city model developed in this study can predict the street-level wind climate with a resolution of meters. The simulation results have been compared with the measured wind data and there is less than 1% difference on wind direction. A case study to assess risk associated with urban wind channels over the urbanized Marina Bay caused by a tropical cyclone, Vamei has been reported in this paper, which demonstrates that CFD models provides an effective tool for urban wind risk assessment. Moreover, the city model found its good usage in improving a real time wind prediction system. As such, it has been concluded that the city model developed in this study is valid and can be used in future studies of urban heat island effect, thermal comfort and pollution prediction.

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