International Congress on Environmental Modelling and Software

1st International Congress on Environmental Modelling and Software - Lugano, Switzerland - June 2002

Jul 1st, 12:00 AM

Computational Simulation of Turbulent Flows and Pollution Dispersion in Complex Urban Canyons

Naifang Bei

Yaping Shao

Computational Simulation of Turbulent Flows and Pollution Dispersion in Complex Urban Canyons

Naifang Bei[1] and Yaping Shao[2]

[1]*Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing*
[2]*Department of Physics and Materials Science, City University of Hong Kong, SAR*

Abstract Detailed computational simulations of turbulent flows and pollution dispersion in city canyons have been carried out using the computational fluid dynamics package CFX-5, which is capable of using unstructured meshes and a variety of turbulence closure schemes. The simulations have been done for city canyons with simple to complex structures. As a validation of CFX-5, a roof garden test is conducted. A comparison of the numerical results with observed data indicates that the simulations of turbulence and pollution dispersion are reasonable. The computational fluid dynamic approach is further applied to the canyon geometry typical to Hong Kong, using the area in the vicinity of Bank of China Tower as an example. It is shown that the characteristic of the circulation in city canyon is related not only to atmospheric conditions but also to the scaling parameters determined by the geometry of urban structure. It is shown that useful results for understanding of the mechanisms of pollution dispersion in urban atmospheric boundary layers can be obtained via a large number of simulations.

Key word index: Turbulence, city canyon, dispersion .

1. INTRODUCTION

Urban pollution dispersion, especially, the urban street canyon problem has been studied extensively in recent years. Field campaigns, wind tunnel experiments and numerical simulations have been carried out to quantify the complex physical processes occurring within a canyon. In the early study by Dabberdt et al. (1973), measurements were made in street canyons of San Jose and St. Louis. They observed the formation of a helical circulation when the roof level wind blows within $\pm 60^{o}$ of the cross-street direction, resulting in higher concentrations of CO on the leeward side of the street. Nicholson (1975) developed an analytical pollution model under the assumption that the mean concentration of street-level air is governed by the mean updraft velocity at the roof level on the upwind side of the street canyon. Field studies by Depaul and Sheih(1984) have improved the understanding of the mechanisms by which pollutants are transported from street canyons under ambient winds perpendicular to the street. Depaul and Sheih (1985) attempted to estimate the exchange rate of pollutants between the street canyon and the upper air. They found that the ventilation velocity, which represents an average velocity of pollutant transport from the canyon and is calculated using pollutant retention time and wind speed, ranges from 15 to 80 cm s^{-1}. The pollutant concentration field at t = 2h exhibits higher concentration on the upwind side than on the downwind side, as shown in many previous studies. This feature is directly linked to the vortex circulation within the canyon, which causes pollutants emitted from the street-level source to be transported upwind and then upward. Nakamura and Oke (1988) made observations of flow and temperature in a street canyon in Kyoto, Japan. They observed a vortex formation when the above roof flow was perpendicular to the canyon. The flow ratio for perpendicular flow conditions is about 2/3. Oke (1988) described different flow regimes of 'isolated roughness (H/W < 0.3)', 'wake interference (0.3 < H/W < 0.7)' and 'skimming flow depending (H/W > 0.7)' on the separation of buildings. Hoydysh and Dabberdt (1988) found that the dispersion of a tracer was strongly dependent on the canyon asymmetry and less dependent on the orientation of the canyon relative to the prevailing wind. Murakami, Mochida and Hayashi (1990) used a combination of wind tunnel experiment, k-ε model prediction and large-eddy simulation to study the flow and pollution transport around buildings. However the results are presented at insufficient resolution to enable detailed inspection although the authors claim that LES performed very well at predicting mean velocities, turbulence kinetic energy, pollution concentrations and surface pressures. Qiu and Kot (1993) performed a field campaign to measure CO, NOX, turbulence and traffic volume in three streets in Guangzhou city of China. It is found that pollution within the canyon was not well correlated to the roof-level wind speed. Leeward pollution was not always considerable higher than the windward face. Pollution dispersion patterns were found to be strongly dependent on canyon configuration. Lee and Park (1994) simulated pollution dispersion in urban canyons using a two-dimensional flow model applicable to street canyons under ambient winds perpendicular to the street. Results show that dispersion characteristics can be simulated and interpreted in terms of flow conditions and structural configurations. The removal of pollutants is effective for a shallow street canyon and is augmented by small Pe and strong ambient winds. For deeper street canyons in which double vortices develop, the transport of pollutant from the lower vortex to the upper vortex is largely controlled by diffusive processes. Macdonald et al. (1998) studied the effect of obstacle width on the dispersion of a ground-level plume in large obstacle arrays by physical modeling using arrays of building-like obstacles at two scales – 1:100 in a boundary layer wind tunnel and 1:10 at a field site. Several phenomena reported by Davidson et al. (1995) and Macdonald et al. (1997) were observed. Some new phenomena that have been observed and measured include: (1) An increase in obstacle aspect ratio beyond W/H = 1 up to the two-dimensional case; (2) For releases inside the array the initial dispersion of the plume is considerably greater than for a release upwind of the array, because in the former case the plume expands rapidly in the low mean velocity and high turbulence to immediately fill an obstacle wake. Baik J. - J. and Kim J. - J. (2002) numerically investigated the pollutant transport from urban street canyons using a two-dimensional flow and dispersion model. Their results from the control experiment with a street aspect ratio of 1 show that at the roof level of the street canyon, the vertical turbulent flux of pollutants is upward everywhere and the vertical flux of pollutants by mean flow is upward or downward. The horizontally integrated vertical flux of pollutants by mean flow at the roof level of the street canyon is downward and its magnitude is much smaller than that by turbulent process. These results indicate that pollutants escape from the street canyon mainly by turbulent process and that the net effect of mean flow is to make some escaped pollutants reenter the street canyon. Further experiments confirm the findings from the control experiment. However, simulations were limited to two-dimensions and a three-dimensional numerical study is needed to examine whether the present results obtained in two dimensions on the escape of pollutants from urban street canyons remain valid in three dimensions.

From the above review on the study of pollution dispersion over city canyon, it is apparent that the three dimensional simulation over the real-scale complex terrain is deficient.

In this paper, the commercial software code CFX from AEA Technology is utilized as a solver. This approach has the advantages that many numerical schemes are available in CFX, and potentially complex geometry can be constructed quickly using the user-friendly pre-processor and multi-block finite-volume grids. Post-processors also allow convenient analysis of results.

2. MODEL VALIDATION

The CFD calculation duplicated the roof garden geometry fairly closely in terms of dimensions and details such as the tiered walls. Computational domain is indicated in Figure 1. The domain extended 115.5m above the garden roof and 100m in the x and y directions beyond the garden walls. 148374 nodes are used in the computational domain. A plane of symmetry was specified at the upper surface. An inlet velocity of 3 m s^{-1} was specified at an angle of 160^{o} to match the prevailing winds during the experiment. The turbulence intensity of the inlet was assumed to $0.05s^{-1}$ and the length of the eddy turbulence is set to 0.1m. Periodic conditions were applied in the y directions. The roughness of the walls of the garden and the fetch is assumed to 0.1m. The initial data of the computational domain is automatically produced by CFX-5. The turbulence model used is the Reynolds stress model. The domain temperature is assumed as 288.0K. Non-buoyant is assumed in the domain. The velocity at the position of (x = -3m, y = 22.075m, z = 18.57m) is used as the reference velocity (u_{ref}) in the analysis. Velocities at 2.0m from the windward wall and 1.9m from the leeward wall are shown in Figure 2(a-b). The solid lines in the two figures are the relative observation. And the digits on the solid line represent the height of the observed data. It can be seen that u and v components are predicted well by CFX-5. However, there are some differences. It may be caused by the details of the garden floor which are not included in the model. The predicted wind vectors of a mid-plane slice at y = 12.25m shown in Figure2(c). It can be found that re-circulation is clearly visible in the corners of the garden.

3. SIMULATION OF POLLUTAN DISPERSION OVER ROOF GARDEN

The computational domain extended 45m above the garden roof and 24.5m in the x and y directions beyond the garden walls. A sub-domain was created at the position of (x=3m, y=12.25m, z =3m) and with the size of 2.0m*2.0m*2.0m. And a source of pollution was added to this sub-domain. The source value is $1.0Kg\cdot m^{-3}\cdot s^{-1}$. The source coefficient is $0.05s^{-1}$. The kinematic diffusivity is $1.0e\text{-}5m^{2}\cdot s^{-1}$. The boundary conditions and the parameters used are the same as those of experiment in model validation.

The concentration profiles for the windward and leeward sides of the garden roof are given in Figure 3(a). It can be seen that the pollutant is transported from the position of the source to the windward of the roof garden while the pollution concentration at the leeward is very small. The longitudinal section (x/w = 0.5) and horizontal section at z/H = 0.5 are shown in Figure 3(b) and Figure 3(c).

4. SIMULATION RESULTS OVER MORE REALISTIC COMPLEX TERRAIN

We selected 59 buildings near Bank of China Tower and their heights are assumed as 120m. The distribution of the buildings and the computation domain is shown in Figure 4. A total of 436524 nodes are used with the grid refined near the walls. All surfaces were assumed to be smooth. The inlet boundary is set to normal speed as the value of 5.0m/s and the outlet boundary condition is set to average static pressures. Relative pressure of the outlet is assumed as zero. A plane of symmetry was specified at the upper surface. Periodic conditions are applied in the y directions.

The horizontal sections of the wind vector distribution at the height of 60m and 90m are shown in Figure 5. It could be found that the circulation characteristic near different buildings is apparent different. The velocity between different buildings is heterogeneous. It is closely related to the geometry of the building and the distances between the buildings. The total vertical momentum flux is computed using output grid scale velocity quantities and is given in Figure 6. The inside box of Figure 6 is the same size as Figure 5. It can also be found that the distribution of the vertical momentum flux is heterogeneous between buildings. And where the distance between the buildings is short, the vertical momentum flux is larger whereas where the distance between the buildings is long, the vertical momentum flux is smaller. The vertical momentum flux of the higher level within the height of the building is generally larger than that of the lower level. In addition, the distribution of vertical the momentum flux is more complicated than that of the case with only one or two buildings. The dispersion characteristic over such different buildings should be studied in the future.

5. SUMMARY AND CONCLUSION

Using the computational fluid dynamics package CFX-5, a validation test and the other two experiments were conducted. The results indicate that it is effective to simulate the flow and pollution dispersion characteristics over the complex terrain using CFX software. The simulation results of the pollution transport in the roof garden indicate that it is mainly contributed by the grid scale circulation flow. The simulation over the Hong Kong Island indicates that the wind velocity and the vertical momentum flux are all heterogeneous between different buildings. It is possible to simulate the circulation and turbulent characteristics between buildings with different geometry and over complex terrain. Although detail analysis should be conducted in the future study.

6. REFERENCES

Baik J. - J. and Kim J. - J. (2002) On the escape of pollutants from urban street canyons. Atmosperic Environment 36, 527-536.

DePaul F. T. and Sheih C. M. (1984) A study of pollutant dispersion in an urban street canyon. Argonne National Laboratory Technical Report ANL/ER-84-1, 84 pp.

Dabberdt W. F., Ludwig F. L. and Johnson W. B. (1973) Validation and applications of an urban diffusion model for vehicular pollutants. Atmos. Envir., 7, P.603-618.

Davidson, M. J., Mylne, K. R., Jones, C. D., Philips, J. C., Perkins, R. J., Fung, J. C. H. And Hunt, J. C. R. (1995) Plume dispersion through large groups of obstacles— a field investigation. Atmospheric Environment 29, 3245-3256.

Hoydysh W. G. And Dabberdt W. F. (1988) Kinetics and dispersion characteristics of flows in asymmetric street canyons. Atmos. Envir., 22(12), p2677-2689.

Hunter L. J., Johnson G. T. and Watson I. D. (1992) An investigation of three-dimensional characteristics of flow regimes within the urban canyon. Atmospheric Enironment 26B(4), 425-432.

Lee I. Y. and Park H. M. (1994) Parameterization of the pollutant transport and dispersion in urban street canyons. Atmospheric Environment 28, 2343-2349.

Macdonald, R. W. (1997) Physical modelling study of flow and dispersion around groups of buildings. Ph.D. thesis, Environmental Technology Centre, UMIST, 276 p.

Murakami S., Mochida A. and Hayashi Y., (1990) Numerical simulation of velocity field and diffusion field in an urban area. Energy and Buildings, 15-16, p.345-356.

Macdonald R. W., Griffiths R. F. and Hall D. J. (1998) A comparison of results from scaled field and wind tunnel modelling of dispersion in arrays of obstacles. Atmospheric Environment 32, 3845-3862.

Nicholson (1975) A pollution model for street-level air. Atmospheric Environment 9, 19-31.

Oke T. R. (1988) Boundary Layer Climates. Methuen, New York, 2nd edition.

Qin Y. and Kot S. C. (1993) Dispersion of vehicular emission in street canyons, Guangzhou city, south China (P.R.C.). Atmos. Envir., 27B(3), p.283-291.

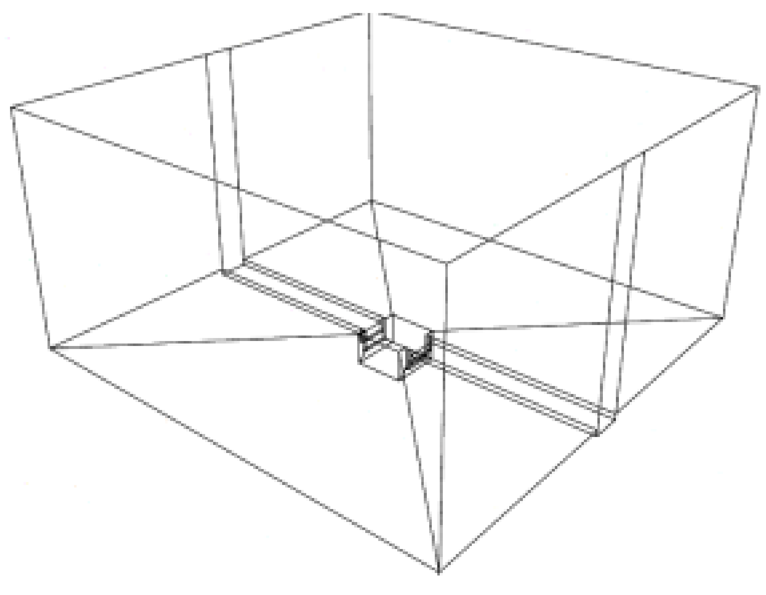
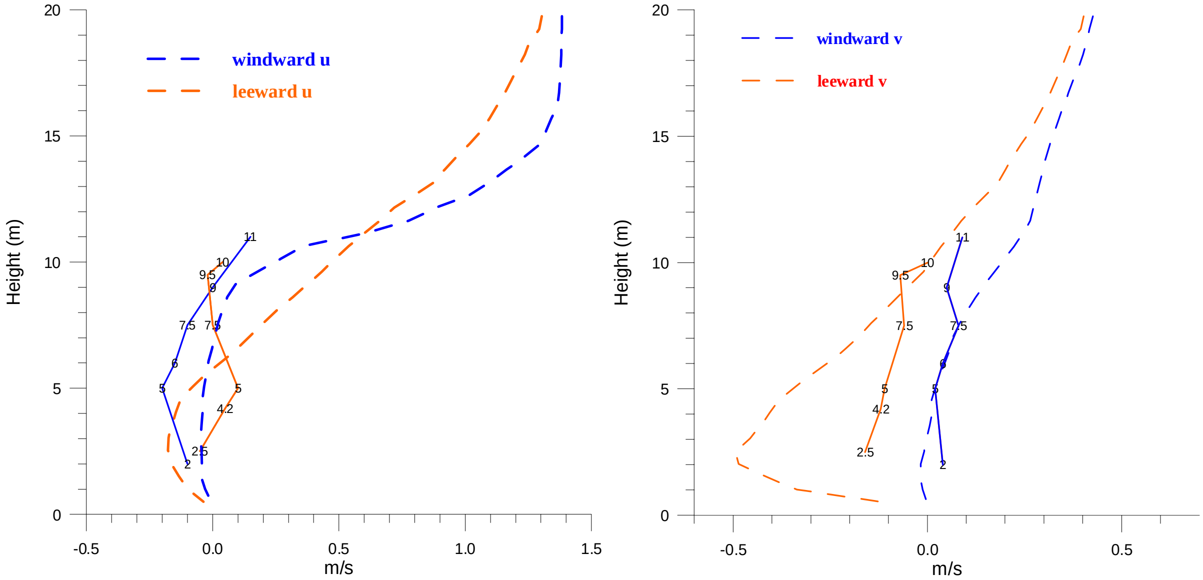
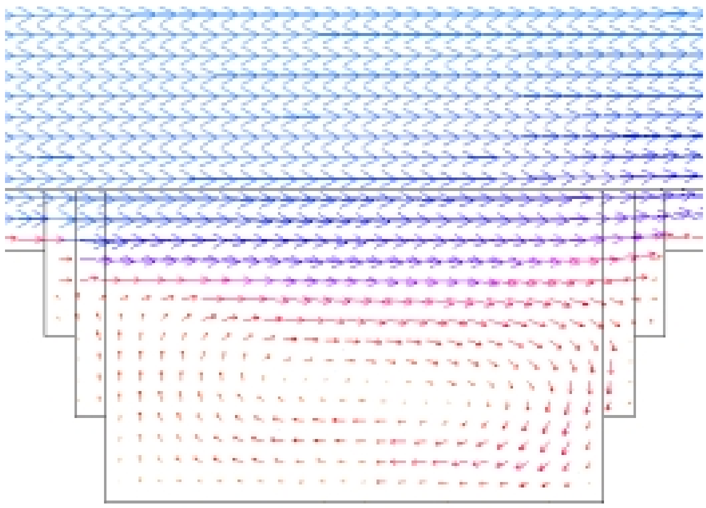


Figure 1 Computational domain in the validation test

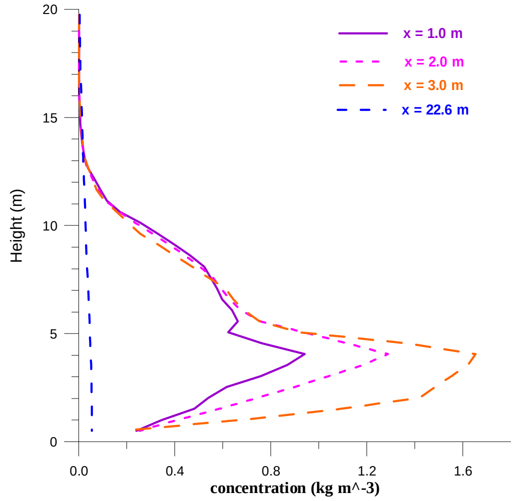


(a) u/uref (b) v/uref

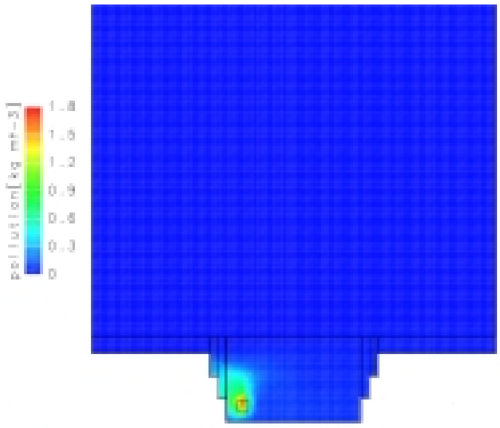


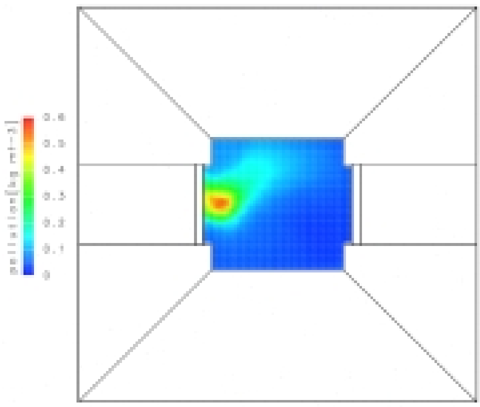
(c) Longitudinal section of velocity vector at y = 12.25m

Figure 2 Velocity profile on windward and leeward side of roof garden(a、b, solid: observed, dashed : simulated) and longitudinal section of velocity vector at y = 12.25m (c)



(a)





(b) (c)

Figure 3 Concentration profile at different position (a), Longitudinal section of the concentration at x/w = 0.5 (b) and horizontal section of the concentration at z/H = 0.5 (c)

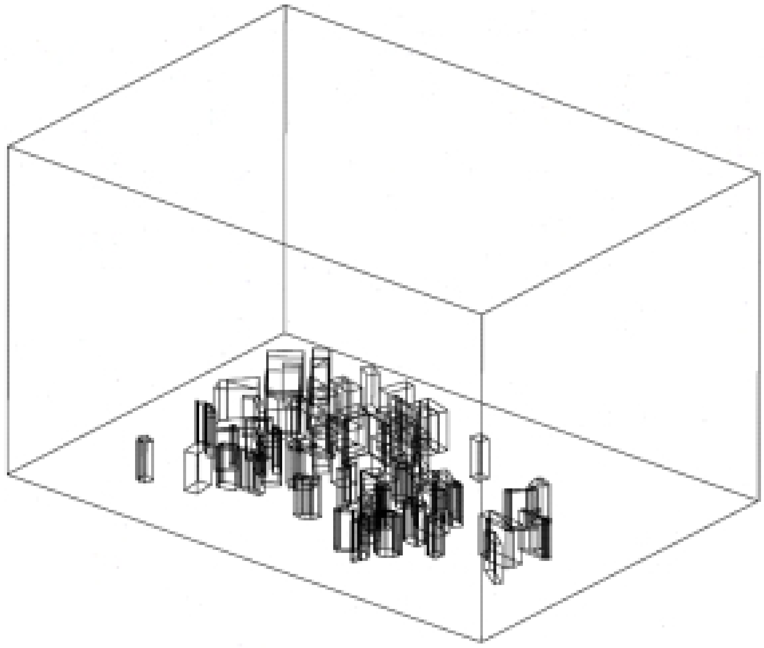
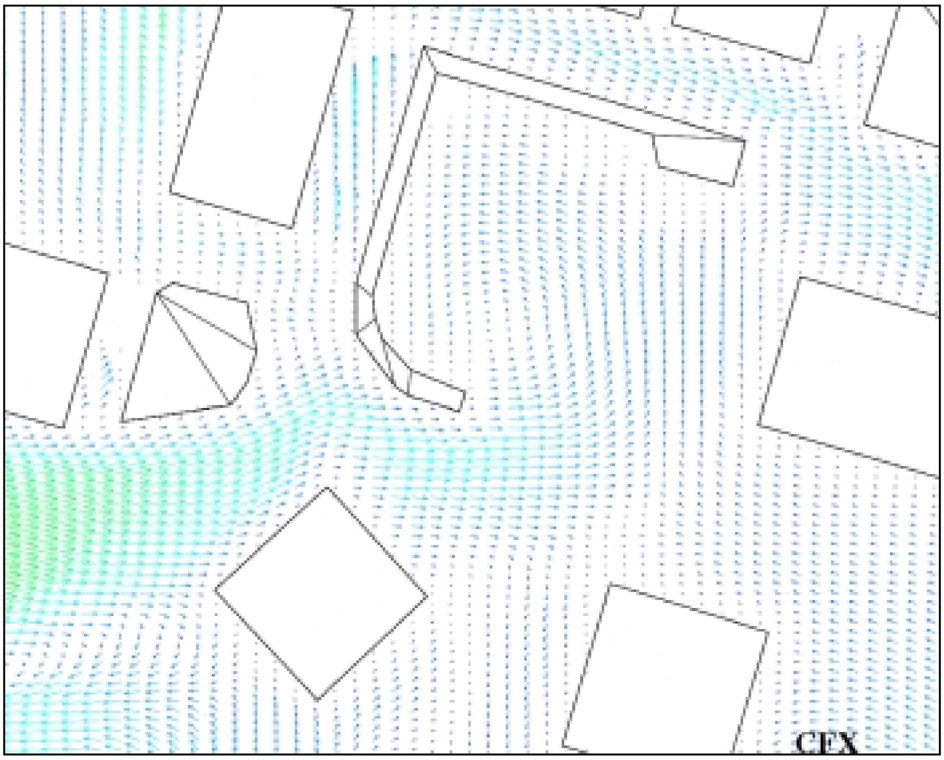
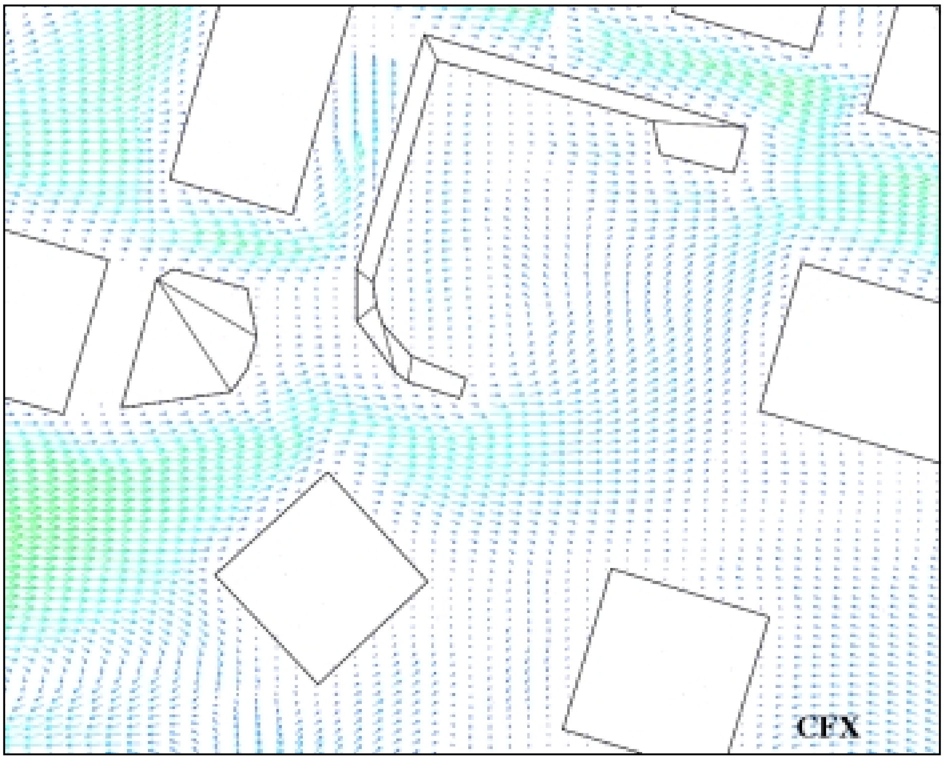


Figure 4 Building distribution near the bank of China of Hong Kong island

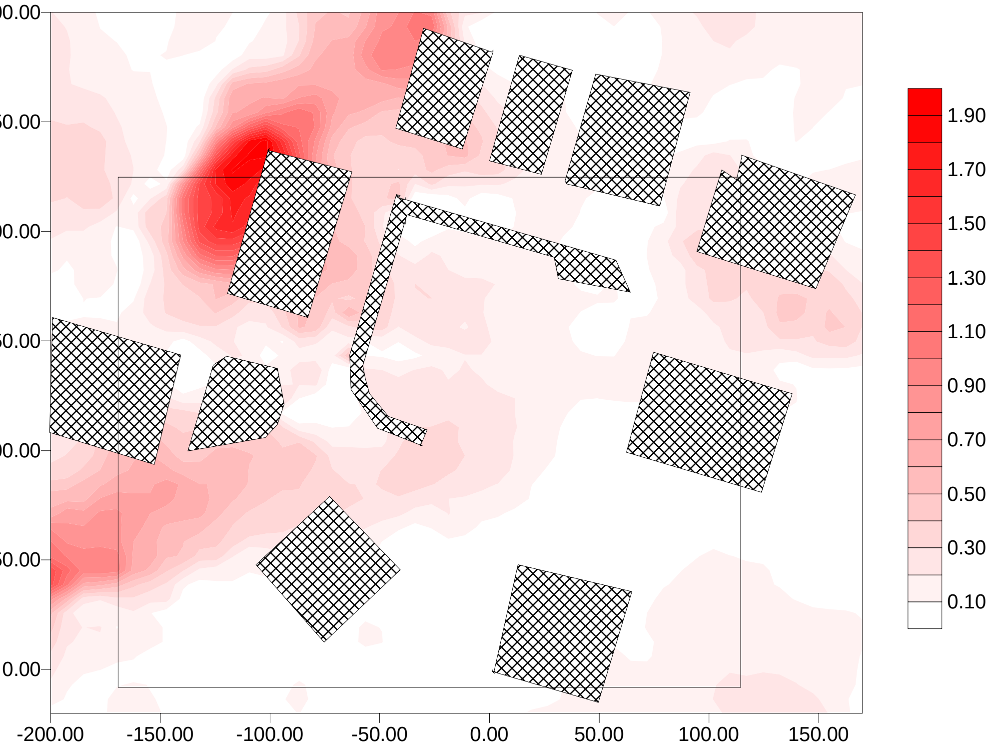


(a) Wind vector at Z = 60 m

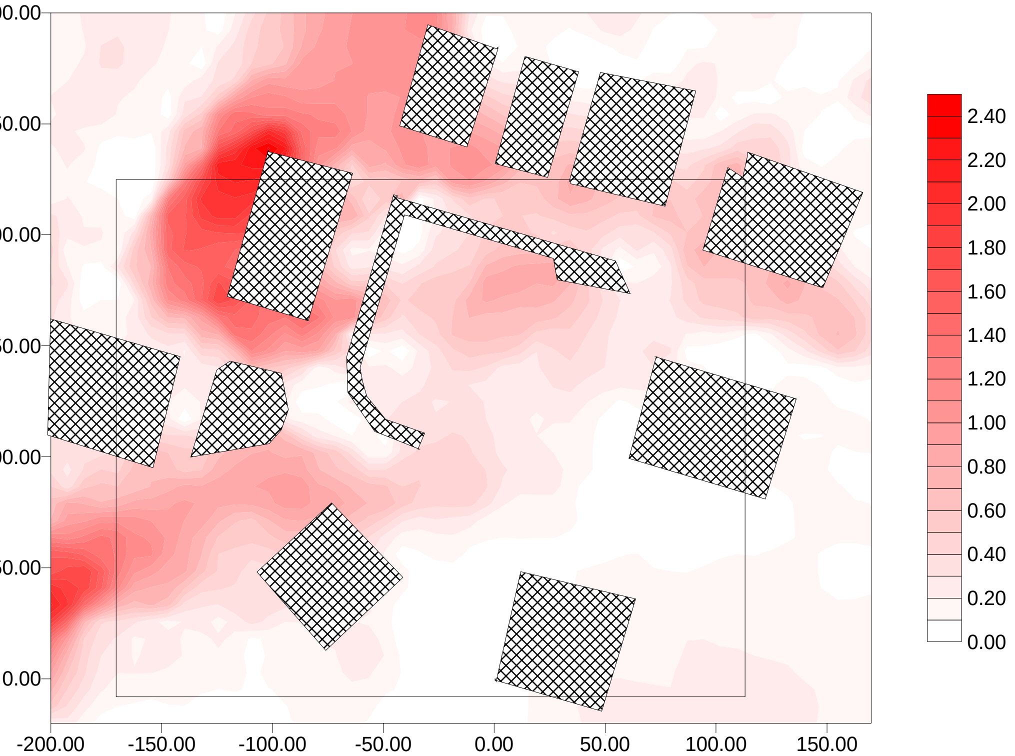


(b) Wind vector at Z = 90 m

Figure 5 Horizontal section of the wind vector at the height of 60m (a) and 90m (b)



(a) Z = 60m



(b) Z = 90m

Figure 6 The distribution of sqrt(uw*uw + vw*vw) where u and w are grid scale quantities

Unit: m^2s^{-2}