Parametric studies of urban morphologies of high density cities and their air ventilation performance under neutral and unstable atmospheric conditions using advanced large-eddy simulations

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1. Introduction

Urban air ventilation has been an issue for high-density cities, such as Hong Kong. Due to rapid urbanisation, especially in Asian cities from the tropical regions, the negative aspects of the urban heat island (UHI) effect have to be mitigated by better urban air ventilation. Bio-climatically, a 1m/s improvement in urban air ventilation due to better design and planning can mitigate a 2°C rise in the UHI (Ng & Cheng, 2012), thus reducing the number of very-hot-days and very-hot-nights (Ng, 2009a). Recent public health researches indicate that the reduction helps to alleviate the problems of heat-stress-related mortality (Chan et al., 2010).

Therefore, there is a need for better city planning and building design to improve urban air ventilation for a more comfortable and sustainable urban living. To seek planning and design measures to achieve long-term improvement of the urban living environment, a series of studies for air ventilation assessment (AVA) have been conducted by researchers from Hong Kong (Ng, 2009b). A set of planning guidelines for promoting better urban air ventilation suggested by these studies has been adopted by the Hong Kong Government. However, the AVA methodology has limitations that it cannot correctly predict the urban air ventilation performance in some areas of Hong Kong where convergence is prominent in weak wind conditions under unstable atmospheric boundary conditions (Ng & Fung, 2008).

To fully optimise the benefits of local wind environment for urban ventilation, the interaction between city morphologies and the atmosphere has been studied by using wind tunnel tests (Kubota et al., 2008; Ng, 2007, 2009a; Plate, 1999; Williams & Wardlaw, 1992) and computational fluid dynamics (CFD) techniques (Mochida et al., 1997; Murakami et al., 1999; Ng et al., 2011; Yoshie et al., 2007). However, all the above urban scale studies were conducted under neutral atmospheric conditions. Wind tunnel studies under stratified atmospheric conditions have been carried out only for very simple building geometries so far, e.g., a single street canyon (e.g., Nezis et al., 2011). In addition, CFD simulation underestimates the wind velocity in the wake region by using the Reynolds-averaged Navier-Stokes (RANS) type models because of their incapability to reproduce vortex shedding from buildings. On the contrary, large-eddy simulation (LES) improved the problem occurred in RANS type models because it resolved the energy containing turbulent eddies explicitly and only parameterised the less important smaller-scale turbulence (Yoshie et al., 2007). Numerous studies have demonstrated the performance of LES, e.g., for unsteady separated flows with vortex shedding (Tamura, 2008).

Assuming neutral conditions, most CFD and wind tunnel studies do not entirely reflect realistic atmospheric situations, especially under conditions of weak background wind, which are common in tropical and sub-tropical areas that buoyancy effects will start to dominate the turbulent exchange and have a significant effect, e.g., on the ventilation ratio. Hence, there is a knowledge gap between the current practice and the realistic situations. Advanced technology should be implemented so as to continue the rigorous investigation of urban air ventilation. The objective of the present study is to further the understanding more systematically by adopting a parametric approach. The PArallelised LES Model (PALM) will be utilized to simulate the atmospheric conditions of both neutral and unstable thermal stratification. Note that this is an ongoing study. Our presentation will focus on the new idea with very preliminary results.

2. Methodology

2.1 Large-eddy simulations

The PALM model has been developed at the Institute of Meteorology and Climatology of the Leibniz Universität Hannover since 1997 (Raasch and Schröter, 2001). It has been validated for simulating flows around solid obstacles (Letzel et al., 2008), and has been widely used in the studies of urban street canyon flows (Abd Razak et al., 2013; Kanda et al., 2013; Ng, 2009a; Park et al., 2012), including high-density urban areas in subtropical cities, such as Hong Kong (Letzel et al., 2012) and Macau (Keck et al., 2014). The code used in this study is the most updated version of PALM (Maronga et al., 2015).

In terms of urban ventilation studies, we especially are interested in pedestrian level wind velocity. The wind velocity ratio (v_r) is used as an indicator. It is calculated by $v_r = v_p / v_\infty$, where v_p is the wind velocity at the pedestrian level (2m above ground), and v_∞ is the wind velocity at the top of the wind boundary layer not affected by the ground roughness (Ng, 2009b). As we mainly focus on v_r, the absolute wind velocity is not so important in simulations. And if the high wind speed is used, more computational time will be needed because the time step has to be shorter. Therefore, we utilized a reasonable low wind velocity input of 1.5m/s to save computational time. The time step sizes can be optimally calculated by PALM codes. Further details of PALM can be retrieved from the online documentation at http://palm.muk.uni-hannover.de/.

2.2 Parametric models of urban morphologies

Four design and planning parameters are used to define the parametric models. These parameters and their representative values are listed in Table 1. A combination of these values can obtain a total of 54 scenarios for study. Results from the 6 typical scenarios will be investigated here. They represent for urban morphologies of low-density, medium-density, and high-density, respectively. The low-density model has a frontal area density (FAD) of 0.1, a ground coverage ratio (GCR) of 25%, and a plot ratio (PR) of 3.0. The medium-density model has a FAD of 0.25, a GCR of 50%, and a PR of 5.0. The high-density model has a FAD of 0.4, a GCR of 75%, and a PR of 8.0. Both homogeneous and inhomogeneous of height differential will be considered. Inhomogeneous building height is generated by a normal distributed random series, which has given a mean of the corresponding homogeneous building height (H) and a standard deviation of H/4.

Table 1 Four design and planning parameters

Parameters to be investigated	**Variables used**		
Height Differential	homogeneous	inhomogeneous	
Frontal Area Density	0.1	0.25	0.4
Ground Coverage Ratio	25%	50%	75%
Plot Ratio	3.0	5.0	8.0

We assume that floor height is 3m, site area is 1km^2, and floor area is about 2000m^2 (for low-density and medium-density) and 4000m^2 (for high-density). Geometry parameters such as building height, building size in both frontal side and perpendicular side, building number, and building matrix can then be calculated. The street width in both parallel and perpendicular directions can be obtained as well. Values of these parameters for the representative low-density, medium-density, and high-density models are listed in Table 2. Two rows of blocks are arranged around the parametric models to prevent wind blows into the urban canyon directly, which makes the situation more realistic. Meanwhile, these blocks are set normalized rather than randomized, so that their impacts on the inner parametric model are comparable. Therefore, the actual domain sizes are 1.2km × 1.2km.

Table 2 Urban morphologies of the low-density, medium-density, and high-density parametric models

Model Density	**Floor Area (m^2)**	**Building Matrix Row**	**Building Matrix Column**	**Building Height (m)**	**Parallel Building Size (m)**	**Frontal Building Size (m)**	**Perpendicular Street Width (m)**	**Parallel Street Width (m)**
Low	2160	12	10	36.0	90.0	24.0	10.0	60.0
Medium	2160	16	15	30.0	60.0	36.0	6.0	26.0
High	3960	13	14	32.0	60.0	66.0	12.0	10.0

3. Results

3.1 Simulations of neutral conditions

Simple cyclic boundary conditions are used in the current simulations of neutral conditions. The total simulation time is 6 hours. The first hour was excluded in the analysis of the results, as the turbulences need this one hour to spin-up. The simulated results from the 2nd to the 6th hours are averaged for analysis. The horizontal resolution is 2m. The vertical resolution is 2m below 300m and stretch above, with a stretch factor of 1.08.

Simulations in a 1.2km × 1.2km realistic urban area in Mong Kok were conducted to validate the PALM model before parametric studies (Figure 1). Two wind directions, southwesterly for summer prevailing wind and easterly for annual prevailing wind, were tested. AVA has suggested that v_r in Kowloon range from 0.05 to 0.1 in streets and congested area, and release to about 0.3 near the water front and in open spaces (Ng, 2009b). The simulated v_r is in a reasonable range compare with AVA studies and previous PALM simulations (Letzel et al., 2012; Keck et al., 2014). Figure 1 suggests that the distributions of v_r are very different from simulations of two wind directions. This implies the importance of FAD. Inside the high-density urban centre, other parameters of urban morphologies such as street pattern, GCR, and building height differential are also affecting pedestrian level ventilation significantly.

Site-averaged v_r is more meaningful. For the site-averaged v_r, AVA requires a buffer zone of at least one building height of the tallest building on site (Ng, 2009b). The tallest building in Figure 1 is 255m. We tested two square regions in the middle of the domain, one is 400m × 400m and the other is 600m × 600m, with a buffer width of 400m and 300m, respectively. Values of site-averaged v_r are list in Table 3. For the southwesterly case, due to a large open area in the southwest region, v_r is relative high. It is 0.11 and 0.16 in the 400m × 400m and the 600m × 600m averaged region, respectively. For the easterly case, v_r is only 0.08 in the centre of the high-density urban zone. It increases to 0.10 in the 600m × 600m averaged region when more open areas are included.

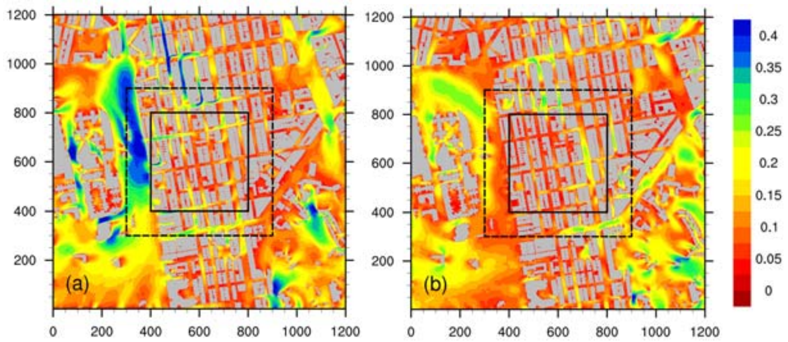

Fig. 1 PALM simulated wind velocity ratio (v_r) in a realistic urban area of Mong Kok, Hong Kong with (a) Southwesterly input, and (b) Easterly input. The solid (dashed) boxes show the domain of 400m × 400m (600m × 600m) for calculating site-averaged v_r.

Table 3 PALM calculated site-averaged wind velocity ratio (v_r) in a realistic urban area of Mong Kok, Hong Kong

Domain size for calculating v_r		400m × 400m	600m × 600m
Wind direction	Southwesterly	0.11	0.16
	Easterly	0.08	0.10

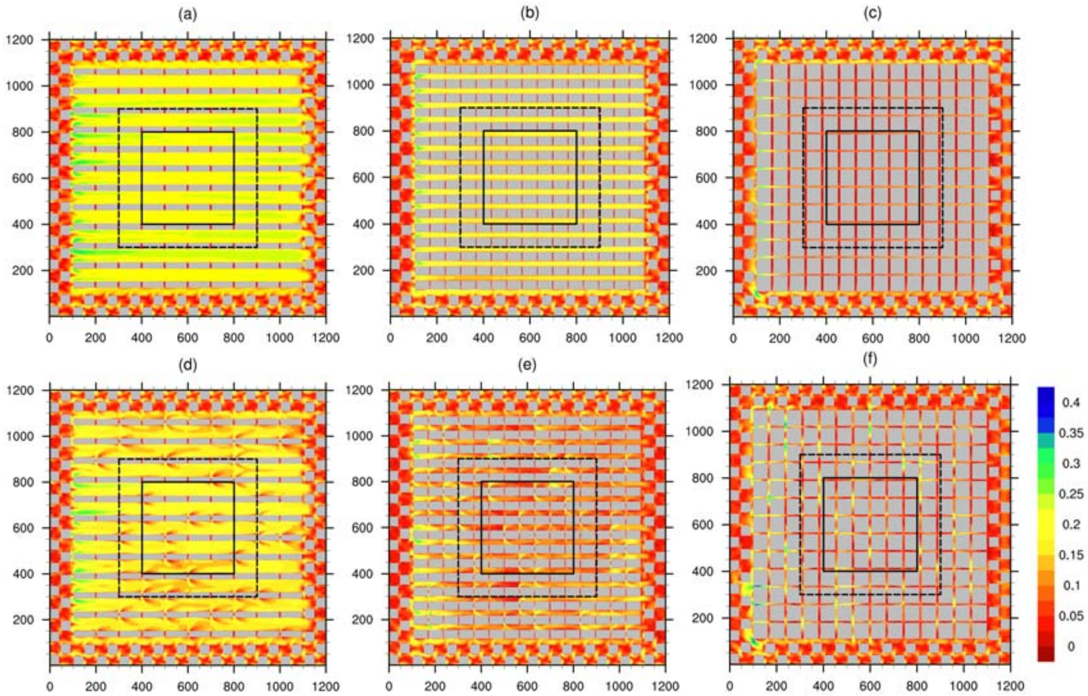

Fig. 2 PALM simulated v_r in parametric models. (a), (b), and (c) are homogeneous low-density, medium-density, and high-density, respectively. (d), (e), and (f) are inhomogeneous low-density, medium-density, and high-density, respectively. The solid (dashed) boxes show the domain of 400m × 400m (600m × 600m) for calculating site-averaged v_r.

Simulations in the realistic urban area imply that air ventilations are significantly affected by urban morphologies. The distributions of v_r in all six representative parametric models calculated by PALM are shown in Figure 2. The values of v_r in around the outer blocks are rather low, suggesting these blocks can prevent the incoming wind (from the left hand side) goes into the urban canyon directly. In Figure 2a, b, and c, it is apparent that the v_r decrease dramatically from low to medium and high density models, as one may has expected. Site-averaged v_r are calculated in the two domains in the urban centre, same as the approach in the realistic urban area. These site-averaged values are listed in Table 4. As urban morphologies such as street patterns and building sizes are uniform in the parametric model, not like the realistic urban area, site-averaged v_r does not change much in two average domains. In the low-density parametric model, it is 0.20 for the homogeneous (height differential) case, and 0.16 for the inhomogeneous case. In the medium-density parametric model, it is 0.14 for the homogeneous case, and 0.09 for the inhomogeneous case. In the high-density parametric model, it is 0.05 for the homogeneous case, and 0.07–0.08 for the inhomogeneous case. Therefore, it seems that in the low-density and medium-density models, inhomogeneous building heights decreases pedestrian level ventilations, while in the high-density model, it increases pedestrian level ventilations.

Table 4 PALM calculated site-averaged v_r in six parametric models

Model Density	**Homogeneous** 400m × 400m (600m × 600m)	**Inhomogeneous** 400m × 400m (600m × 600m)
Low	0.20 (0.20)	0.16 (0.16)
Medium	0.14 (0.14)	0.09 (0.09)
High	0.05 (0.05)	0.07 (0.08)

3.2 Simulations of unstable stratifications

In the simulations of unstable atmospheric stratifications, non-cyclic boundary conditions are applied in the streamwise direction, so that the wind leaving at the outflow does not re-enter at the inflow. In the spanwise direction, cyclic boundary conditions are adopted. In order to guarantee a turbulent inflow, we used a turbulence recycling method, which needs a precursor run for generating the initial turbulence field of the main run. The precursor run is allowed to have a smaller domain along x and y than the main run. In such a case, the domain of the main run is filled by cyclic repetitions of the precursor run data. The turbulent signal imposed at the inlet is taken from a recycling plane which is placed at a fixed distance from the inlet. Topography should be placed sufficiently downstream, so that it does not affect the inflow turbulence.

Preliminary results for a simulation of unstable stratification over the Kowloon Peninsula in Hong Kong are achieved. In this case, the domain size of the precursor run is 3072m × 3072m × 2650m. A geostrophic wind of 1.5m/s from the southwest, surface heat flux of 0.165 K m/s (i.e., 200 W/m^2), constant potential temperature of 308K profile beneath 700m height and a capping inversion on top with 0.1K / 100m gradient, are prescribed. The simulation time is 7200s. Figure 3 shows the profiles of horizontal wind speed components (u, v), and temperature (θ) profiles from the precursor run at the last time step.

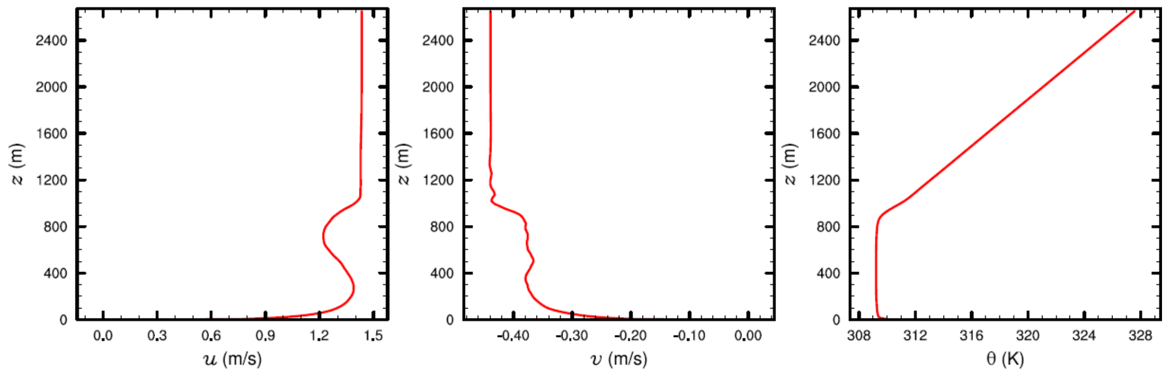

Fig. 3 Horizontal wind velocity components (u, v) and temperature (θ) profiles calculated by the precursor run at the last time step.

For the main run, the domain size is 9984m ×6144m × 2650m, the recycling plane locates at 3072m, the distance from inflow boundary to city is 5km, the distance from city to outflow boundary is 1km, and the simulation time is 3600s. Distributions of v_r over Kowloon Peninsula at the first vertical grid level and the last time step in this simulation of unstable atmospheric condition are shown in Figure 4. However, these results are from the very first simulation, where we still have some problems to solve. So far we used a constant heat flux in horizontal direction. This means that the sea surface has the same heat flux as the land surface. This will be changed in future simulations, i.e., reduced heat flux over sea surface.

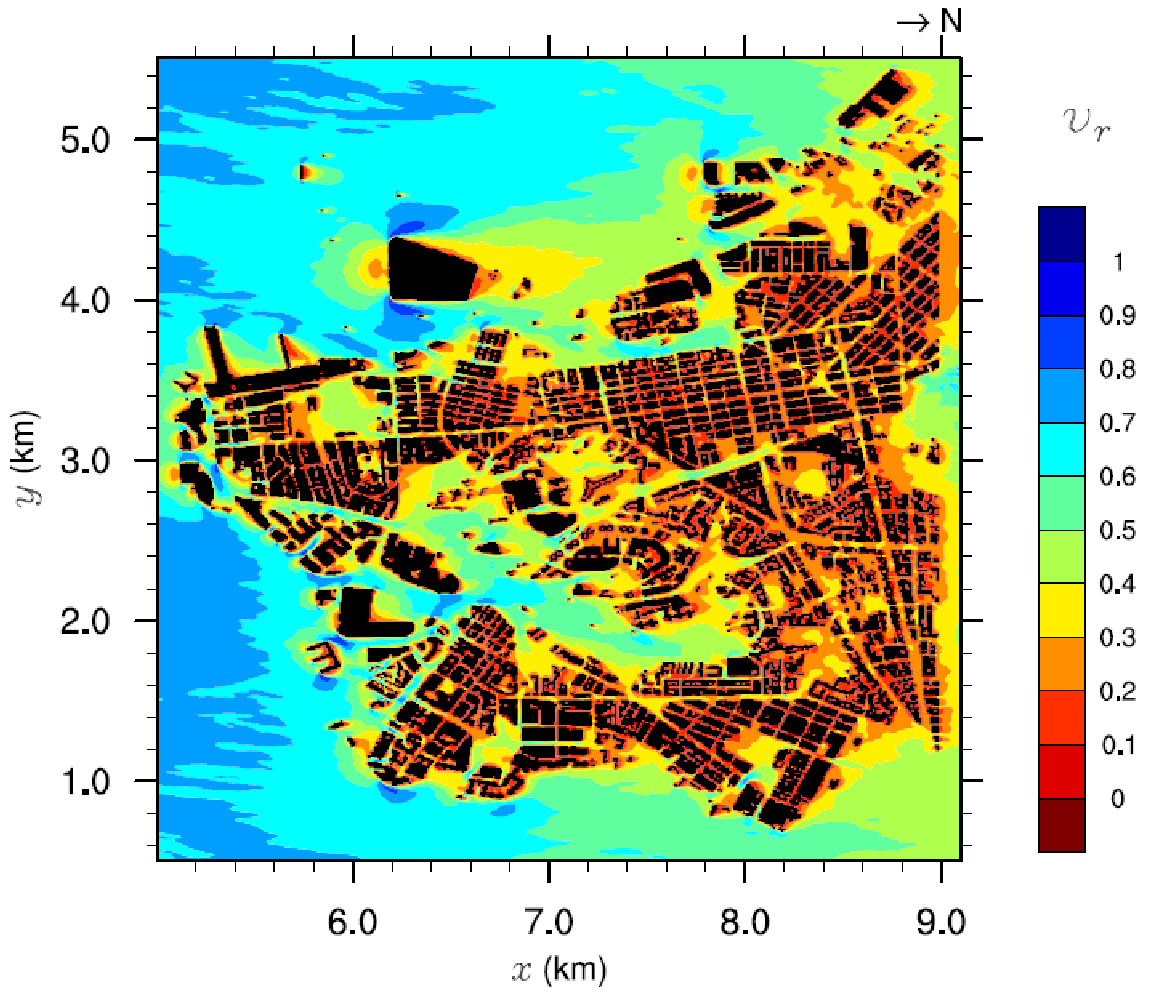

Fig. 4 Distributions of v_r in Kowloon Peninsular under unstable atmospheric stratification simulated by PALM

4. Discussion and conclusions

Urban air ventilation studies of neutral atmospheric conditions are justified by the assumption that the urban canopy layer is neutrally stratified due to the additional strong mixing induced by the buildings. This is the case under the assumption of medium/strong background winds. For weak background winds, the atmospheric stratification will become an important factor, large eddies at city scale will affect the pedestrian level wind environment. High-resolution LES for unstable atmospheric conditions covering whole city districts has never been carried out in the past and it will allow a very essential step towards simulations of the real world, overcoming the former limitations of RANS and wind tunnel studies.

The PALM model is optimized for running on massively parallel computers. It can perform on huge numerical grids, making it appropriate for use in studies involving very large domains (10–20km) of very fine scale grids (1–2m). Such features can support a rigorous investigation so as to scrutinize the coupling effect of the large-scale convective eddies of the free atmosphere together with the wind condition at the pedestrian level. Our recent study conducted a large area (154km^2) and fine grid (2m) simulation of Macau under neutral atmospheric conditions (Keck et al. 2014), which shows the capability of PALM to cope with the large meso/urban scale and the small street/building scale at the same time.

The present study demonstrates the use of PALM for urban ventilation studies by adopting a parametric approach, as well as a simulation for unstable stratification over the Kowloon Peninsula using non-cyclic boundary conditions. However, this is an ongoing study and the results achieved so far are very preliminary and in need of further improvements. Preliminary features of impacts of urban morphologies on air ventilations can be observed from Figure 2, which presents simulations of three representative scenarios. A combination of all parameters given in Table 1 can obtain a total of 54 scenarios. A comprehensive investigation of all these scenarios in the next step will achieve more insights of the issue. More importantly, large domain simulations of both realistic and parametric scenarios under different types of atmospheric stratification will be conducted. A comparative study on simulations of air ventilations under neutral and unstable conditions will fill the above mentioned knowledge gap between the current practice and the real situations.

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