LES studies on pedestrian level ventilation in Hong Kong

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Abstract

Hong Kong is one of the most densely built-up and populated cities in the world. An adequate air ventilation at pedestrian level would ease the thermal stress in its humid subtropical climate, but the high-density city severely reduces the natural ventilation.

This project uses the parallelized large-eddy-simulation (LES) model PALM to investigate pedestrian level ventilation in Kowloon. The results contribute to the development of guidelines for urban planning in Hong Kong. A sensitivity study is carried out to quantify the dependence of PALM on numerical and physical parameters and to determine an appropriate urban LES set-up for two 1 km^2 test sites in Kowloon (Tsim Sha Tsui, Mong Kok) that are investigated for prevailing E and SW wind. Furthermore, the influence of a new, very tall building on Tsim Sha Tsui ventilation is assessed. Results reveal the critical dependence of ventilation on several parameters. Isolated tall buildings may have a pronounced impact on ventilation both locally and downstream.

Key words: urban large-eddy simulation, high-density city, pedestrian level ventilation

1. INTRODUCTION

Urban human comfort in the high-density city Hong Kong suffers from environmental problems due to climatic conditions (hot and humid summers) and local and regional air pollution. After Hong Kong was hit by the severe acute respiratory syndrome (SARS) in 2003, Team Clean (2003) recommended a mandatory air ventilation assessment (AVA) for all future (re)development projects in Hong Kong. AVA focusses on weak wind conditions typical of Hong Kong's high building density following the motto “the more wind the better” (Ng, 2009).

Outdoor thermal comfort depends mainly on wind velocity, air temperature, radiation and humidity (Cheng and Ng, 2006). AVA seeks only to enhance pedestrian level ventilation as the most important factor for Hong Kong. The wind velocity ratio v_r is used as a simple ventilation indicator; v_r=v_p-v_{inf} is defined as the ratio of the wind velocity v_p at pedestrian level, 2 m above ground, and v_{inf} well above the roof tops. Hong Kong typically has v_{inf}=6 to 8 m/s at 500 m above ground and v_r ranging from 0.05-0.1 in streets/congested quarters to 0.3 near the water-front/in open spaces (Ng, 2009). So v_p ranges from 0.3 to 2.4 m/s. This is insufficient for outdoor thermal comfort in summer Hong Kong; Cheng and Ng (2006) demand at least v_p=1 m/s, which implies $v_r \geq 0.15$.

The main purpose of this study is to quantify the influence of numerical and physical parameters on the site-averaged ventilation. Such parameters include buffer size around the assessment area, simulation/averaging time and vertical grid size; Reynolds number, local roughness length and measurement locations. Using the appropriate set-up, two 1 km^2 test sites in Kowloon (Tsim Sha Tsui/TST, Mong Kok/MK) are investigated for prevailing E and SW wind, and the influence of a new, very tall building on Tsim Sha Tsui ventilation is assessed.

2. MODEL DESCRIPTION

Classical tools to assess the urban wind environment are the wind tunnel and standard computational fluid dynamics (CFD) models. The wind tunnel is a robust and reliable tool (Ng, 2009), but not cheap. Also, it normally cannot capture land-sea breeze or mountain-valley breeze circulations in Hong Kong (cf. Yan, 2007). Nested CFD models may overcome this. Reynolds-Averaged Navier-Stokes (RANS) models, standard CFD in wind engineering, have low computational cost but known deficiencies in building wakes (e.g. Mochida and Lun, 2008) and urban weak wind regions (Yoshie et al., 2007). Yet these are critical for AVA in Hong Kong.

This feasibility study introduces urban large-eddy simulation (LES) as an alternative assessment tool without these deficiencies. Improved data quality and quantity of LES come at much higher CPU cost, but today's supercomputers and efficient parallel algorithms make urban LES applications feasible (Tamura, 2008). This study uses the urban version of the parallelized LES model PALM (Letzel et al., 2008). PALM is a model for the atmospheric or oceanic boundary layer that is highly parallelized (MPI, OpenMP) with single processor optimization for different processor architecures, so it is suitable for computational challenges such as urban LES. Solid obstacles are explicitly resolved on the Cartesian grid by a mask method (simplified version of Briscolini and Santangelo, 1989). PALM here simulates an isothermal, dry urban boundary layer, using cyclic lateral boundary conditions, no-slip conditions at the bottom and free-slip conditions at the top. An external pressure gradient drives the flow (no Coriolis force) so that volume flow is conserved. A 1D wind profile based on a priori information is used for initialization. GIS data (buildings, gentle [20~40 m] hills) are input into PALM using GRASS GIS.

3. SITE DESCRIPTION

Two urban areas (TST & MK) in Hong Kong have been selected for this study. Both areas are on the Kowloon penisula of Hong Kong's territory. The annual prevailing winds are from E, and the summer prevailing winds are from SW. Both areas are nearly flat; both have very high living density of some 50,000 to 70,000 persons per square kilometer; and both have tall buildings and narrow streets.

TST is located at the tip of the penisula. The eastern waterfront has slightly lower building density and coverage. The centre part is very dense and with some very tall builidngs. The western part has bulkier buildings that occupy the entire waterfront. MK is located in the centre of the land mass. It has more regular and orthogonally laid out streets. There is a mixture of very tall buildings and many older and smaller buildings.

The two selected areas represent the typical urban morphological conditions of high density Hong Kong.

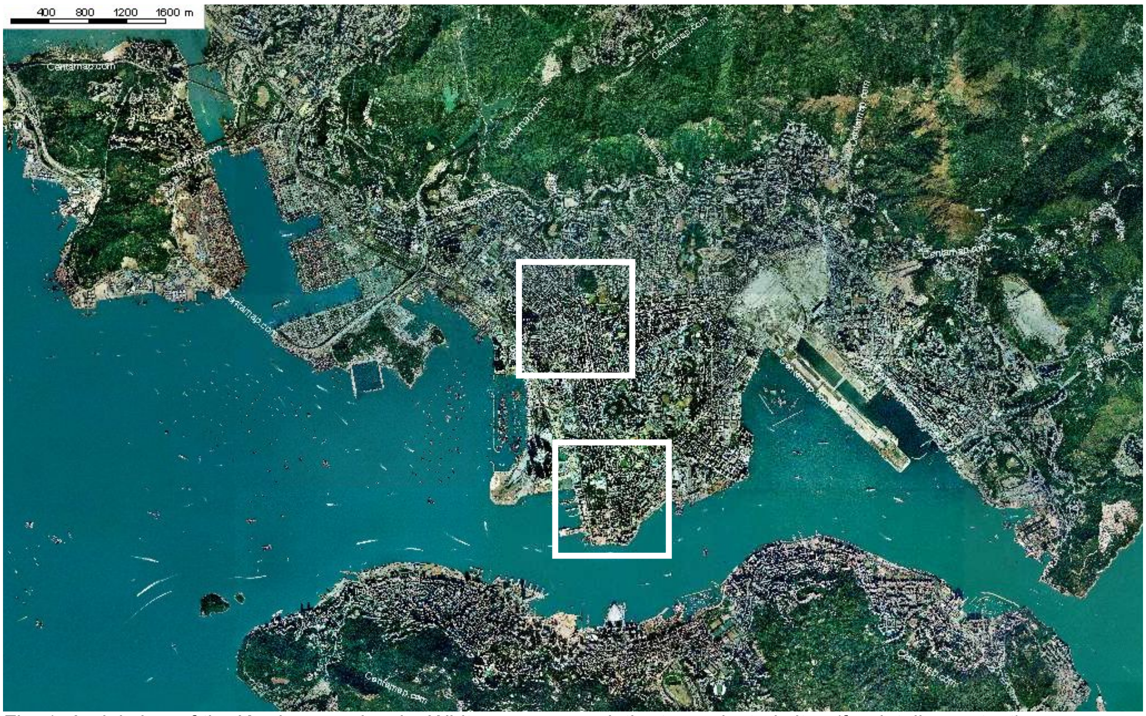


Fig. 1: Aerial view of the Kowloon peninsula. White squares mark the two selected sites (for details see text).

4. RESULTS

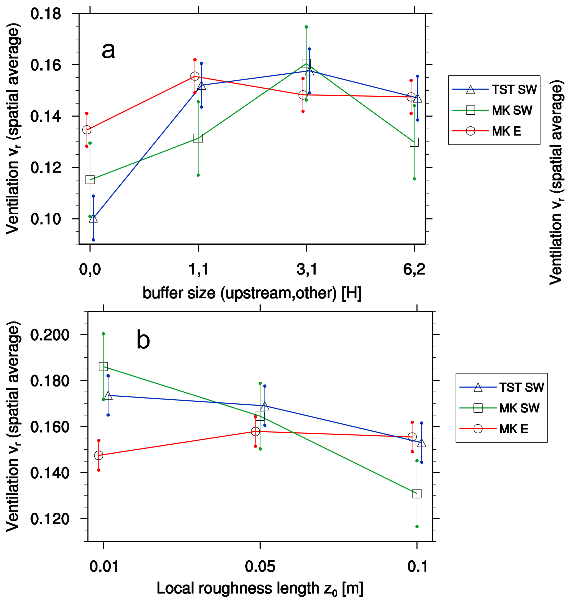
4.1. Sensitivity Study

The sensitivity study quantifies the influence of numerical and physical parameters on the site-averaged ventilation: buffer size around the assessment area, simulation/averaging time and vertical grid size, Reynolds number, local roughness length and horizontal measurement locations. The test simulations in this section have a reduced assessment area of $(320\ m)^2$ and a reduced grid size of $\Delta_{x,y}$=2.5 m, Δ_z=2 m compared to the full-size, high-resolution assessment simulations in section 4.2. Each parameter study covers three cases: MK for E and SW prevailing wind and TST for SW prevailing wind, with a bulk velocity of 1.5 m/s unless otherwise stated.

Since LES models explicitly resolve turbulence – as opposed to RANS CFD models – one has to allow for this turbulence to develop and reach a quasi-steady state during the initial “spin-up phase” of an LES, plus for a sufficiently long “averaging time” for adequate statistics. The total simulation time is the sum of both. According to tests for TST and MK using a simulation time of up to 24 h (not shown), a **spin-up time** of 4 h plus an **averaging time** of 2 h are sufficient for calcuation of site-averaged pedestrian level ventilation.

AVA (Ng, 2009) demands a buffer of at least 1 H around the assessment area, where H is the height of the tallest building on site. This applies to wind tunnel or numerical experiments with inflow-outflow boundary conditions. At the time the LES experiments were conducted, however, only cyclic lateral boundary conditions were available in PALM, which necessitated sensitivity tests on the **minimum buffer size** in PALM. Four buffers have been tested (upstream buffer/buffer at 3 other sides, in units of H): (0,0), (1,1), (3,1), (6,2). Fig. 2a shows that, as expected, a zero (0,0) buffer is insufficient, since results significantly deviate from the other buffers. Results using the 3 other buffers agree quite well (within numerical uncertainty), which suggests that the AVA standard (1,1) buffer also applies to cyclic boundary conditions at these sites. However, there is an exception, MK SW buffer (3,1), where the site-averaged ventilation v_r is significantly enhanced caused by artificial lateral (spanwise) channeling. This example demonstrates that such buffers cannot just be adopted to new sites without careful quality assurance. However, for the purpose of this investigation the AVA standard (1,1) buffer is proven sufficient.

PALM's staggered grid implies a vertical grid size of Δ_z=0.8 m for the pedestrian level z_p=2 m (AVA). Moving this **measurement height** to 2.5 m would allow to use Δ_z=1 m. This saved ~22% of simulation cost in performance



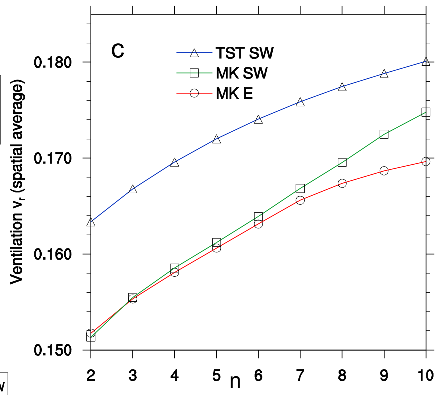


Fig. 2: Sensitivity of site-averaged ventilation v_r to (a) buffer size, (b) local roughness length and (c) horizontal measurement locations (calculation of site-average starts at the n^{th} grid point adjacent to vertical walls) for TST (SW wind) and MK (E and SW wind).

The x-ordinates of MK E and TST SW in panels (a) and (b) are slightly displaced for the sake of better visibility.

tests. Sensitivity tests (not shown) did not reveal any significant difference (within numerical uncertainty) between z_p=2 m (Δ_z=0.8 m) and z_p=2.5 m (Δ_z=1 m). Therefore using z_p=2.5 m (Δ_z=1 m) will be used in section 4.2.

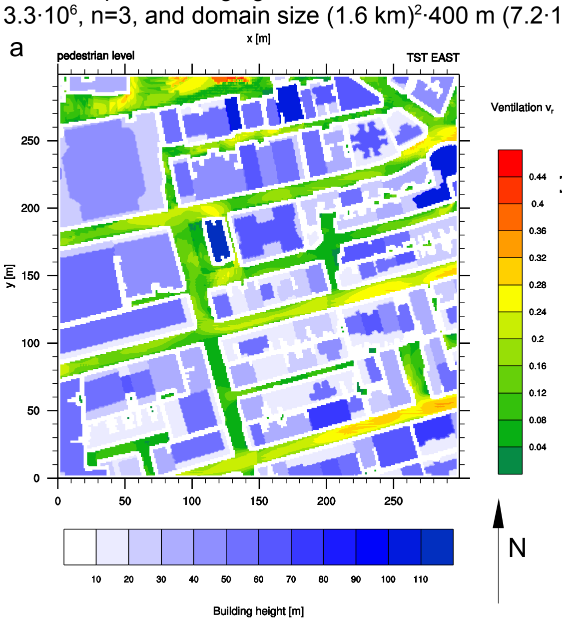
Some urban structures may not be included in the GIS data or may be subgrid-scale in PALM (e.g. projecting obstructions), yet they have the potential to slow down the flow. PALM increases the wall roughness to qualitatively account for their effect. As expected, the sensitivity of v_r to **local roughness length** z_0 (Fig. 2b) is significant, but only for TST SW and MK SW, not for MK E. This is probably due to the skimming flow observed in large parts of MK E, which leads to a very low ventilation regardless of the wall roughness.

As expected, in a fully turbulent regime v_r does not depend on **Reynolds number**, which was confirmed by tests comparing Re=$1.7{\cdot}10^6$, $3.3{\cdot}10^6$, $1.1{\cdot}10^7$ (not shown). This allows to save simulation cost by using a low $v_{inf}\approx$2 m/s.

AVA sets no clear standard on **representativeness of measurement locations**. For measurement accuracy, wind tunnel measurements are often done at canyon centers or open spaces, for example. Yet these locations mainly represent areas with relatively high v_r. Indeed, Fig. 2c highlights a strong dependency of v_r on horizontal measurement locations ("n"). Without a clear standard on representativeness, different AVA studies may not be comparable. In order to account for weak and strong wind regions alike, n=3 will be used in section 4.2.

4.2. Case studies

Based on section 4.1, the five high-resolution assessment simulations for MK and TST under E and SW prevailing wind (TST SW: with versus without a recently constructed 210 m tall building) have the following set-up: spin-up time 4 h plus averaging time 2 h, a buffer size of ~1 H in all directions, z_p=2.5 m ($\Delta_{x,y,z}$=1 m), z_0=0.1 m, Re= $3.3{\cdot}10^6$, n=3, and domain size (1.6 km)^2·400 m ($7.2{\cdot}10^8$ grid points). Figs. 3 & 4 show some exemplary results.



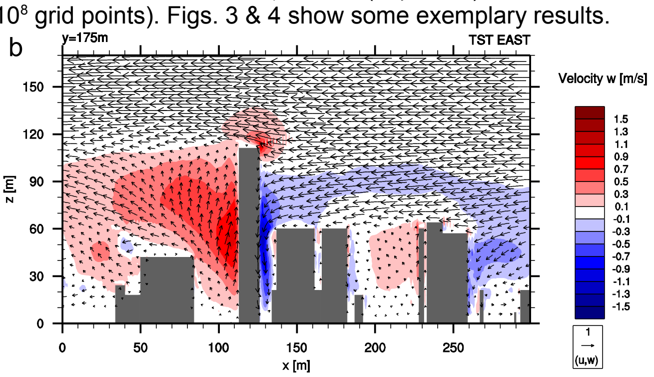
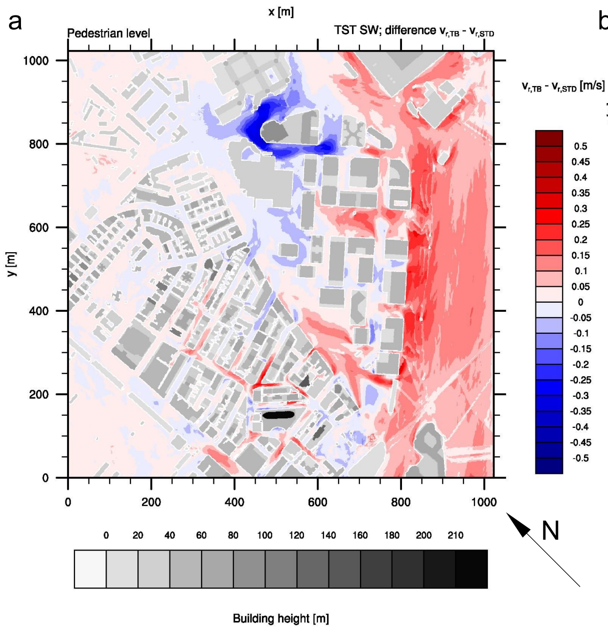


Fig. 3: Time-averaged ventilation pattern for TST E, zoomed into part of the assessment area.
(a) Horizontal cross-section of v_r at pedestrian level (v_r: green-red colour scale; building heights: white-blue colour scale). (b) Vertical (xz) cross-section of vertical velocity w at y=175 m with an overlay vector plot of the velocity components (u,w) in that sectional plane.



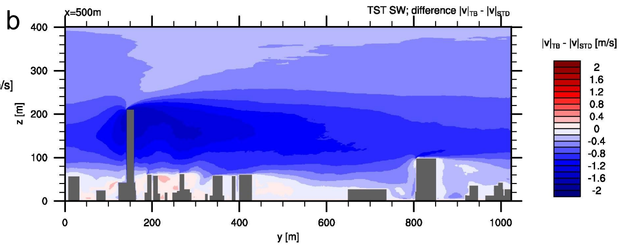


Fig. 4: *Difference* in time-averaged ventilation pattern for the 1 km^2 assessment area of TST SW *with (TB) minus without (STD)* a recently constructed 210 m tall building (visible in black at x=500 m, y=150 m).
(a) Horizontal cross-section of $v_{r,TB}$ - $v_{r,STD}$ at pedestrian level in blue-red colour scale (building heights in greyscale). (b) Vertical (yz) cross-section of absolute velocity difference $|v|_{TB}$ - $|v|_{STD}$ at x=500 m.

As expected for E wind, Fig. 3a shows large v_r in long, almost E-W oriented streets (thanks to channeling) and low v_r in streets that are laid out perpendicular to the ambient wind direction and in other areas without a connecting ventilation path.

Interestingly, the rather isolated 110 m tall building at y=175 m locally also enhances v_r. Fig. 3b clearly demonstrates that this is due to vertical advection: the large downdraught upstream/updraught downstream must be balanced by a strong low (pedestrian) level flow around this building. This example shows that isolated tall buildings have the potential to locally enhance v_r.

However, the downside of isolated tall buildings is that they reduce wind availability further downstream, which can affect a large wake area (Kataoka et al., 2007). Fig. 4a shows that for SW wind, the new 210 m tall building leads to a dramatic reduction of v_r in a region as far as 600~700 m (~3H !) downstream because its large wake reduces wind availability at roof level in that region (z=100m, y=800~850m, Fig. 4b).

5. IMPLICATIONS

The **sensitivity study** suggests that cyclic LES with 1H buffer is acceptable to obtain v_r for nearly flat sites. The observed strong dependence of v_r on roughness and measurement locations, for which AVA sets no clear standards, points at possible AVA clarifications. **Case studies** revealed the ambivalent character of isolated tall buildings: *locally* they may enhance v_r, but they can reduce wind availability as far as 3H *downstream*. To account for these adverse downstream effects, the required AVA assessment area (radius ≥1H) should be enlarged.

However, this urban LES feasibility study only used a very limited number of test sites and approach wind conditions. Therefore, any implied AVA improvements must be considered tentative until a possible *universal validity* has been confirmed by parametric studies on idealized, generic city quarters. Since these were beyond the scope of this feasibility study, they are recommended for further research.

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