Meteorologische Zeitschrift, Vol. **21**, No. 6, 575–589 (December 2012)

Open Access Article

LES case study on pedestrian level ventilation in two neighbourhoods in Hong Kong

MARCUS OLIVER LETZEL[1,2,*], CAROLIN HELMKE[1], EDWARD NG[3], XIPO AN[3], ALAN LAI[3] and SIEGFRIED RAASCH[1]

[1]Institute of Meteorology and Climatology, Leibniz Universität Hannover, Herrenhäuser Str. 2, 30419 Hannover, Germany
[2]Current affiliation: Ingenieurbüro Lohmeyer GmbH & Co. KG
[3]School of Architecture, Chinese University of Hong Kong, Shatin, NT, Hong Kong

(Manuscript received December 1, 2011; in revised form August 8, 2012; accepted October 22, 2012)

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 case study investigates pedestrian level ventilation in two neighbourhoods in Kowloon, downtown Hong Kong using the parallelized large-eddy-simulation (LES) model PALM. The LES technique is chosen here for a city quarter scale pedestrian comfort study despite of its high computational cost. The aims of the paper are a) to get a comprehensive overview of pedestrian level ventilation and a better understanding of the ventilation processes in downtown Hong Kong, b) to test the LES technique on this urban scale compared to the wind tunnel and c) to investigate how numerical/physical parameters influence ventilation. This case study is restricted to neutral stratification in order to allow a direct comparison with the wind tunnel. A sensitivity study quantifies the dependence of site-averaged ventilation on numerical and physical parameters and determines an appropriate urban LES set-up for two 1 km^2 neighbourhoods in Kowloon (Tsim Sha Tsui, Mong Kok) that are investigated for prevailing E and SW wind. The results reveal the critical dependence of ventilation on the urban morphology. Air paths, street orientations, ground coverage, sites fronting the water, inter connectivity of spaces, building podium size and building heights can all affect the pedestrian wind environment. Isolated tall buildings may have a pronounced impact on ventilation both locally and downstream.

Keywords: urban large-eddy simulation, high-density city, wind environment, pedestrian level ventilation, Hong Kong.

1 Introduction

Since 2006, more than 50% of the world's population lives in cities. By 2007, 19 cities have a population of more than 10 millions. This number is increasing, and by 2025 it is expected that more than 26 cities would have a population of more than 10 millions (UN-HABITAT, 2008). Moreover, in order to cope with the increase of city dwellers, designers and planners are now designing higher density cities of more compact urban forms (NG, 2010). Buildings are taller, streets are narrower, and cities will have smaller and lesser open spaces. The environmental consequences of high density compact city, especially in cities in the tropics and sub-tropics, are that solar access, daylight, and city ventilation are compromised. On the other hand, the urban heat island effect is intensified and air pollution is worsened, partly due to the decrease of urban ventilation because of the taller, bulkier and more closely packed buildings of the city. Current and future urban planning needs to consider urban climate (MILLS et al., 2010; NG, 2012). Urban climatic maps are a tool to assist urban planers and designers with this task (REN et al., 2011).

This world trend towards high density living can be epitomized in the case of Hong Kong, a city of 7.5 million situated on the south-east coast line of China at the latitude of 23 degree north. Hong Kong has one of the world's highest city population densities of some 60,000 persons per square kilometer. In some development sites in the city core, it is not atypical to have a site development density of two to three thousand inhabitants per hectare (COX, 2011; NG and WONG, 2004).

After Hong Kong was hit by the severe acute respiratory syndrome (SARS) in 2003, one of the recommendations by TEAM CLEAN (2003) to improve the urban living environment was a mandatory air ventilation assessment (AVA) for all future (re)development projects in Hong Kong. Contrary to planning guidelines for strong wind conditions in other countries, AVA focusses on weak wind conditions that are typical of Hong Kong's high building density, following the motto "the more wind the better" (NG, 2009).

*Corresponding author: Marcus Oliver Letzel, current affiliation: Ingenieurbüro Lohmeyer GmbH & Co. KG, An der Roßweid 3, 76229 Karlsruhe, Germany, e-mail: letzel@muk.uni-hannover.de.

DOI 10.1127/0941-2948/2012/0356
0941-2948/2012/0356 $ 6.75

Outdoor thermal comfort depends mainly on wind velocity, air temperature, radiation and humidity (CHENG and NG, 2006). As a first step, 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; $v_r = v_p/v_\infty$ is defined as the ratio of the wind velocity v_p at pedestrian level, 2 m above ground, and v_∞ at a height well above the roof tops where the flow does not "feel" the underlying city any longer (here: top of model domain). For outdoor thermal comfort in summer Hong Kong CHENG and NG (2006) demand at least v_p = 1 m/s, which implies $v_r \geq 0.15$ given a typical v_∞ = 6 to 8 m/s at 500 m above ground (HONG KONG OBSERVATORY, 2011; YIM et al., 2007). Actually, site-averaged values of v_r in Kowloon, Hong Kong range from 0.05-0.1 in streets/congested quarters to 0.3 near the waterfront/in open spaces (NG, 2009). Hence, large parts of the city need to increase their pedestrian level ventilation.

Assessment tools

City scale wind movement and air ventilation at coarse resolutions of around a hundred meters have been studied using various mesoscale and urban canopy models. This allows a generic areal average understanding of the effects of various urban parameters on the urban climate of the city (LIN et al., 2008; ATKINSON, 2003; CIONCO, 1997). For more detailed information, classical assessment tools are the wind tunnel and standard computational fluid dynamics (CFD) models. The wind tunnel is a robust and reliable tool (NG, 2009), yet it may not be practical for all future AVA projects due to its cost. Also, it normally cannot capture the complex meso-scale wind field associated with land-sea breeze and mountain-valley breeze circulations in Hong Kong (cf. YAN, 2007). Coupling CFD with mesoscale models may overcome this (cf. SCHLÜNZEN et al., 2011; XIE, 2011).

Reynolds-Averaged Navier-Stokes (RANS) models, standard CFD in wind engineering, are designed for low computational cost; they filter out and parameterize all turbulent fluctuations of the air flow. However, there are known RANS deficiencies in building wakes (e.g. MOCHIDA and LUN, 2008; RODI et al., 1997) and urban weak wind regions (YOSHIE et al., 2007), i.e. especially within the urban canopy. Yet these are critical for Hong Kong AVA.

Large-eddy simulation (LES) is an advanced CFD model class. First, LES overcomes the RANS deficiencies (RODI et al., 1995). This is because LES by definition explicitly resolves the large, energy containing turbulent eddies, and only small (subgrid) scale turbulence still needs to be parameterized (SAGAUT, 2006). Second, LES delivers additional data that are not available from RANS: since LES explicitly resolves turbulent fluctuations in space and time, peak values (velocities, concentrations) and higher order statistics can be directly computed from LES data like from wind tunnel data. Third, LES can collect simultaneous 3D data which is still impossibe in the wind tunnel. The significantly improved data quality and quantity of LES come at much higher CPU cost (and hardware requirements) than RANS, but today's supercomputers and efficient parallel algorithms make urban LES applications feasible (TAMURA, 2008). Given the ever rising computational power ("Moore's Law") and its reducing relative cost, urban LES assessments may become a standard within a few years.

With rapid development, CFD is now widely utilized for urban wind field studies (LI et al., 2006; BLOCKEN et al., 2011). Guidelines for practical applications of RANS-type CFD are available (TOMINAGA et al., 2008; FRANKE, 2006; FRANKE et al., 2011, 2004a,b; BARTZIS et al., 2004; SCAPERDAS and ATKINS, 2004; AIAA, 1988). There have been numerous CFD studies of urban ventilation at the city scale using various techniques and different simplification schemes (SKOTE et al., 2005; COCEAL and BELCHER, 2005; COCEAL et al., 2006). Parametric understandings using simplified arrays that mimic the urban reality have also been carried out (HANNA et al., 2002; MACDONALD, 2000; CHU et al., 2005; YANG and LI, 2011).

Increasingly, researchers are now performing local modelling with realistic urban cases (TOMINAGA et al., 2004; YOSHIE et al., 2007; LIU et al., 2011). TSENG et al. (2006) studied an area with some 30 buildings of Baltimore, MD, XIE and CASTRO (2009) studied an intersection in central London using a domain of 1.2 km·0.8 km·0.2 km containing some 50 buildings. AKASHI (2008) conducted CFD studies of 2.5 km·1.5 km·0.5 km in central Tokyo. Various scenarios have been tested. The pedestrian level wind velocities and air temperatures of different designs have been compared so as to identify the optimized solution.

The most notable recent example has been a large domain RANS study by ASHIE and KONO (2011) on the metropolitan area of Tokyo. An area of 33 km·33 km covering Tokyo's 23 wards has been studied with $5 \cdot 10^9$ grid points using 300 nodes of the Earth Simulator. The results allow detailed investigation of the horizontal distribution of 2 m air temperature, wind speed and direction. The information allows focused areas to be defined for further studies.

Case study

In the present paper, the LES technique is chosen for a pedestrian comfort case study on the scale of an entire city quarter despite of its high computational cost because it outperforms conventional CFD (RANS) models in building wakes and weak wind regions (KATAOKA et al., 2007) which are known to dominate the assessment areas in Hong Kong. The aims of the paper are a) to get a comprehensive overview of pedestrian level ventilation and a better understanding of the ventilation processes in downtown Hong Kong, b) to test the LES technique on this urban scale compared to the wind tunnel and c) to investigate how numerical/physical parameters influence ventilation. The results contribute to the development of guidelines for urban planning practice in Hong Kong, e.g. urban climatic maps.

Some distinct advantages of LES over RANS models, e.g. the ability to directly calculate wind gustiness or other higher-order statistics, are not explored here.

The aims of this study imply two limitations. First, this study is restricted to neutral stratification without Coriolis force, which is required for a direct comparison with the wind tunnel. I.e., thermal effects on street canyon circulations (e.g. BOHNENSTENGEL et al., 2004; OFFERLE et al., 2007; LI et al., 2010; CAI, 2012; PARK et al., 2012) in a high-density city due to e.g. radiation effects and anthropogenic heat release are excluded. From a scientific point of view, this initial approach may need to be complemented by a consideration of stratified situations at some later stage. However, for now, the agreed priorities and methodologies for actual urban planning practice in Hong Kong (NG, 2009) imply this simple, initial approach.

Second, the requested urban LES on a scale as large as a real-city quarter has a high computational load. This makes a case study imperative: only a small number of selected real-city cases can be simulated. I.e., the results of this study are not necessarily generalizable. More generic results can be obtained using generic/idealized geometries (e.g. XIE et al., 2008; YOSHIE et al., 2008). According to the classification of generic and applied CFD studies by GOUSSEAU et al. (2011) this study is an applied CFD study.

The paper is organized as follows. The LES model and the test sites are briefly described in sections 2 and 3, respectively. The results section 4 is divided into a sensitivity study (4.1) and case studies (4.2). In section 4.1, the influence of numerical and physical parameters on the site-averaged ventilation is quantified. Such parameters include buffer size around the assessment area, *simulation*/averaging time and vertical grid size, Reynolds number, local roughness length and measurement locations. Section 4.2 presents several case studies. Using the appropriate set-up, two 1 km^2 test sites in Kowloon (Tsim Sha Tsui/TST, Mong Kok/MK) are investigated in subsection 4.2.1 for annual prevailing E and summer prevailing SW wind (HONG KONG OBSERVATORY, 2011), and the influence of a new, super tall building on Tsim Sha Tsui ventilation is assessed. LES results are validated based on a cross-comparison between LES and wind tunnel results for the test sites in subsection 4.2.2, followed by LES v_r comparison studies and a comparison of ventilation in Hong Kong and Tokyo in subsections 4.2.3 and 4.2.4, respectively. Section 5 discusses practical implications of this study for urban design, followed by general conclusions in section 6.

2 Model description

This study uses the parallelized LES model PALM (RAASCH and SCHRÖTER, 2001; LETZEL et al., 2008a). PALM is a model for the atmospheric or oceanic boundary layer that is highly parallelized (MPI, OpenMP) with single processor optimization for different processor architectures, so it is suitable for computational challenges such as urban LES. Solid obstacles are explicitly resolved on the Cartesian grid by a simplified mask method (BRISCOLINI and SANTANGELO, 1989). PALM is validated for urban flow/flow around solid obstacles (LETZEL et al., 2008a; KANDA et al., 2012). PALM has been applied to real urban morphologies of European and Asian type (LETZEL et al., 2008a,b, LETZEL et al., 2012; KANDA et al., 2012; TACK et al., 2012).

PALM is a finite difference model; it calculates the non-hydrostatic, incompressible Boussinesq equations, the 1st law of thermodynamics and equations for subgrid-scale (SGS) turbulent kinetic energy (TKE) and scalar conservation; the equations are filtered implicitly following the volume-balance approach (SCHUMANN, 1975). Turbulence closure uses the 1½th order DEARDORFF (1980) scheme. The wall model assumes a Prandtl layer at each surface (Monin-Obukhov similarity). Variables are staggered according to the marker-and-cell method/Arakawa C grid (HARLOW and WELCH, 1965; ARAKAWA and LAMB, 1977). The second-order advection scheme by PIACSEK and WILLIAMS (1970) is used. The 3rd-order Runge-Kutta scheme is used for time integration. Incompressibility is ensured by the fractional step method, and the resulting Poisson equation for the perturbation pressure is solved by the default FFT pressure solver.

In this study, PALM simulates an isothermal, dry urban boundary layer, using cyclic horizontal boundary conditions (cf. section 4.1), a Prandtl layer as rough wall function at the bottom and free-slip conditions at the top. The atmospheric flow is controlled by a direct, external pressure gradient (no Coriolis force) to maintain a constant bulk velocity u_b. The bulk velocity u_b is defined as the arithmetic average velocity of a vertical cross-section perpendicular to the mean wind direction. A 1D wind profile based on a priori information is used for initialization. Digital Elevation Model (DEM) data of 1 m resolution (buildings up to ~210 m, gentle hills up to 20~40 m height) are converted into PALM bottom topography using GRASS GIS (http://grass.osgeo.org/, NETELER and MITASOVA 2007).

3 Site description

Two urban areas (TST & MK) in Hong Kong have been selected for this study. Both areas are on the Kowloon peninsula of Hong Kong's territory (FIG. 1 shows the assessment areas used for the case studies TST E and MK E in section 4.2). The annual prevailing winds are

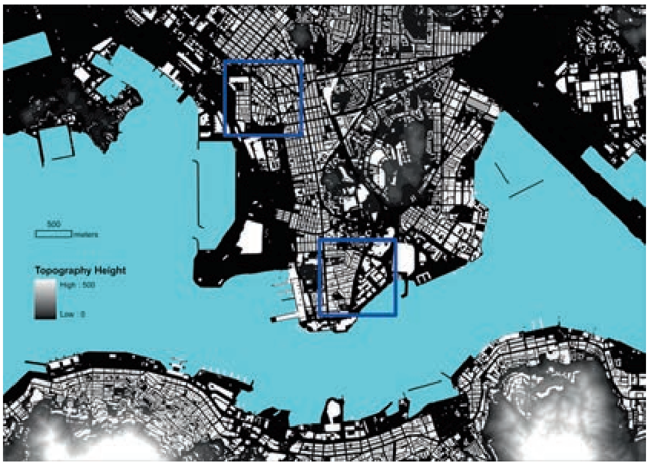

Figure 1: Topographic map of the Kowloon peninsula. Blue squares mark the assessment areas of the two selected sites, Mong Kok in the North and Tsim Sha Tsui in the South (for details see text).

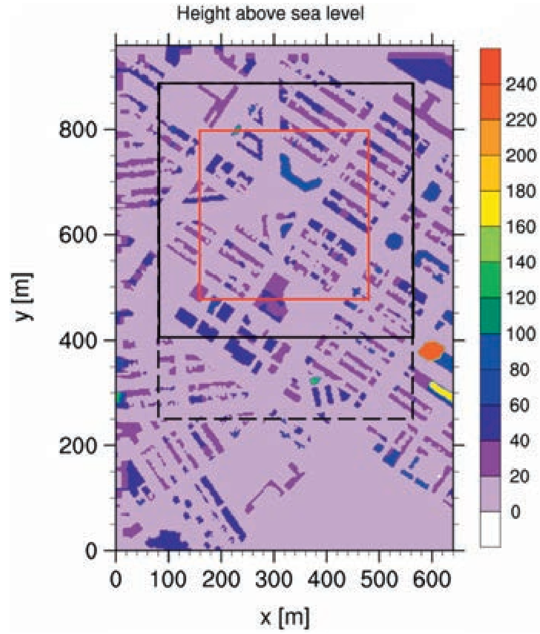

Figure 2: Topography and different buffer sizes of the sensitivity study MK SW. Red frame: assessment area (buffer 0H upstream, 0H other sides), black frame: (1H, 1H buffer), black dashes: (3H, 1H buffer), whole plot: (6H, 2H buffer); wind direction: ↑. The domain has been rotated against N for SW inflow.

from E, and the summer prevailing winds are from SW (Hong Kong Observatory, 2011). Both areas are nearly flat; both have very high living density of some 50,000 to 70,000 persons per square kilometer (Cox, 2011); and both have tall buildings and narrow streets (Chen and Ng, 2011).

TST is located at the tip of the peninsula. The eastern waterfront has slightly lower building density and coverage. The centre part is very dense with some very tall buildings. 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.

4 Results

4.1 Sensitivity study

Pedestrian level ventilation v_r in high-density cities is highly influenced by the complex urban morphology. Since the site-averaged v_r serves as an indicator for architects and urban planners to judge the effect of proposed (re)developments, v_r should be highly site-dependent but free from external influence such as experimental or meteorological conditions. The sensitivity study quantifies the influence of selected external numerical and meteorological 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 horizontally reduced assessment area of 320·320 m^2 and a coarser grid size of $\Delta_{x,y}$ = 2.5 m, Δ_z = 2 m compared to the full-size, high-resolution assessment simulations of the case studies in section 4.2. This is unavoidable due to computational limitations in view of the large number of test simulations. The vertical grid size is constant within the urban canopy and stretched starting well above the tallest building up to $\Delta_{z,\max}$ = 3 m. Each parameter study covers three cases: MK for E and SW prevailing wind and TST for SW prevailing wind, with bulk velocity u_b = 1.5 m/s unless otherwise stated.

Since LES models explicitly resolve turbulence – as opposed to RANS models – one has to allow time 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. For each of the three cases, the standard deviation of ten non-overlapping 2 h time averages of v_r (between t = 4 h and 24 h) is used for the error bars in Figs. 3 and 4 below.

AVA (Ng, 2009) demands a buffer zone of at least 1 H around the assessment area, where H is the height of the tallest building on site, which may relax the domain size requirements by Franke et al. (2011) and Tominaga et al. (2008). This applies to wind tunnel or numerical experiments with inflow-outflow boundary conditions. At the time the LES experiments were conducted, however, only cyclic horizontal boundary conditions were available in PALM, which necessitated sensitivity tests on the **minimum buffer size** in PALM.

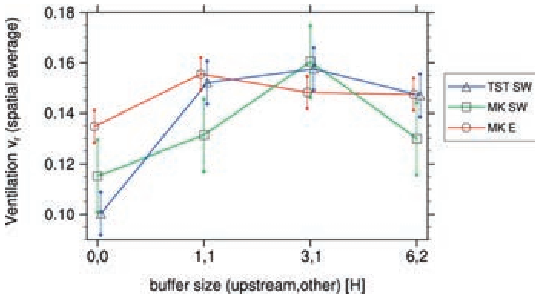

Figure 3: Sensitivity of site-averaged ventilation v_r to buffer size (H) for TST (SW wind) and MK (E and SW wind). The x-ordinates of MK E and TST SW are slightly displaced for the sake of better visibility.

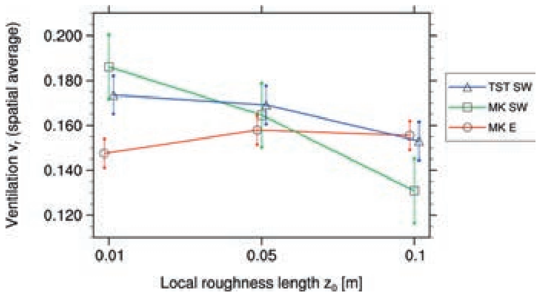

Figure 4: Sensitivity of site-averaged ventilation v_r to local roughness length z_0 (m) for TST (SW wind) and MK (E and SW wind). The x-ordinates of MK E and TST SW are slightly displaced for the sake of better visibility.

Four buffer sizes have been tested (upstream buffer/buffer at three other sides, in units of H): (0,0), (1,1), (3,1), (6,2). Within the buffer zones, buildings were modelled based on DEM data just as inside the assessment area. As an example, Fig. 2 shows the location of the buffer zones relative to the assessment area for MK SW. Here and in the following, the site-averaged v_r is the horizontal average of v_r of the assessment area only (i.e. excluding any buffer zone). Fig. 3 shows that, as expected, a zero (0,0) buffer size is insufficient, since results significantly deviate from the other buffers. Since the flow quickly adjusts to the large roughness of the modelled buildings within the buffer zone, results using the three other buffer sizes agree quite well (within model uncertainty), which suggests that the AVA standard (1,1) buffer also applies to 30 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 due to artificial diagonal channeling (cf. Fig. 2). This example demonstrates that such buffers should not blindly 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 $\Delta_z = 0.8$ m in order to measure at the pedestrian level $z_p = 2$ m in accordance with AVA. Moving this **measurement height** to 2.5 m would allow to use $\Delta_z = 1$ m. This saved ~22% of simulation cost in performance tests. Sensitivity tests (not shown) did not reveal any significant difference (within numerical uncertainty) between $z_p = 2$ m ($\Delta_z = 0.8$ m) and $z_p = 2.5$ m ($\Delta z = 1$ m). Therefore $z_p = 2.5$ m ($\Delta_z = 1$ m) is used in the following sections.

Some urban structures may not be included in the DEM data or may be subgrid-scale in PALM, yet they have the potential to slow down the flow. For example, Hong Kong's ubiquitous projecting obstructions are not part of the DEM dataset. PALM uses rough walls to qualitatively account for their effect. The same **local roughness length** z_0 is applied in each local grid box adjacent to a horizontal or vertical surface. Three z_0 values are considered: 0.1 m: very rough walls due to large vertical projections that are not included in the DEM data (e.g. Fig. 10.18 in NG, 2010), 0.05 m: moderately rough walls e.g. with air conditioning appliances, 0.01 m: relatively smooth walls. As expected, the sensitivity of v_r to local roughness length z_0 (Fig. 4) is significant, but only for TST SW and MK SW, not for MK E. This is likely due to the skimming flow observed in large parts of MK E, which leads to a very low ventilation regardless of the wall roughness. Wind tunnel obstacles need to be sufficiently aerodynamically rough in order to avoid local flow relaminarization, i.e. wind tunnel models also have rough walls. The full-scale roughness z_0 of wooden wind tunnel obstacles is not negligible. Since AVA does not require to quantify z_0, CFD and wind tunnel results may not be comparable if their local z_0 is unknown.

As expected, in a fully turbulent regime v_r does not depend on **Reynolds number** $\mathrm{Re} = \frac{u_b H_{av}}{v_m}$, where H_{av} is the average building height and v_m is molecular viscosity. This 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 $v_\infty \approx 2$ m/s which is lower than the observed annual mean of 6 to 8 m/s (cf. section 1).

AVA sets no explicit standard on **representativeness of measurement locations**. However, measurement techniques/accuracy often demand wind tunnel measurements at canyon centers or open spaces, for example. Yet these locations mainly represent areas with relatively large v_r. Indeed, Fig. 5 highlights a strong dependency of v_r on horizontal measurement locations (measurement located at least "n" grid boxes away from the nearest vertical wall, for details cf. Fig. 5). 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 is used in the following sections. However, the results are expected to underpredict those wind tunnel measurements that focus on canyon centers or open spaces (corresponding to larger values of n).

4.2 Case Studies

High-resolution assessment simulations are carried out which form the basis of the following case studies. Based

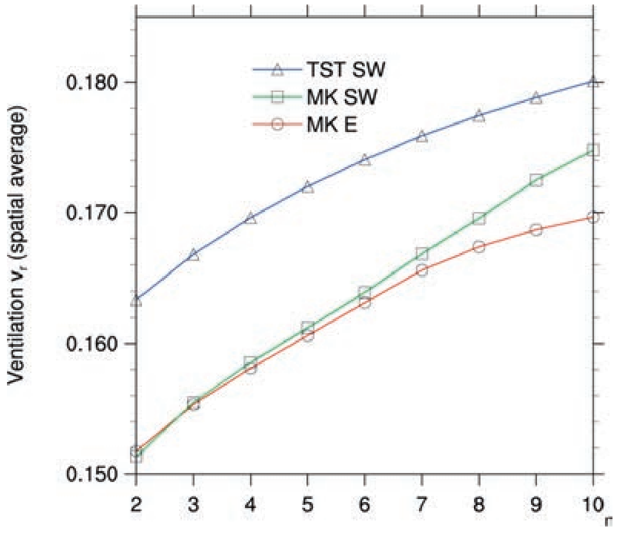

Figure 5: Sensitivity of site-averaged ventilation v_r to horizontal measurement locations (calculation of site-average starts at the n[th] grid point adjacent to vertical walls, i.e. the first n-1 grid points adjacent to vertical walls are excluded from the site-average) for TST (SW wind) and MK (E and SW wind).

on section 4.1, the high-resolution LES for MK and TST under E and SW prevailing wind 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), local z_0 = 0.1 m (estimated based on site inspection), Re = $3.3 \cdot 10^6$, n = 3, and domain size $(1.6\ \text{km})^2 \cdot 400$ m ($7.2 \cdot 10^8$ grid points).

An exception is the comparison TST SW *with* versus *without* a recently constructed 210 m super tall building (Fig. 7) which is conducted with a domain size of 1.6 km·2 km·960 m ($1.6 \cdot 10^9$ grid points).

4.2.1 Exemplary LES results

Figs. 6 & 7 show some exemplary results. As expected for E wind, Fig. 6a shows large v_r in long, almost E-W oriented streets (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. 6b clearly demonstrates that this is due to vertical advection: the large downdraught upstream/updraught downstream is balanced by a strong low (pedestrian) level flow around this building. Vertical advection induced by the same building is also obvious in the passive tracer turbulence animation by LETZEL and GAUS (2008) – for details cf. LETZEL et al., 2008a. 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. 7a shows that for SW wind, the new 210 m super 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 = 100 m, y = 800~850 m, Fig. 7b).

4.2.2 Validation of LES results with wind tunnel measurements

Since there are no established guidelines for the validation of turbulence-resolving CFD codes such as LES and DNS, the best possible validation at present using the available data is a cross-comparison of v_r derived from wind tunnel measurements and v_r extracted from LES.

Wind tunnel (WT) measurements of v_r at the pedestrian level in the same urban areas are conducted using the wind tunnel facilities at Hong Kong University of Science and Technology[1]. The tests were conducted in accordance to the international practice requirements (AWES, 2001; ASCE, 1999). Wind velocities were measured at 5 mm from the ground in the 1:400 model. This corresponds to 2 m in reality. Coupled with the readings at the boundary layer level of 500 m, the wind velocity ratio v_r of the test points can be computed.

In order to improve representativeness (cf. SCHATZMANN and LEITL, 2009, 2011), instead of a point to point direct comparison, a zonal comparison is made based on v_r of various urban morphologies. The test points were categorized into several groups, according to their different surrounding morphologies, as defined in column 1 of Table 1. The v_r of the wind tunnel measurements and the simulated LES results are as respectively in column 2 and 3 of Table 1. Additionally, column 4 displays normalized LES data (multiply v_r (LES) by the average ratio v_r (WT) /v_r (LES) in the total assessment area). The purpose of column 4 is to check whether both tools, WT and LES, are equally able to emphasize the relative differences between the different morphology zones. This ability is required for a practical planning tool so that urban planners can clearly evaluate different planning scenarios as compared to the current state. Column 5 specifies the zonal test points.

The correlation between the two sets of results is shown in Fig. 8, and R^2 = 0.91 (column 2 vs. column 3, before normalization) and R^2 = 0.93 (column 2 vs. column 4, after normalization) are obtained.

Both wind tunnel and LES studies report v_r in the range of 0.14 to 0.35. The difference between the unobstructed open spaces and the more obstructed in-land urban areas is around 3 times. Examining the impact of the street orientation, v_r in the parallel streets shows a higher magnitude than that in the perpendicular streets, meaning that the channeling flow dominates the ventilation in the assessment area, i.e. air path creation along the most fre-

[1]Technical reports are available from http://www.pland.gov.hk/pland_en/p_study/prog_s/ucmapweb/.

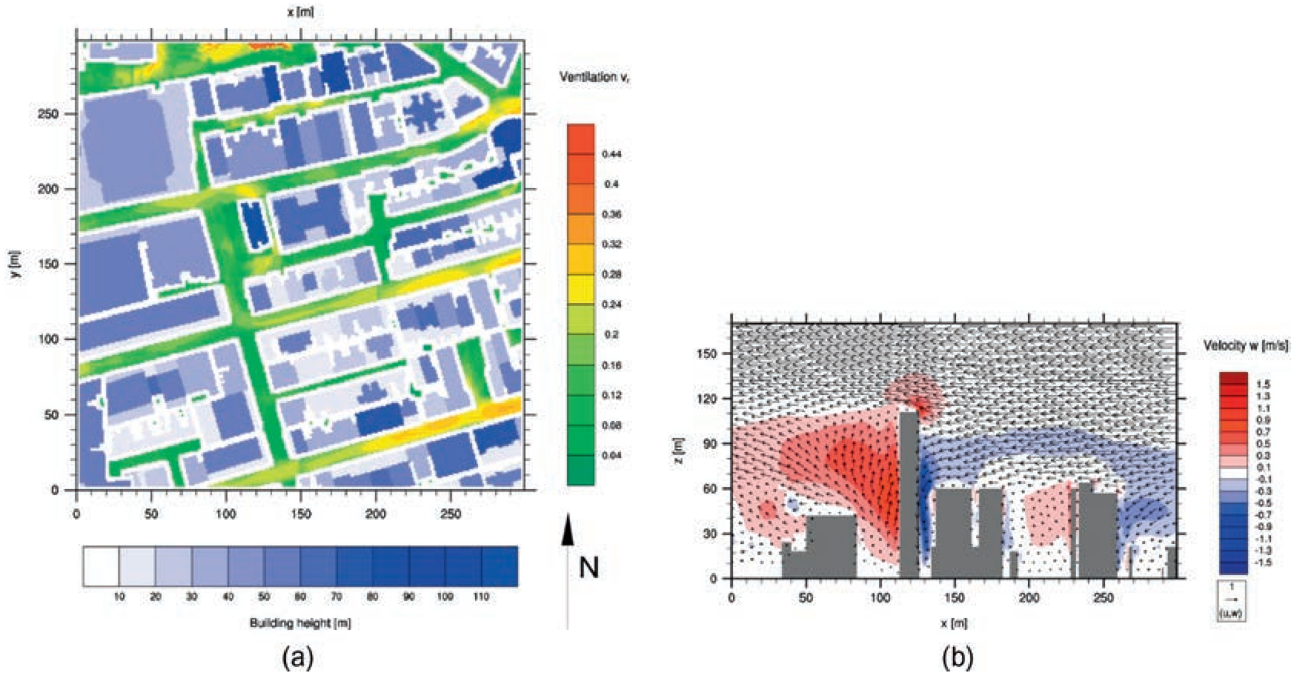

Figure 6: Time-averaged ventilation pattern for TST E, zoomed into part of the assessment area. (a) Horizontal cross-section of v_r at pedestrian level (v_r: green-red colour scale; building heights: white-blue colour scale). Wind direction: ←. (b) Vertical (xz) cross-section of vertical velocity w at y = 175 m with an overlay vector plot of the velocity components (u,w) in that sectional plane. Wind direction: ←.

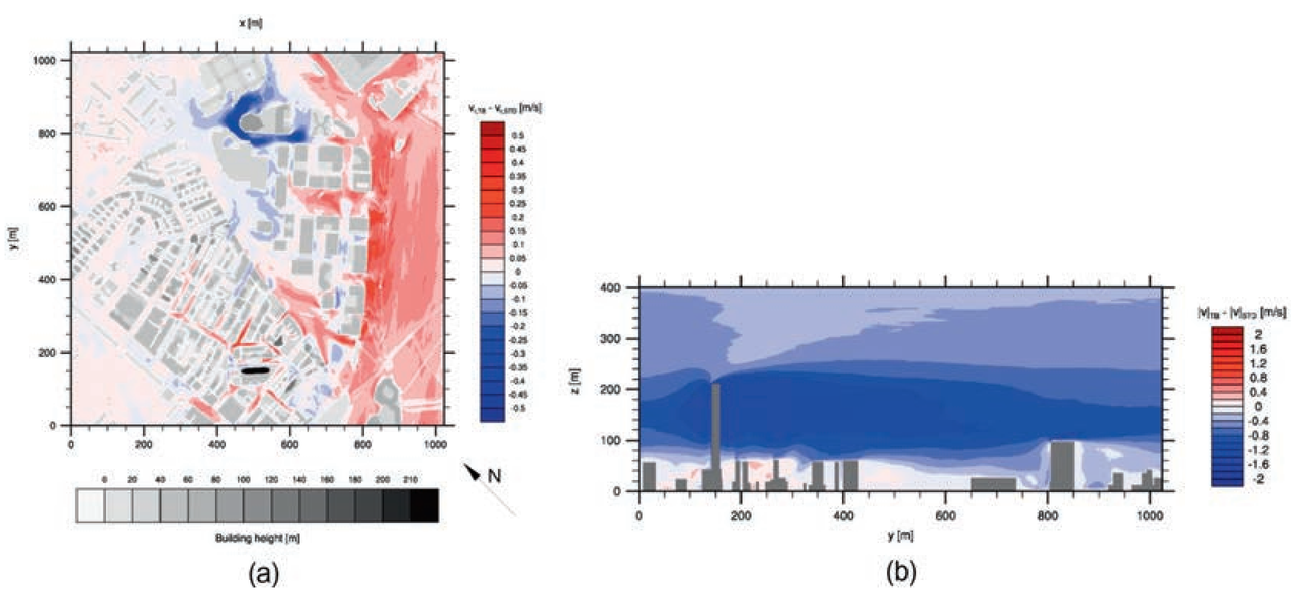

Figure 7: *Difference* in time-averaged ventilation pattern for the 1 km^2 assessment area of TST SW *with* (TB) minus *without* (STD) a recently constructed 210 m super tall building (visible in black at x = 500 m, y = 150 m). (a) Horizontal cross-section of ventilation difference $v_{r,\mathrm{TB}} - v_{r,\mathrm{STD}}$ at pedestrian level in blue-red colour scale (building heights in greyscale). Wind direction: ↑. (b) Vertical (yz) cross-section of absolute velocity difference $|v|_{\mathrm{TB}} - |v|_{\mathrm{STD}}$ at x = 500 m. Wind direction: →.

quent incoming flow direction is an important consideration in urban planning. Table 1 also shows that the differences between narrow and main streets flows are not big. In view of the $\gtrsim$40 m tall buildings that form most of the street canyons considered here, the increase in canyon width from ~10 m (narrow streets) to ~15 m (main streets) is only slight and hence cannot substantially improve the deep canyon flow regime.

Overall, the validation shows a good correlation between LES results and WT measurements for the same sites based on a local, zonal comparison.

Table 1: A zonal comparison of v_r between LES results and WT results. Main streets refer to streets with width approximately equal to or larger than 15 meters, and narrow streets refer to those with width less than 10 meters. High ground coverage (GC) refers to areas with GC larger than 60% and low GC refers to areas with GC lower than 20%, while mid GC refers to those in between. Test points are labelled according to their definition in HONG KONG PLANNING DEPARTMENT (2008, pp. 41-46).

Zones of urban morphology	v_r (WT)	v_r (LES)	v_r (LES, normalized)	Test points
Narrow streets (canyon flow)	0.14	0.11	0.14	TSA26, TSC19, TSC24
Main streets (canyon flow)	0.15	0.12	0.15	TSA01, TSA03, TSA05, TSA06, TSA10,TSB16, TSC29
Narrow streets (parallel flow)	0.22	0.20	0.25	TSA09, TSA11
Main streets (parallel flow)	0.24	0.22	0.28	TSA25, TSA29, TSA30, TSB08
High ground coverage	0.13	0.11	0.14	TSA04, TSA14, TSA20, TSA26, TSA27
Mid ground coverage	0.23	0.21	0.27	TSB05, TSB09, TSB13, TSB15, TSB23, TSB24, TSB25
Low ground coverage	0.34	0.24	0.32	TSB19, TSC26, TSC31, TSC33
Waterfront/open spaces	0.33	0.28	0.35	TSC34
Total assessment area	0.22	0.18	0.22	All

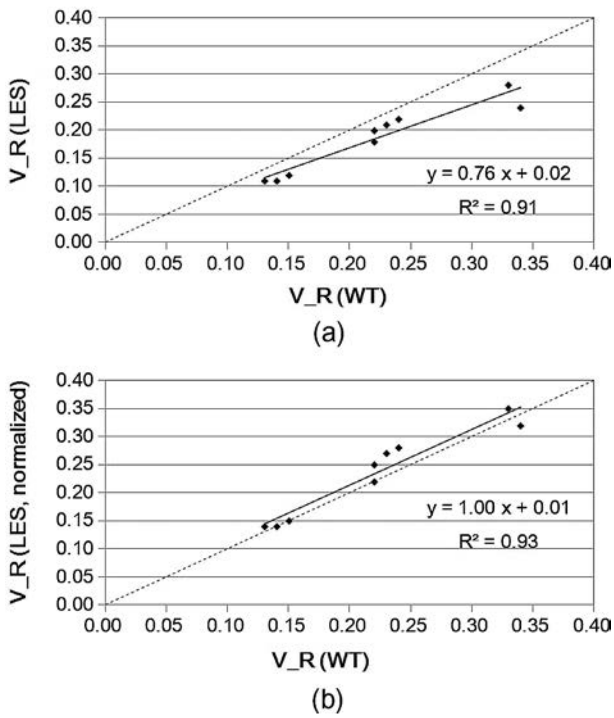

Figure 8: (a) A correlation between v_r of LES and WT. (b) A correlation between v_r of LES and WT. The WT and the LES data are normalized using the average v_r of the assessment area.

4.2.3 LES v_r comparison studies

The LES study result can report a continuous two-dimensional distribution of v_r of the whole assessment area; the frequency distribution of v_r in each assessment area can also be calculated. This gives a quantitative understanding of the air ventilation performance of the areas. The v_r frequency histograms of TST and MK under E and SW wind are plotted in Fig. 9. The mean, median, upper and lower quantiles of v_r are presented in Table 2.

Note that for TST, for E wind, the v_r found is noticeably larger than for SW wind; the mean v_r is 0.20 for TST E versus 0.15 and 0.16 for the other cases. This is due to the unobstructed waterfront of TST in the East. For TST, when wind comes from SW it has to travel over a long stretch of urban areas before arriving at the study area. For MK, the reported v_r for E and SW wind are similar. This is due to the homogenous urban surroundings. The reported mean v_r of 0.15 is comparable to the mean v_r of TST for SW wind. It is of interest to note that the street grid of MK is north-south orientated. One would therefore expect to see a larger mean v_r, or a more profound difference of v_r for streets parallel and perpendicular to the wind direction for the East wind simulation as compared to the v_r results for SW wind. This appears not to be the case. It may be due to the very high roughness of the city areas where flows are highly mixed and turbulent. The traditional way of examining wind flow based on the simple canyon flow schema may not therefore be the most appropriate. A different understanding may be demanded here.

All in all, for inland urban areas in Hong Kong, the LES study suggests a median v_r on the order of 0.15. Allowing a typical v_∞ = 6 to 8 m/s at 500 m above ground in Hong Kong, a median v_r of 0.15 can translate to wind speeds of around 1 m/s for 50% of the time. However, an urban thermal comfort study by CHENG and NG (2006) states the need for 1.5 m/s wind for 50% of the time for human urban thermal comfort in tropical cities. Therefore, the LES results indicate that in urban Hong Kong, the wind environment needs to be improved by better urban planning and building design.

4.2.4 A comparison study of v_r between urban Hong Kong and Metropolitan Tokyo

A comparative study of the distribution of v_r of Hong Kong, Tsim Sha Tsui and Tokyo, Shinjuku is made. Both are typical of areas of high building density in Hong Kong and Tokyo, respectively. The Tokyo data is taken from LETZEL (2007). Statistical values of v_r in Hong Kong and Tokyo are listed in Table 3, and a histogram showing the frequency distribution of v_r is presented in Fig. 10. The v_r of Hong Kong is lower than that of Tokyo. This

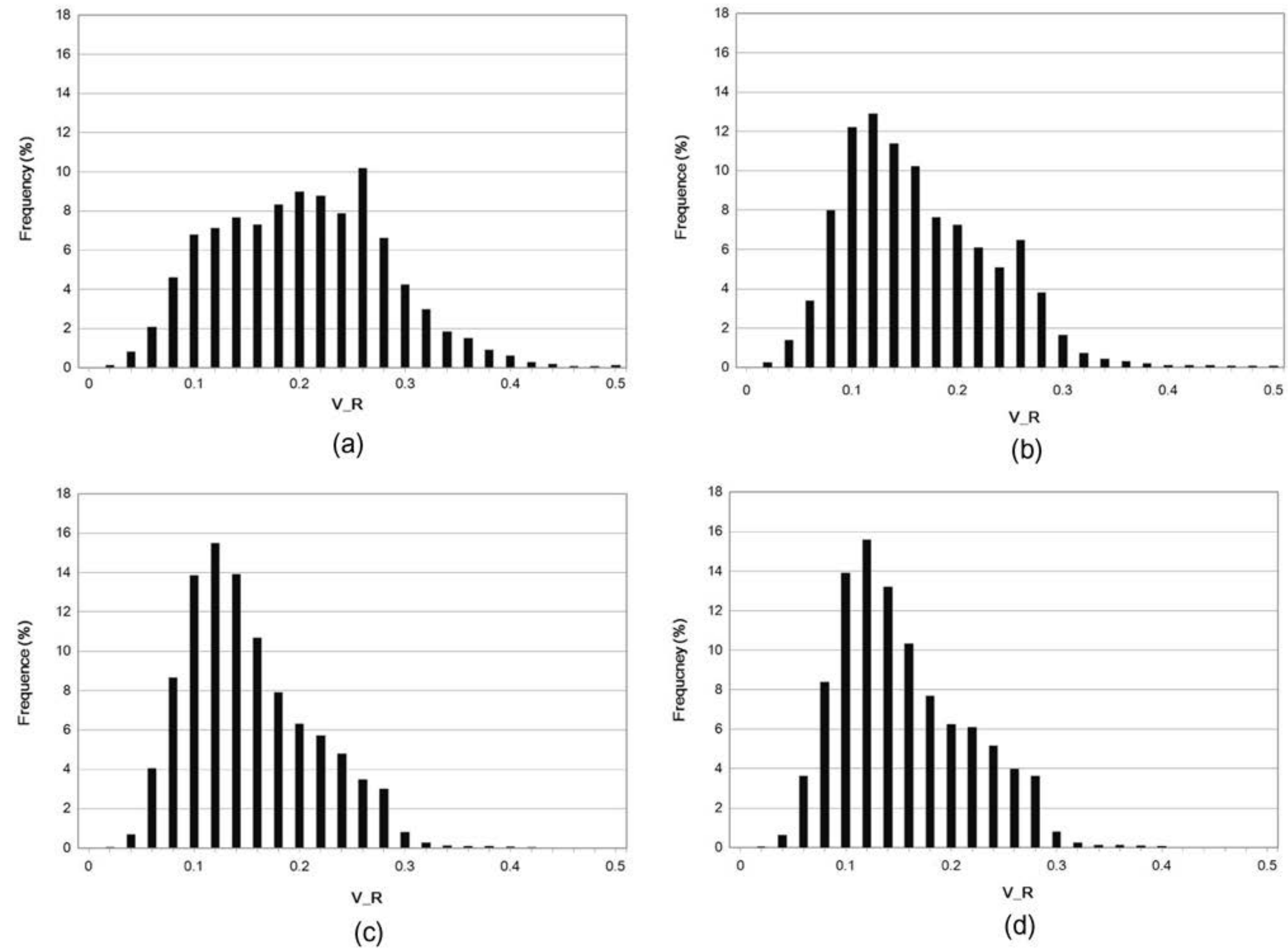

Figure 9: Histogram cumulative frequencies of v_r of (a) TST E, (b) TST SW, (c) MK E and (d) MK SW based on the LES study.

Table 2: Statistic values of v_r for TST and MK (LES study).

Site	Mean	25%	Median	75%
TST E	0.20	0.14	0.20	0.26
TST SW	0.16	0.11	0.16	0.21
MK E	0.15	0.11	0.15	0.19
MK SW	0.15	0.11	0.15	0.20

Table 3: Statistic values of v_r for HK & Tokyo Shinjuku LES studies

Site	Mean	25%	Median	75%
HK	0.17	0.11	0.17	0.22
Tokyo Shinjuku	0.19	0.14	0.19	0.24

is due mainly to the fact that the urban area in Hong Kong has a ground coverage of 40% or more, whereas that in Tokyo is around 25%. KUBOTA et al. (2008) showed that a higher ground coverage of building lowers the wind velocity ratio near the ground. Also, the frequency distribution of Hong Kong is positively skewed, whereas Tokyo is more symmetrical. This is due to the taller buildings, narrower streets and larger building surface area in urban Hong Kong as compared to Tokyo. Referring to the lower quartile v_r of 0.11 in Hong Kong and 0.14 in Tokyo, it can be estimated that in Hong Kong, 25% of the urban area can only experience pedestrian level wind up to 0.7 to 0.9 m/s for 50% of the time. This is almost half of the desirable wind environment of 1.5 m/s for 50% of the time, whereas in Tokyo the problem is less serious. To address the problem, refer to Table 1, planners are recommended to reduce urban ground coverage and create air paths and open spaces. In a nutshell, there is a need to increase urban porosity and increase the air volume at pedestrian level.

5 Practical implications for urban design

The two study cases of Tsim Sha Tsui and Mong Kok in Hong Kong using LES have revealed important planning lessons for planners and policy makers. The study results in Figs. 11 to 15 are maps of MK and TST for E and SW wind showing the calculated pedestrian level ventilation v_r.

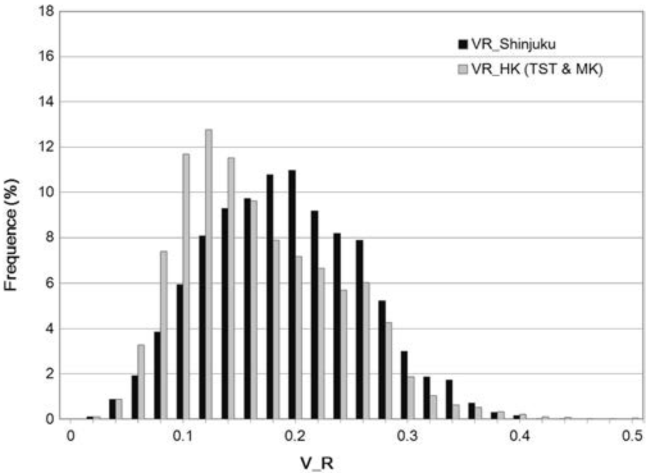

Figure 10: Histograms of v_r frequencies of Tokyo (Shinjuku) and Hong Kong. The Hong Kong data includes v_r of TST E, TST SW, MK E and MK SW.

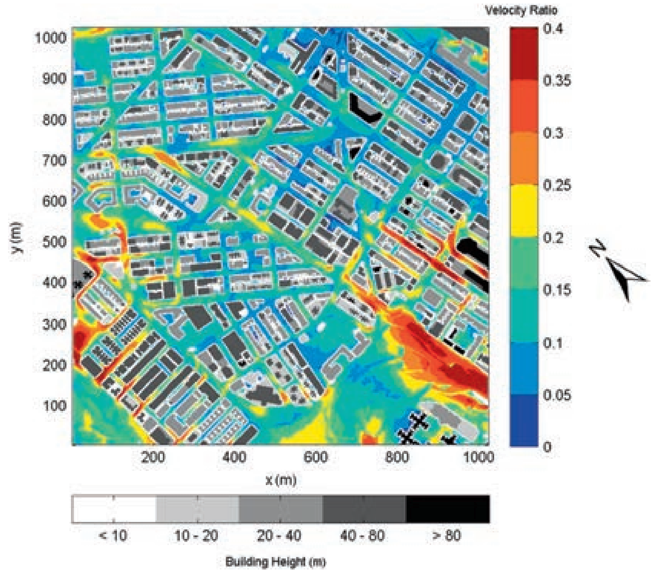

Figure 12: Pedestrian level v_r at Mong Kok for Southwest wind.

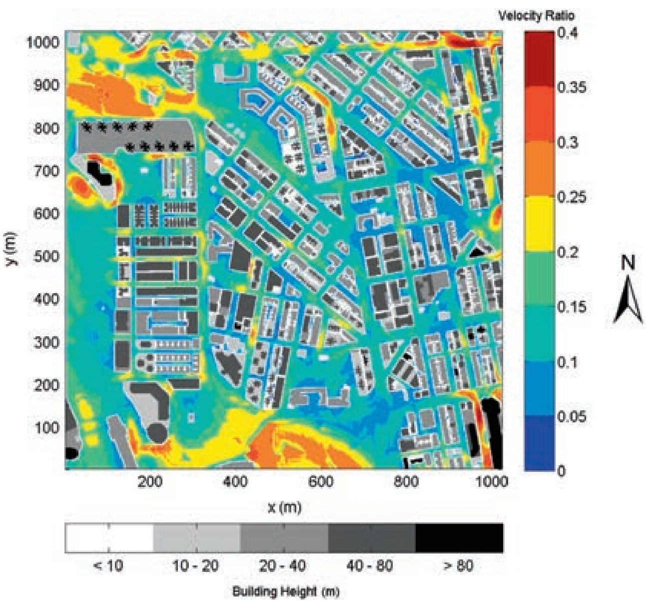

Figure 11: Pedestrian level v_r at Mong Kok for East wind.

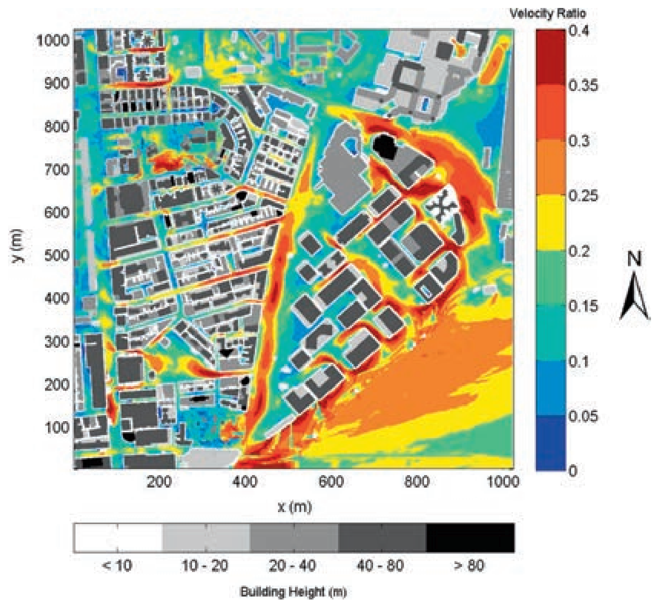

Figure 13: Pedestrian level v_r at Tsim Sha Tsui for East wind.

The Government of Hong Kong has, since 2006, published a set of urban planning guidelines (Hong Kong Planning Department, 2009). Best practice suggestions have been developed for different district levels and different site levels (Table 4). It is possible to elaborate some of these best practices based on the LES studies.

Regarding breezeways and air paths, the LES simulation results reveal that wide breezeways in the direction of the winds have higher v_r in the order of 0.2 to 0.3. Narrower air paths can still have v_r in the range of 0.1 to 0.2. Interconnected breezeways and air paths are particularly conducive to urban air ventilation. Dead ends and corners with low v_r of 0.05 or less should be avoided. The importance of the width of the air path can be noted in the number of narrow streets (x = 450 m, y = 450 m; x = 470 m, y = 550 m) in Fig. 13. It can be noted that wind from the East has difficulties penetrating the narrow streets effectively even though the streets are parallel to the incoming wind. The same can also be observed at x = 900 m, y = 250 m of Fig. 12. v_r along the street also quickly decreases and v_r near the exit of the streets is low.

Regarding the street orientation, the results show that narrow streets perpendicular to the wind direction have low v_r of 0.1 or less. Whereas, streets that are parallel to the wind can mostly enjoy v_r of 0.1 and above. The observation is not straight forward and can depend on the width of the street as well as the building heights

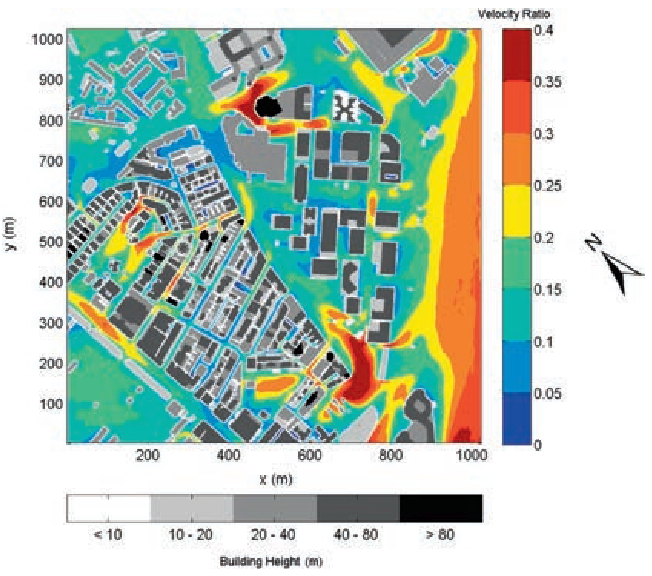

Figure 14: Pedestrian level v_r at Tsim Sha Tsui for Southwest wind without the new building.

on both sides of the street. For example, for TST under East wind (Fig. 13), the wide street in the middle has high v_r despite the fact that it is perpendicular to the incoming wind. As to the street pattern, it is noted that at x = 950 m, y = 850 m of Fig. 12, the dead end has caused v_r to decrease way before the street terminates. The low v_r, of lower than 0.1, over a length of street 150 m long is highly undesirable in terms of urban thermal comfort in the hot and humid summer months of Hong Kong (NG and CHENG, 2012).

Waterfront sites with buildings that are well spaced can allow the incoming sea breezes coming into the urban areas. This is evident in the TST under East wind study. v_r of up to 0.4 well into the inland areas can be noted (Fig. 13).

As to building height profile, it is noted that a good variation of building heights in close proximity is good for urban ventilation as it promotes mixing and down-washes. The benefits are particularly noticeable when there is an open space in front or even behind the tall building. It seems that wind follows the building and spiral down to the open space before dispersing into the surrounding narrow 30 sites. This is evident with a tall building located at x = 200 m, y = 600 m in Fig. 13 (cf. x = 120 m, y = 175 m in Fig. 6).

The importance of interconnected open spaces can be seen at x = 650 m, y = 550 m of Fig. 13. Here a building cuts the open space into two and thus greatly reduces the v_r at its wakes by 0.05-0.1. In future, such planning should be avoided.

The effects of large podium structure to urban ventilation are most noticeable when the surrounding streets are narrow. In Mong Kok, the reduced air space has created very low v_r regardless of the orientation of the streets. In addition, it can be noted that urban areas of high ground coverage generally have lower v_r (KUBOTA et al., 2008).

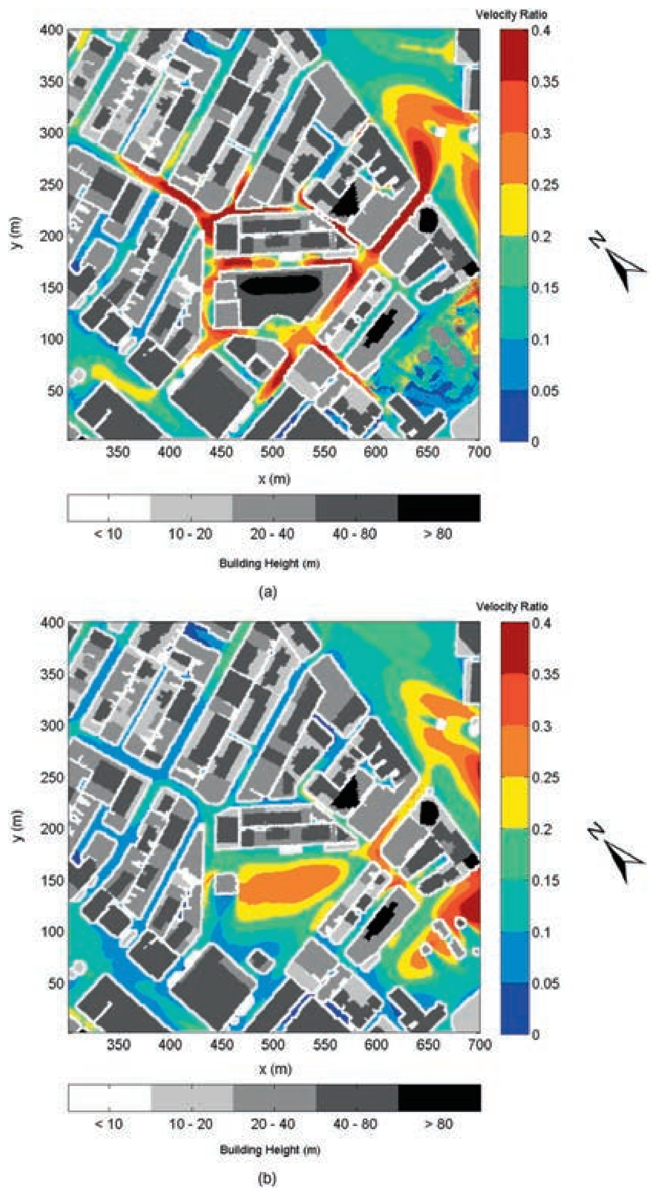

Figure 15: Pedestrian level v_r at Tsim Sha Tsui for Southwest wind (zoom), (a) with the new building and (b) without the new building.

This is evident at x = 900 m, y = 600 m of Fig. 11, x = 450 m, y = 300 m of Fig. 12 and x = 350 m, y = 300 m of Fig. 14.

Ironically, it is noted that a tall building, especially if it is isolated, may not be bad for urban ventilation at the pedestrian level locally (Fig. 15 a). For TST under South West wind direction, it can be noted that a super tall building (>210 m) can noticeably increase the ground level pedestrian wind environment from 0.1–0.3 to 0.15–0.4. The benefits can even be felt more than 100 m away. This is due to the enhanced turbulence in the wake of the tall building. The open space at the ground level in the super tall building case has been occupied by a big podium. The super tall tower sits on the podium. However, the locally enhanced momentum transfer harvests the incoming wind at the expense of the wind

Table 4: District levels and site levels for which best practice guidelines on urban ventilation are given in the Hong Kong Planning Standards and Guidelines (HONG KONG PLANNING DEPARTMENT (2009).

District level	Site Level
Site Disposition	Podium Structure
Breezeways/Air Paths	Building Disposition
Street Orientation, Pattern and Widening	Building Permeability
Waterfront Sites	Building Height and Form
Height Profile	Landscaping
Greening and Disposition of Open Space and Pedestrian Area	Projecting Obstructions

available further downstream (Fig. 7; see also KATAOKA et al., 2007).

6 Conclusions

The sensitivity study suggests that cyclic LES with a buffer zone of 1H around the assessment area is normally acceptable to obtain pedestrian level ventilation v_r for nearly flat sites, where H the height of the tallest building on site. The observed strong dependency of v_r on both local wall roughness and measurement locations, for which the air ventilation assessment (AVA) sets no clear standards, points at possible AVA clarifications, otherwise CFD and wind tunnel studies may not be comparable.

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 (currently: radius $\geq$1H) could be enlarged. It can be noted that the wind environment depends greatly on the urban morphology of the city. Air paths, street orientations, ground coverage, sites fronting the water, inter connectivity of spaces, building podium size and building heights can all affect the pedestrian wind environment. For planners, getting some of these parameters right is very important. It is useful in further parametric studies to understand them beyond what can be deduced from results of this study.

Finally, it should be noted that this urban LES case 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 further parametric studies on idealized, generic city quarters. Since these were beyond the scope of this feasibility study, they are recommended for further research.

Acknowledgments

Financial support by a Chinese University of Hong Kong Social Science Panel Direct Grant, by the German Research Foundation (DFG) under grant RA 617/15-1/2 and by the German National Academic Exchange Service (DAAD) is gratefully acknowledged. GIS data of Hong Kong were provided by the HKSAR Planning Department under the project "Urban Climatic Map and Standards for Wind Environment". The simulations worth 1.4 M€ were performed on the North German supercomputing center HLRN (www.hlrn.de). The authors are grateful to two anonymous reviewers who provided valuable comments.

References

AIAA, 1988: Guide for the verification and validation of computational fluid dynamics simulations. Technical Report AIAA G-077–1998.

AKASHI, T., 2008: Creating the "wind paths" in the city to mitigate urban heat island effects – a case study in central district of Tokyo. – In: Proceedings of COBRA 2008 the construction and building research conference of the Royal Institution of Chartered Surveyors, Sept 2008, Dublin Institute of Technology, Ireland, 1–11.

ARAKAWA, A., V. R. LAMB, 1977: Computational design of the basic dynamical processes of the UCLA general circulation model. – In: J. CHANG (Ed.), General circulation models of the atmosphere, volume 17 of Methods in Computational Physics, Academic Press, 173–265.

ASCE, 1999: Manual and Report on Engineering Practice No. 67 for Wind Tunnel Studies of Buildings and Structures. – American Society of Civil Engineers, Virginia, USA.

ASHIE, Y., T. KONO, 2011: Urban-scale CFD analysis in support of a climate-sensitive design for the Tokyo bay area. – Int. J. Climatol. **31**, 174–188. DOI:10.1002/joc.2226

ATKINSON, B. W., 2003: Numerical modeling of urban heat island intensity. – Bound.-Lay. Meteorol. **109**, 285–310. DOI:10.1023/A:1025820326672

AWES, 2001: Wind Engineering Studies of Buildings. – Australasian Wind Engineering Society, Australia.

BARTZIS, J. G., D. VLACHOGIANNIS, A. SFETSOS, 2004: Best practice advice for environmental flows, QNET-CFD network newsletter. – Technical Report **2** (4), QNET-CFD.

BLOCKEN, B., T. STATHOPOULOS, J. CARMELIET, J. L. M. HENSEN, 2011: Application of computational fluid dynamics in building performance simulation for the outdoor environment: an overview. – Journal of Building Performance Simulation **4**, 157–184. DOI:10.1080/19401493.2010.513740

BOHNENSTENGEL, S., K. H. SCHLÜNZEN, D. GRAWE, 2004: Influence of thermal effects on street canyon circulations. – Meteorol. Z. **13**, 381–386. DOI:10.1127/0941-2948/2004/0013-0381

BRISCOLINI, M., P. SANTANGELO, 1989: Development of the mask method for incompressible unsteady flows. – J. Comput. Phys. **84**, 57–75. DOI: 10.1016/0021-9991(89)90181-2

CAI, X.-M., 2012: Effects of wall heating on flow characteristics in a street canyon. – Bound.-Lay. Meteorol. **142**, 443–467. DOI:10.1007/s10546-011-9681-6

CHEN, L., E. NG, 2011: Quantitative urban climate mapping based on a geographical database: a simulation approach using hong kong as a case study. – Int. J. Appl. Earth Obs. **13**, 586–594. DOI:10.1016/j.jag.2011.03.003

CHENG, V., E. NG, 2006: Thermal comfort in urban open spaces for Hong Kong. – Architectural Science Review **49**, 236–242. DOI:10.3763/asre.2006.4932

CHU, A. K. M., R. C. W. KWOK, K. N. YU, 2005: Study of pollution dispersion in urban areas using Computational Fluid Dynamics (CFD) and Geographic Information System (GIS). – Envion. Modell. Softw. **20**, 273–277. DOI:10.1016/j.envsoft.2004.05.007

CIONCO, R. M., 1997: High resolution urban morphology data for urban wind flow modeling. – Atmos. Environment **32**, 7–17. DOI: 10.1016/S1352-2310(97)00274-4

COCEAL, O., S. E. BELCHER, 2005: Mean winds through an inhomogeneous urban canopy. – Bound.-Lay. Meteorol. **115**, 47–68. DOI:10.1007/s10546-004-1591-4

COCEAL, O., T. G. THOMAS, I. P. CASTRO, S. E. BELCHER, 2006: Mean flow and turbulence statistics over groups of urban-like cubical obstacles. – Bound.-Lay. Meteorol. **121**, 491–519. DOI:10.1007/s10546-006-9076-2

COX, W., 2011: Demographia, world urban areas (world agglomerations). – 7th annual edition. www.demographia.com/db-worldua.pdf, accessed on 1 April 2012.

DEARDORFF, J. W., 1980: Stratocumulus-capped mixed layers derived from a three-dimensional model. – Bound.-Lay. Meteorol. **18**, 495–527. DOI:10.1007/BF00119502

FRANKE, J., 2006: Recommendations of the COST action C14 on the use of CFD in predicting pedestrian wind environment. – In: The Fourth International Symposium on Computational Wind Engineering, Yokohama, Japan.

FRANKE, J., C. HIRSCH, A. G. JENSEN, H. W. KRÜS, M. SCHATZMANN, P. S. WESTBURY, S. D. MILES, J. A. WISSE, N. G. WRIGHT, 2004a: Recommendations on the use of CFD in predicting pedestrian wind environment. – In: J. P. A. J. VAN BEECK (Ed.), Proceedings of the International Conference on Urban Wind Engineering and Building Aerodynamics, 5-7 May 2004. von Karman Institute, Sint-Genesius-Rode, Belgium.

FRANKE, J., C. HIRSCH, A. G. JENSEN, H. W. KRÜS, M. SCHATZMANN, P. S. WESTBURY, S. D. MILES, J. A. WISSE, N. G. WRIGHT, 2004b: Recommendations on the use of CFD in wind engineering. – In: J. P. A. J. VAN BEECK (Ed.), Proceedings of the International Conference on Urban Wind Engineering and Building Aerodynamics, 5–7 May 2004. von Karman Institute, Sint-Genesius-Rode, Belgium. COST Action C14, Impact of Wind and Storm on City Life Built Environment.

FRANKE, J., A. HELLSTEN, H. SCHLÜNZEN, B. CARISSIMO, 2011: The COST 732 best practice guideline for CFD simulation of flows in the urban environment: a summary. – Int. J. Environ. Poll. **44**, 419–427. DOI:10.1504/IJEP.2011.038443

GOUSSEAU, P., B. BLOCKEN, T. STATHOPOULOS, van G. J. F. HEIJST, 2011: CFD simulation of near- field pollutant dispersion on a high-resolution grid: A case study by LES and RANS for a building group in downtown Montreal. – Atmos. Environment. **45**, 428–438. DOI:10.1016/j.atmosenv.2010.09.065

HANNA, S. R., S. TEHRANIAN, B. CARISSIMO, R. W. MACDONALD, R. LOHNER, 2002: Comparisons of model simulations with observations of mean flow and turbulence within simple obstacle arrays. – Atmos. Environment **36**, 5067–5079. DOI:10.1016/S1352-2310(02)00566-6

HARLOW, F. H., J. E. WELCH, 1965: Numerical calculation of time-dependent viscous incompressible flow of fluid with free surface. – Phys. Fluids. **8**, 2182–2189. DOI:10.1063/1.1761178

HONG KONG OBSERVATORY, 2011: Summary of meteorological and tidal observations in Hong Kong 1999-2010. www.weather.gov.hk/publica/pubsmo.htm, accessed on 18 April 2012.

HONG KONG PLANNING DEPARTMENT, 2008: Urban climatic map and standards for wind environment - feasibility study, working paper 2B: Wind tunnel benchmarking studies, batch I. Technical report, The Government of the Hong Kong Special Administrative Region.

HONG KONG PLANNING DEPARTMENT, 2009: Hong Kong Planning Standards and Guidelines. www.pland.gov.hk/pland_en/tech_doc/hkpsg, accessed on 1 April 2012.

KANDA, M., A. INAGAKI, T. MIYAMOTO, 2012: New aerodynamic parameterization for real urban surfaces derived from LES. – In: ICUC 8 – 8th International Conference on Urban Climates, 6th-10th August, 2012, UCD, Dublin Ireland, number 118.

KATAOKA, H., T. TAMURA, Y. OKUDA, M. OHASHI, 2007: Numerical evaluation of the wake field behind high-rise buildings by RANS and LES. – Cross comparison among computed and wind-tunnel experimental results. – In: Twelfth International Conference on Wind Engineering, Cairns, Australia.

KUBOTA, T., M. MIURA, Y. TOMINAGA, A. MOCHIDA, 2008: Wind tunnel tests on the relationship between building density and pedestrian-level wind velocity: Development of guidelines for realizing acceptable wind environment in residential neighborhoods. – Building and Environment **43**, 1699–1708. DOI:10.1016/j.buildenv.2007.10.015

LETZEL, M. O., 2007: Large-Eddy Simulation Feasibility Study of Tsim Sha Tsui, Kowloon, Project Report for "Urban Climatic Map and Standards for Wind Environment – Feasibility Study". Technical report, Hong Kong Planning Department, The Government of the Hong Kong Special Administrative Region. 14 pp.

LETZEL, M. O., G. GAUS, 2008: Turbulent flow in a densely built-up area in Kowloon, downtown Hong Kong. – Dynamic Visualization in Science (13118) , http://palm.muk.uni-hannover.de/wiki/gallery/movies/city#dyvis_13118, accessed on 18 November 2012.

LETZEL, M. O., M. KRANE, S. RAASCH, 2008a: High resolution urban large-eddy simulation studies from street canyon to neighbourhood scale. – Atmos. Environment **42**, 8770–8784. DOI:10.1016/j.atmosenv.2008.08.001

LETZEL, M. O., G. GAUS, S. RAASCH, N. JENSEN, M. KANDA, 2008b: Turbulent flow around high-rise office buildings in downtown Tokyo. – Dynamic Visualization in Science (13110), http://palm.muk.uni-hannover.de/wiki/gallery/movies/city#dyvis_13110, accessed on 18 November 2012.

LETZEL, M., W. BÄCHLIN, S. RAASCH, M. KECK, 2012: LES runs with the model PALM for a model comparison (in German). Technical Report Project 61905-11-10, Ingenieurbüro Lohmeyer GmbH & Co. KG, Karlsruhe Research report for the BBK project No. 364 "Development of a tool for the optimization of emergency response in case of hazmat release in urban areas" (in German), subcontracted by the University of Hamburg.

LI, X.-X., C.-H. LIU, D. Y. C. LEUNG, K. M. LAM, 2006: Recent progress in CFD modelling of wind field and pollutant transport in street canyons. – Atmos. Environment **40**, 5640–5658. DOI:10.1016/j.atmosenv.2006.04.055

LI, X.-X., R. E. BRITTER, T. Y. KOH, L. K. NORFORD, C.-H. LIU, D. ENTEKHABI, D. Y. C. LEUNG, 2010: Large-eddy simulation of flow and pollutant transport in urban street canyons with ground heating. – Bound.-Lay. Meteorol **137**, 187–204. DOI:10.1007/s10546-010-9534-8

LIN, C. Y., F. CHEN, J. C. HUANG, W. C. CHEN, Y. A. LIOU, W. N. CHEN, S. C. LIU, 2008: Urban heat island effect and its impact on boundary layer development and land – sea circulation over northern Taiwan. – Atmos. Environment **42**, 5635–5649. DOI:10.1016/j.atmosenv.2008.03.015

LIU, Y. S., G. X. CUI, Z. S. WANG, Z. S. ZHANG, 2011: Large eddy simulation of wind field and pollutant dispersion in downtown macao. – Atmos. Environment **45**, 2849–2859. DOI: 10.1016/j.atmosenv.2011.03.001

MACDONALD, R. W., 2000: Modeling the mean velocity profile in the urban canopy layer. – Bound.-Lay. Meteorol. **97**, 25–45. DOI:10.1023/A:1002785830512

MILLS, G., H. CLEUGH, R. EMMANUEL, W. ENDLICHER, E. ERELL, G. MCGRANAHAN, E. NG, A. NICKSON, J. ROSENTHAL, K. STEEMER, 2010: Climate information for improved planning and management of mega cities (needs perspective). – Procedia Environ. Sci. **1**, 228–246. DOI:10.1016/j.proenv.2010.09.015

MOCHIDA, A., I. Y. F. LUN, 2008: Prediction of wind environment and thermal comfort at pedestrian level in urban area. – J. Wind Eng. Ind. Aerodyn. **96**, 1498–1527. DOI:10.1016/j.jweia.2008.02.033

NETELER, M., H. MITASOVA, 2007: Open Source GIS: A Grass GIS Approach. – Springer, 406 pp. DOI:10.1007/978-0-387-68574-8

NG, E., 2009: Policies and technical guidelines for urban planning of high-density cities – air ventilation assessment (AVA) of Hong Kong. – Building and Environment **44**, 1478–1488. DOI:10.1016/j.buildenv.2008.06.013

NG, E., editor, 2010: Designing High-Density Cities for Social and Environmental Sustainability. – Earthscan, London, **432**.

NG, E., 2012: Towards planning and practical understanding of the need for meteorological and climatic information in the design of high-density cities: A case-based study of Hong Kong. – Int. J. Climatol. **32**, 582–598. DOI:10.1002/joc.2292

NG, E., V. CHENG, 2012: Urban human thermal comfort in hot and humid Hong Kong. – Energy and Buildings, **55**, 51–65. DOI:10.1016/j.enbuild.2011.09.025

NG, E., K. S. WONG, 2004: Efficiency and liveability: Towards sustainable habitation in Hong Kong. – In: International Housing Conference in Hong Kong. Hong Kong Housing Authority.

OFFERLE, B., I. ELIASSON, C. S. B. GRIMMOND, B. HOLMER, 2007: Surface heating in relation to air temperature, wind and turbulence in an urban street canyon. – Bound.-Lay. Meteorol **122**, 273–292. DOI: 10.1007/s10546-006-9099-8

PARK, S.-B., J.-J. BAIK, S. RAASCH, M. O. LETZEL, 2012: A large-eddy simulation study of thermal effects on turbulent flow and dispersion in and above a street canyon. – J. Appl. Meteor. Clim. **51**, 829–841, DOI:10.1175/JAMC-D-11-0180.1

PIACSEK, S. A., G. P. WILLIAMS, 1970: Conservation properties of convection difference schemes. – J. Comput. Phys. **6**, 392–405. DOI:10.1016/0021-9991(70)90038-0

RAASCH, S., M. SCHRÖTER, 2001: PALM – A large-eddy simulation model performing on massively parallel computers. – Meteorol. Z. **10**, 363–372. DOI:10.1127/0941-2948/2001/0010-0363

REN, C., E. Y.-Y. NG, L. KATZSCHNER, 2011: Urban climatic map studies: a review. – Int. J. Climatol. **31**, 2213–2233. DOI:10.1002/joc.2237

RODI, W., J. H. FERZIGER, M. BREUER, M. POURQUIÉ (Eds.), 1995: Workshop on Large Eddy Simulation of Flows past Bluff Bodies, Rottach-Egern, Germany.

RODI, W., J. H. FERZIGER, M. BREUER, M. POURQUIÉ, 1997: Status of Large Eddy Simulation: Results of a workshop. – J. Fluids Eng. **119**, 248–262. DOI:10.1115/1.2819128

SAGAUT, P., 2006: Large Eddy Simulation for Incompressible Flows. – Springer-Verlag, Berlin/Heidelberg/New York, 556.

SCAPERDAS, A., S. G. ATKINS, 2004: Best practice advice for civil construction and HVAC, QNET-CFD network newsletter. – Technical Report **2**(4), QNET-CFD.

SCHATZMANN, M., B. LEITL, 2009: Evaluation of numerical flow and dispersion models for appications in industrial and urban areas. – Chem. Eng. Technol. **32**, 241–246. DOI:10.1002/ceat.200800578

SCHATZMANN, M., B. LEITL, 2011: Issues with validation of urban flow and dispersion CFD models. – J. Wind Eng. Ind. Aerodyn. **99**, 169–186. DOI:10.1016/j.jweia.2011.01.005

SCHLÜNZEN, K. H., D. GRAWE, S. I. BOHNENSTENGEL, I. SCHLÜTER, R. KOPPMANN, 2011: Joint modelling of obstacle induced and mesoscale changes – current limits and challenges. – Energy and Buildings **43**, 1139–1148. DOI:10.1016/j.jweia.2011.01.009

SCHUMANN, U., 1975: Subgrid scale model for finite difference simulations of turbulent flows in plane channels and annuli. – J. Comput. Phys. **18**, 376–404. DOI:10.1016/0021-9991(75)90093-5

SKOTE, M., M. SANDBERG, U. WESTERBERG, L. CLAESSON, A. V. JOHANSSON, 2005: Numerical and experimental studies of wind environment in an urban morphology. – Atmos. Environment **39**, 6147–6158. DOI:10.1016/j.atmosenv.2005.06.052

TACK, A., J. KOSKINEN, A. HELLSTEN, P. SIEVINEN, I. ESAU, J. PRAKS, M. HALLIKAINEN, 2012: Morphological database of Paris for atmospheric modeling purposes. – IEEE Journal of Selected Topics in Applied Earth Observation and Remote Sensing Vol. 5, 1803–1810. DOI:10.1109/JSTARS.2012.2201134

TAMURA, T., 2008: Towards practical use of LES in wind engineering. – J. Wind Eng. Ind. Aerodyn. **96**, 1451–1471. DOI:10.1016/j.jweia.2008.02.034

TEAM CLEAN, 2003: Report on measures to improve environmental hygiene in Hong Kong. – The Government of the Hong Kong Special Administrative Region.

TOMINAGA, Y., A. MOCHIDA, T. SHIRASAWA, R. YOSHIE, H. KATAOKA, K. HARIMOTO, T. NOZU, 2004: Cross comparisons of CFD results of wind environment at pedestrian level around a high-rise building and within a building complex. – J. Asian Arch. Build. Eng. **3**(1), 63–70.

TOMINAGA, Y., A. MOCHIDA, R. YOSHIE, H. KATAOKA, T. NOZU, M. YOSHIKAWA, T. SHIRASAWA, 2008: AIJ guidelines for practical applications of CFD to pedestrian wind environment around buildings. – J. Wind Eng. Ind. Aerodyn. **96**, 1749–1761. DOI:10.1016/j.jweia.2008.02.058

TSENG, Y.-H., C. MENEVEAU, M. B. PARLANGE, 2006: Modeling flow around bluff bodies and predicting urban dispersion using large eddy simulation. – Environ. Sci. Technol. **40**, 2653–2662. DOI:10.1021/es051708m

UN-HABITAT, 2008: State of the world's cities, 2008/2009: harmonious cities. – Earthscan, London, 264.

XIE, Z.-T., 2011: Modelling street-scale flow and dispersion in realistic winds – towards coupling with mesoscale meteorological models. – Bound.-Lay. Meteorol **141**, 53–75. DOI:10.1007/s10546-011-9629-x

XIE, Z. T., I. P. CASTRO, 2009: Large-eddy simulation for flow and dispersion in urban streets. – Atmos. Environment **43**, 2174–2185. DOI:10.1016/j.atmosenv.2009.01.016

XIE, Z.-T., O. COCEAL, I. P. CASTRO, 2008: Large-eddy simulation of flows over random urban-like obstacles. – Bound.-Lay. Meteorol. **129**, 1–23. DOI:10.1007/s10546-008-9290-1

YAN, Y. Y., 2007: Surface wind characteristics and variability in Hong Kong. – Weather**62**, 312–316. DOI:10.1002/wea.46

YANG, L., Y. LI, 2011: Thermal conditions and ventilation in an ideal city model of Hong Kong. – Energy and Buildings **43**, 1139–1148. DOI:10.1016/j.enbuild.2010.06.005

YIM, S. H. L., J. C. H. FUNG, A. K. H. LAU, S. C. KOT, 2007: Developing a high-resolution wind map for a complex terrain with a coupled MM5/CALMET system. – J. Geophys. Res. **112**(D05106). DOI:10.1029/2006JD007752

YOSHIE, R., A. MOCHIDA, Y. TOMINAGA, H. KATAOKA, K. HARIMOTO, T. NOZU, T. SHIRASAWA, 2007: Cooperative project for CFD prediction of pedestrian wind environment in the Architectural Institute of Japan. – J. Wind Eng. Ind. Aerodyn. **95**, 1551–1578. DOI:10.1016/j.jweia.2007.02.023

YOSHIE, R., H. TANAKA, T. SHIRASAWA, T. KOBAYASHI, 2008: Experimental study on air ventilation in a built-up area with closely-packed high-rise buildings (in Japanese). – J. Environ. Eng., AIJ **73**(627), 661–667.