Urban roughness sublayer characteristics: sensitivity to planetary boundary layer schemes and multilayer urban models

Wanliang ZHANG[1], Jimmy C.H. Fung[1,2], Michael, M.F. Wong[1]

[1]Division of Environment and Sustainability, The Hong Kong University of Science and Technology, wzhangcy@connect.ust.hk

[2]Department of Mathematics, The Hong Kong University of Science and Technology

This presentation participates in OSPP

Outstanding Student & PhD candidate Presentation contest

Abstract

In this study, we examined the sensitivity of simulated wind speed and local friction velocity profiles to the a) planetary boundary layer (PBL) schemes in WRF, and b) the multilayer urban canopy models (UCMs). The validation is done by utilizing the high-resolution LiDAR measurements and the empirical equation proposed by Rotach (2001).

1. PBL schemes coupled with UCMs can reproduce the inflection point at the canopy height in the wind speed profile as opposed to the bulk parameterization of surface momentum flux. The UCMs result in an increasing trend of the local friction velocity (u_*) below the roughness sublayer (RSL or z_*) height followed by descending whereas the bulk method suggests the momentum flux is monotonically decreasing from the ground level.
2. The TKE-ACM2 PBL scheme featuring a non-local momentum transfer can generate height from 1.4-1.8 times the average building height (H) under the unstable atmospheric conditions. In contrast, under stable conditions the RSL approaches $z_* = H$. The former coincides with Oikawa and Meng (1995).
3. TKE-ACM2 produces a monotonically decreasing yet of small gradient u_* above the RSL under unstable conditions, which is deemed as the constant flux layer (CFL). The average depth of CFL ranges from $3H$ to $4H$.
4. The Boulac PBL scheme which uses the same 1.5-order turbulence closure model as TKE-ACM2 produces $z_* = H$ regardless of atmospheric stabilities. Closer inspections show u_* peaks at $z_* = H$ which corresponds to the maximum wind speed gradient.
5. Inter-scheme differences are found in UCMs when coupled with the TKE-ACM2 scheme: BEM that considers the thermal exchange between the buildings and atmosphere results in a consistently unstable regime throughout the day; different parameterizations of C_{drag} in calculating the aerodynamic drag have profound influences in the simulated wind speeds.

Background

- ✓ The height of the maximum u_* serves as a surrogate for the top of RSL (z_*).
- ✓ The profile of local friction velocity (u_*) representing the drag effects of buildings below z_* is fitted by Rotach (2001) using a variety of wind tunnel results and field measurements (shown in Figure 1).
- ✓ Hong Kong and nearby mega-cities in the Pearl River Delta region are characterized by a high urban fraction with densely built medium- to high-rise buildings.
- ✓ We utilized different PBL models coupled with different UCMs to examine whether the effects of buildings are adequately reflected through the wind speed and u_* profiles.

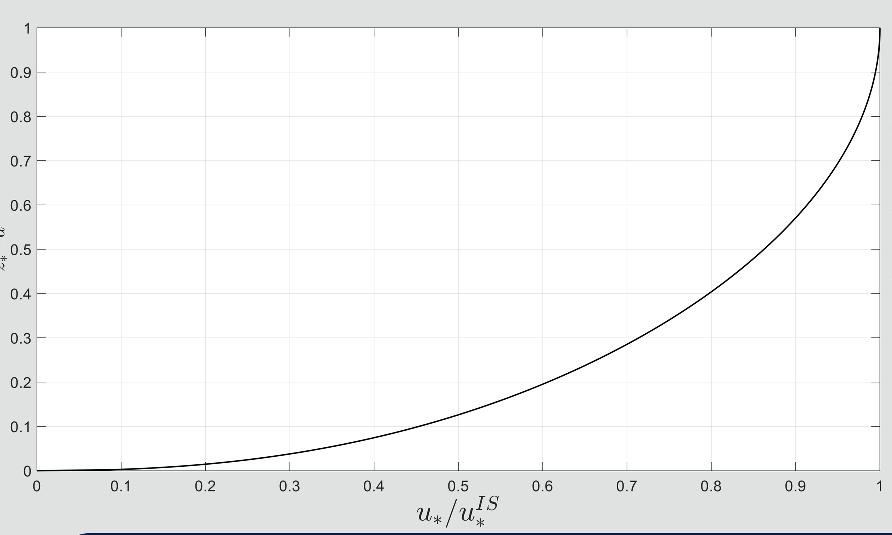


Figure 1: Local friction velocity u_* as a function of non-dimensional height. Reproduced from Rotach (2001) following Eqn.2

u_*^{IS}: u_* at the top of RSL
d: zero-displacement height

References

Oikawa, S., & Meng, Y. (1995). Turbulence characteristics and organized motion in a suburban roughness sublayer. *Boundary-Layer Meteorology*, *74*(3), 289–312. https://doi.org/10.1007/BF00712122

Rotach, M. W. (2001). Simulation Of Urban-Scale Dispersion Using A Lagrangian Stochastic Dispersion Model. *Boundary-Layer Meteorology*, *99*(3), 379–410. https://doi.org/10.1023/A:1018973813500

Methodology

PBL schemes

The two PBL schemes are briefly described below. The key difference between TKE-ACM2 and Boulac is that TKE-ACM2 uses a transilient matrix (Mu) approach to determine the non-local momentum flux, heat flux and TKE flux under convective conditions while Boulac adopts a counter-gradient term (γ) for the heat flux only.

	Turbulence closure model	Momentum flux	Heat flux
TKE-ACM2	1.5-order TKE-based turbulence closure model	$\overline{u'w'}_{i+1/2} = -K_m \frac{\partial u}{\partial z_{i+1/2}} + \mathrm{Mu}(\mathrm{PBLH} - z_{i+\frac{1}{2}})(u_1 - u_i)$	$\overline{\theta' w'}_{i+1/2} = -K_h \frac{\partial \theta}{\partial z_{i+1/2}} + \mathrm{Mu}(h - z_{i+\frac{1}{2}})(\theta_1 - \theta_i)$
Boulac		$\overline{u'w'}_{i+1/2} = -K_m \frac{\partial u}{\partial z_{i+1/2}}$	$\overline{\theta' w'}_{i+1/2} = -K_h (\frac{\partial \theta}{\partial z_{i+\frac{1}{2}}} - \gamma)$

Multi-layer urban canopy models

The Building Effects Parameterization (BEP) and Building Energy Model (BEM) are used with abovementioned two PBL schemes. Cases adopting the bulk parameterization of surface layer fluxes using the revised MM5 scheme are also shown as the reference in **Results** section. In WRFv4.3, the drag coefficient (C_{drag}) in BEM is revised to be a function of building plan area fraction (λ_p) which is different to the constant value in BEP ($C_{drag} = 0.4$). Therefore, we performed additional BEP simulations using the new $C_{drag}(\lambda_p)$ which is modelled as:

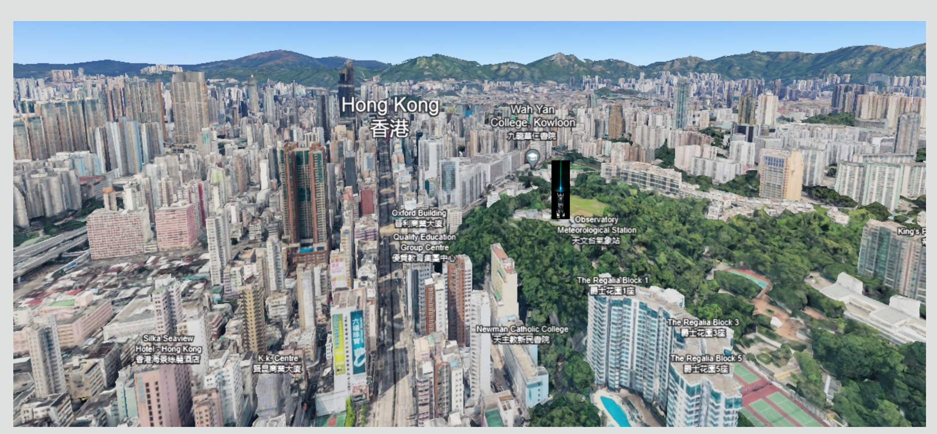
$C_{drag} = 3.32\lambda_p^{0.47}$, for $\lambda_p \leq 0.29$ or $C_{drag} = 1.85$, for $\lambda_p > 0.29$

where the building plan area fraction λ_p is calculated using the building width (BW) and the street width (SW):

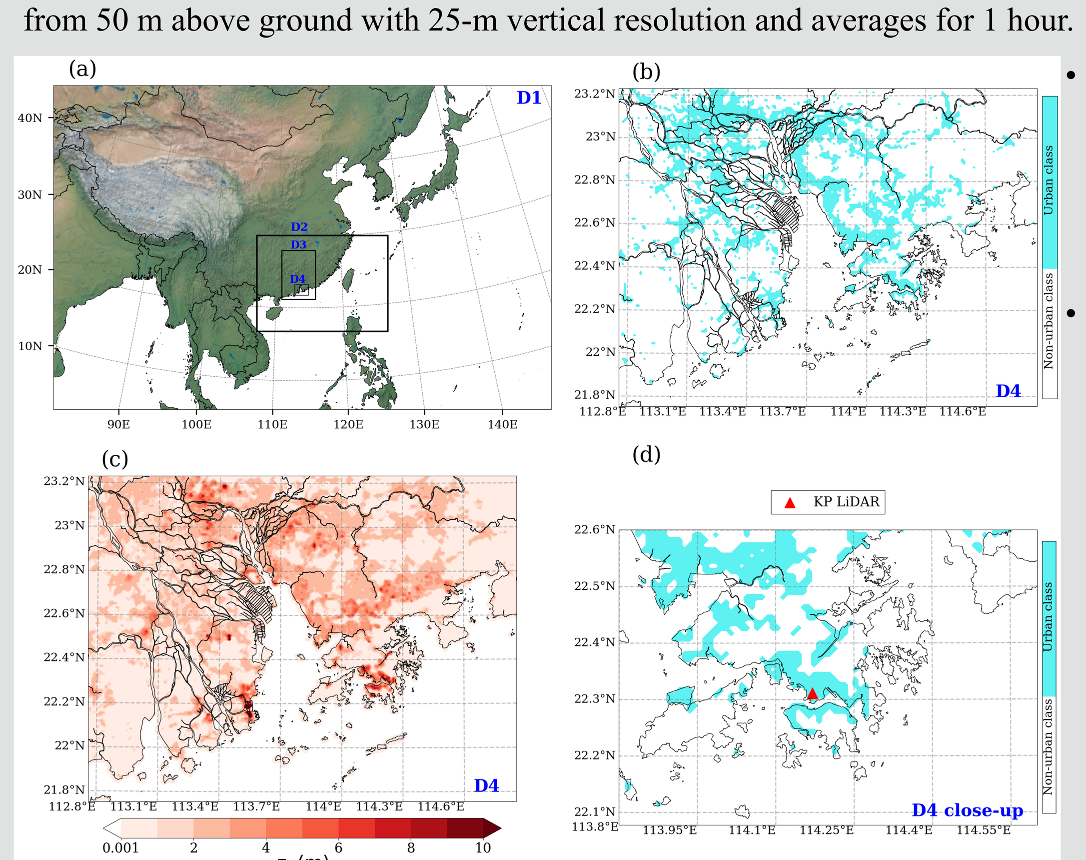
$$\lambda_p = \frac{BW}{SW + BW} \qquad \text{Eqn.1}$$

Simulation domain and LiDAR observation

Figure 2: Fetch of King's Park LiDAR observation site at the highly urbanized area in Hong Kong
a) North-east view b) South-west view



The four-nest domain is shown in **Figure 3a**. The urban fraction in the inner most domain 4 is shown in **Figure 3b**. The roughness length for case using bulk method of surface momentum fluxes is shown in **Figure 3c**. **Figure 3d** depicts the location of the LiDAR unit located in center Kowloon, Hong Kong. The Doppler LiDAR provides three-dimensional wind speeds measurements from 50 m above ground with 25-m vertical resolution and averages for 1 hour.



- Bulk method simulations: $\overline{u'w'}_0$ calculated using MOST where z_0 horizontal contour is shown in **Figure 3c**. There, z_0 is derived from the urban geometrical properties and is no longer obtained from the traditional look-up table method.
- BEP and BEM simulations: We assume an *idealized urban morphology* in which the urban class is all set to class 2. Key urban parameters are summarized as follows:

Building height (H)	60 m (100%)
Street width (SW)	25 m
Building width (BW)	17 m
Parameters related to thermal	Default values in URBPARM.TBL

Figure 3: four-nest domain with the inner most domain in the PRD region in southern China. Light blue indicates the urban area. Wind LiDAR location is drawn in green marker.

Results

The momentum ($\sqrt{u^2 + v^2}$) and the local friction velocity $u_* = (\overline{u'w'}^2 + \overline{v'w'}^2)^{1/4}$ profiles simulated by TKE-ACM2 and Boulac are shown below. u_* is normalized by the maximum value, u_*^{IS} of which height is deemed as the top of the RSL (z_*) and the bottom of the Inertial Sublayer, or the **C**onstant **F**lux **L**ayer (CFL). For validation purposes, the curve fitted by Rotach (2001) shown in Eqn.2 for u_* within the RSL are drawn with the black solid line.

$$u_* = u_*^{IS}[\sin\left(\frac{\pi}{2}\frac{z - d}{z_* - d}\right)^{1.28}]^{1/3} \qquad \text{Eqn.2}$$

where d is the zero-displacement height.

TKE-ACM2 PBL scheme results

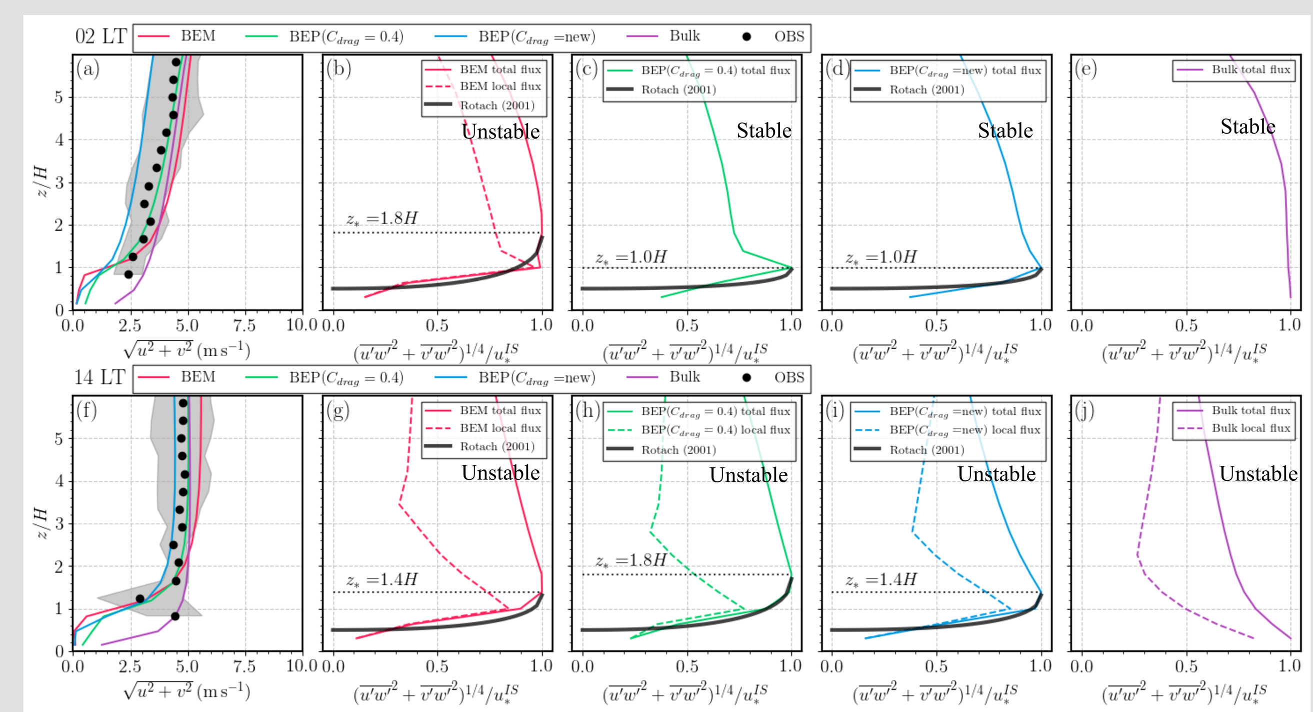


Figure 4: Wind speed and Reynolds stress profiles averaged at 02 (night) and 14 (day) local time (LT). The y-axis is normalized by the building height which is homogeneously 60 m. The dashed lines represent the local fluxes ($-K\frac{\partial U}{\partial z}$). The black markers represent the LiDAR observations for wind speeds, and the black solid lines depict the u_* calculated from Eqn. 2

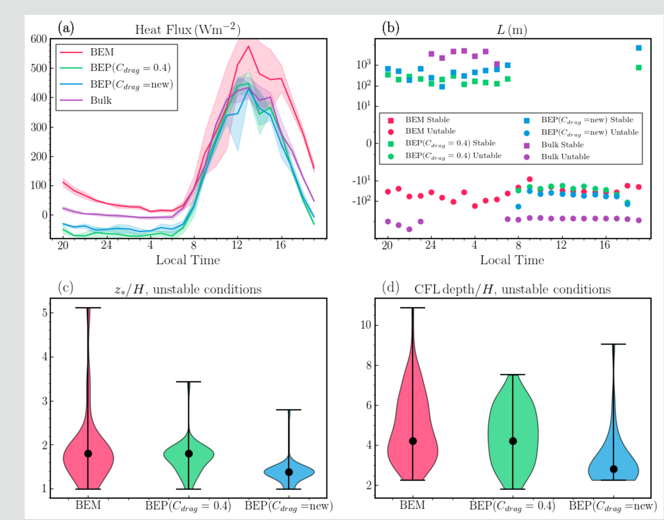


Figure 5: Diurnal profiles for
a) the residual heat flux
b) Monin-Obukhov length (L)
c) RSL height (z_*) normalized by the building height (60 m). The bulk method for surface layer fluxes produces greatest Reynold's stress at the first layer.
d) the constant flux layer (CFL) depth calculated above the RSL. The CFL depth is the height at which u_* first decreases to 90% of u_*^{IS}

Boulac PBL scheme results

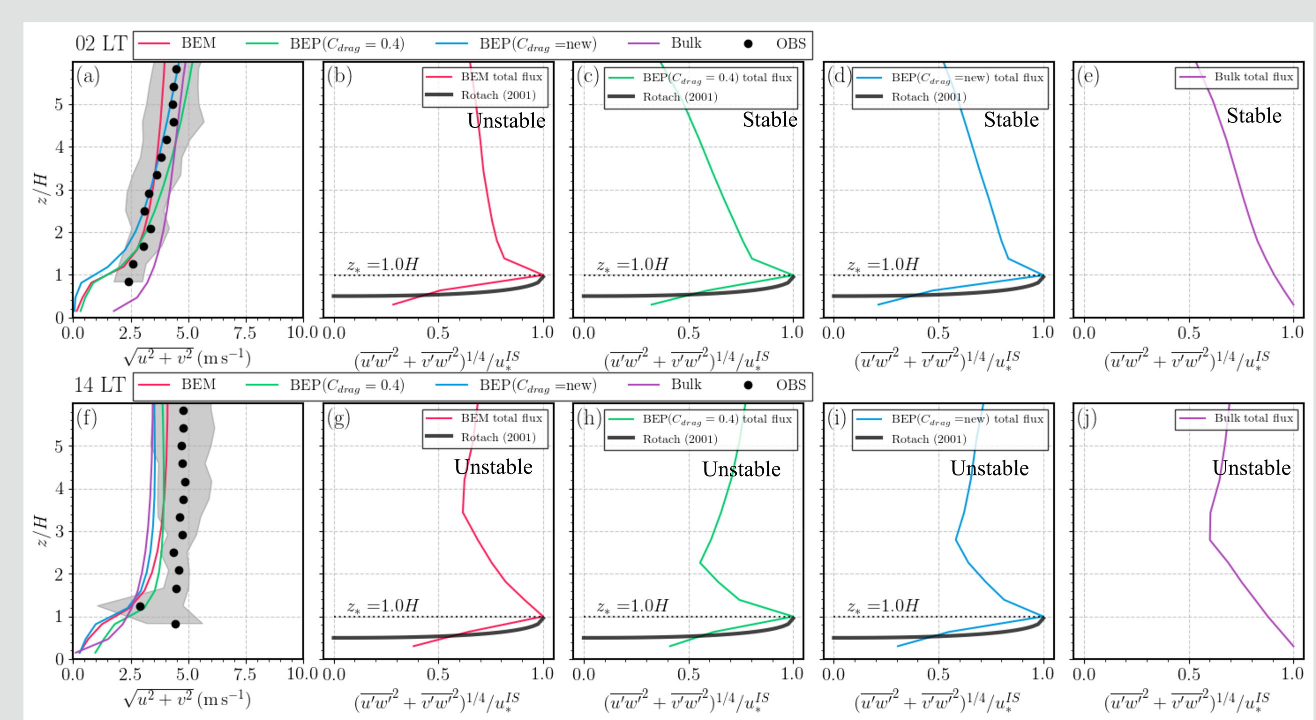


Figure 6: Wind speed and Reynolds stress profiles averaged at 02 (night) and 14 (day) local time (LT). The y-axis is normalized by the building height which is homogeneously 60 m.. The black markers represent the LiDAR observations for wind speeds, and the black solid lines depict the u_* calculated from Eqn. 2

Discussions

- **BEP** using two different C_{drag} shows consistent reductions of wind speeds compared to the bulk method and **agrees better with LiDAR measurements**. BEM shows slower wind speeds below $z = 2H$ and generates accelerated wind speeds above.
- All multi-layer UCMs can reproduce the increasing trend of u_* below z_* as well as the descending trend beyond z_*. The bulk method shows a monotonic decrease of u_*.
- BEM results in a consistently unstable conditions over the urban area by considering the energy exchange between the buildings and atmosphere (Figure 5a).
- The max local flux ($-K\frac{\partial U}{\partial z}$) always occurs at $\frac{z}{H} = 1$, regardless of the atmospheric stabilities. This leads to $z_* = H$ under stable conditions which are typically during the nighttime.
- Under unstable conditions, the total flux generated by TKE-ACM2 peaks at around $z = 1.5H$, which is attributable to that the non-local momentum flux reaches the maximum at an elevated height. In this case, the profile of u_* agrees well with the trend in the curve fitted by Rotach (2001) within the RSL. The height of RSL $z_* \approx 1.5H$ shows satisfactory alignment with Oikawa and Meng (1995) but it deviates from other research where z_* is found greater than $2H$.