### Highlight article

249 Cyanobacterial bloom dynamics in Lake Taihu  
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Numerical study of the effects of Planetary Boundary Layer structure on the pollutant dispersion within built-up areas

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ABSTRACT

The effects of different Planetary Boundary Layer (PBL) structures on pollutant dispersion processes within two idealized street canyon configurations and a realistic urban area were numerically examined by a Computational Fluid Dynamics (CFD) model. The boundary conditions of different PBL structures/conditions were provided by simulations of the Weather Researching and Forecasting model. The simulated results of the idealized 2D and 3D street canyon experiments showed that the increment of PBL instability favored the downward transport of momentum from the upper flow above the roof to the pedestrian level within the street canyon. As a result, the flow and turbulent fields within the street canyon under the more unstable PBL condition are stronger. Therefore, more pollutants within the street canyon would be removed by the stronger advection and turbulent diffusion processes under the unstable PBL condition. On the contrary, more pollutants would be concentrated in the street canyon under the stable PBL condition. In addition, the simulations of the realistic building cluster experiments showed that the density of buildings was a crucial factor determining the dynamic effects of the PBL structure on the flow patterns. The momentum field within a denser building configuration was mostly transported from the upper flow, and was more sensitive to the PBL structures than that of the sparser building configuration. Finally, it was recommended to use the Mellor–Yamada–Nakanishi–Niino (MYNN) PBL scheme, which can explicitly output the needed turbulent variables, to provide the boundary conditions to the CFD simulation.

Introduction

Air exchange between the pedestrian level and the free flow above the buildings is limited within built-up areas, and the anthropic pollutants released near ground are not effectively removed, which could deteriorate the air quality there and impose harmful impacts on the health of the citizens. Therefore, it is helpful to study the dispersion processes within the built-up areas and enrich our fundamental understanding of the air quality problems within building clusters.

Traditionally, the methods to study flow fields and the pollutant dispersion process within built-up areas have included field measurements and laboratory physical experiments (i.e., wind-tunnel and water-tank experiments). However, it has been found that field measurements and physical experiments are limited by their low spatial resolution and...
high cost (Mestayer et al., 2005; Xie et al., 2003; Allwine et al., 2002; Li et al., 2008; Baik et al., 2000). During the past decades, the rapid increase of computing power and the development of numerical models have made it possible to numerically examine the complex flow fields and environmental issues within built-up areas at high resolution (Li et al., 2007; Baik et al., 2009; Miao et al., 2013).

The flow patterns of regions with buildings are quite different from that without the influence of buildings (Baik et al., 2009; Miao et al., 2013), and differences exist in the distribution of turbulent variables and pollutant concentration as well. Thus, it is necessary to employ high resolution Computational Fluid Dynamics (CFD) models to explicitly examine the dynamic effects of buildings and to better understand the 3D flow fields and the associated concentration patterns within complex built-up areas (Li et al., 2006).

Many numerical studies (Chan et al., 2001; Kim and Baik, 2004; Tong and Leung, 2012; Miao et al., 2014b; Baik et al., 2009) have been conducted to understand the effects of building configurations (i.e., the ratio of the building height to the street canyon width) and the direction of ambient wind. However, how the Planetary Boundary Layer (PBL) structure/condition affects the flow patterns and the dispersion processes at the pedestrian level within built-up areas is rarely studied and poorly understood. The PBL is part of the troposphere that is directly influenced by the presence of the earth’s surface, and the structure of the PBL varies according to the change of surface forcings. For example, in the daytime, as the land surface is warmed by the sun radiation, the convective unstable PBL can be well established and grow up to a few kilometers over land. After sunset, as the land surface cools by the nocturnal radiation process, the bottom portion of the troposphere is transformed into the nocturnal stable PBL. The stability and structure of the PBL (i.e., stable, unstable) can not only affect the regional air quality (Hu et al., 2014), but is also another key factor affecting pedestrian level dispersion processes among buildings.

In this study, to bridge the aforementioned knowledge gap, the effects of PBL stability and structure on dispersion within urban areas were examined using the Weather Researching and Forecasting (WRF) and CFD models.

### 1. Model description and numerical setup

In this study, three different PBL structures (stable, unstable and extremely unstable) were evaluated within three kinds of building configuration (2D street canyon, 3D street canyon and realistic building cluster). The different PBL structures were provided by well-designed WRF simulations, and the high resolution wind and turbulent fields were calculated by a CFD model that can explicitly resolve the buildings.

#### 1.1. Weather Researching and Forecasting model

The mesoscale meteorological model employed in this study is the WRF model version 3.6 (released in 18 April 2014), which is designed to serve the needs of both forecasting and research. The model is developed collaboratively by the National Center for Atmospheric Research (NCAR), the National Oceanic and Atmospheric Administration (NOAA), the Air Force Weather Agency (AFWA), the Naval Research Laboratory, the University of Oklahoma, and the Federal Aviation Administration (FAA). For further details, readers are referred to http://www.ucar.edu/wrf/users.

Three 2-way nested domains were set (Fig. 1 and Table 1), with horizontal grid spacings of 27, 9 and 3 km, respectively. There were 55 vertical layers set from the ground level to the 50-hPa level. The physics parameterization schemes and domain configurations used are summarized and presented in Table 1. Specifically, we used the Rapid Radiative Transfer Model for General circulation models (RRTMG) scheme (Iacono et al., 2008) to simulate the radiation processes. For the cloud physics process, the Thompson graupel scheme (Thompson et al., 2008) was selected. The other physics options include the Kain–Fritsch Cumulus scheme (Kain, 2004) for the two outer nested domains, the Mellor–Yamada–Nakanishi–Niino (MYNN) PBL scheme (Nakanishi and Niino, 2006), the Noah land surface model (LSM) (Chen and Dudhia, 2001) and the single-layer urban canopy model (UCM) (Kusaka et al., 2001; Kusaka and Kimura, 2004). The land use dataset used was that based on Moderate-resolution Imaging Spectroradiometer (MODIS).

![Fig. 1 – Nested computational domains in the Weather Researching and Forecasting model (WRF) simulation.](image-url)
The WRF initial and boundary conditions were set by using the 6-hourly 1° × 1° National Centers for Environmental Prediction (NCEP) Final Analysis (FNL) dataset, and a 42-hour simulation (0800 LST 03 October to 0200 LST 05 October, 2010) was conducted. The first 16 hr were used as spin-up time, and the interval of the WRF simulation output was an hour. During the simulation period, the Beijing area was controlled by a high pressure system (Tian et al., 2013).

It is also worth noting that unlike the previous study of Miao et al. (2013, 2014a), the MYNN PBL scheme was employed in this study; from the WRF version 3.4, the simulated Turbulent Kinetic Energy (TKE) and its dissipation rate (Nakanishi and Niino, 2006) can be directly output by the bl_mynn_tkebudget option in the namelist.input file. Therefore, it is unnecessary to parameterize the turbulent variables (Miao et al., 2013) in this study. Similar to the previous study of Miao et al. (2013), the WRF 3 km resolution simulations located nearest to the Zhongguancun of Beijing (116.306°E, 39.978°N) were extracted out and used for the boundary conditions of the CFD simulation.

### 1.2. Computational Fluid Dynamics model

As with the CFD model, we used the version 2.1.1 of the Open Source Field Operation and Manipulation (OpenFOAM) software package. The model is managed and distributed by the not-for-profit organisation called OpenFOAM Foundation, which is based in the UK. For further details of the CFD model, please refer to http://www.openfoam.com.

Similar to the previous studies of Miao et al. (2014a, 2014b), to calculate the Reynolds Average Navier–Stokes (RANS) equations, the simpleFoam solver of OpenFOAM was used in this study by using the standard $k$-$\varepsilon$ turbulence model. The Semi-implicit Method for Pressure-Linked Equations (SIMPLE) model was used to decouple the momentum and pressure equations. The simulations were performed at a grid size of 27, 9, and 3 km, with 55 vertical layers below 1500 m. The Thompson graupel scheme was used for microphysics, and the Kain–Fritsch scheme was used for the first and second domains. The Rapid Radiative Transfer Model for General circulation models (RRTMG) scheme was used for radiation, and the Noah Land Surface Model (LSM) with Urban Canopy Model (UCM) was used for the land surface. The Mellor-Yamada-Nakanishi-Niino (MYNN) scheme was used for the PBL.

### Table 1 – Domain configurations and physic options of the Weather Researching and Forecasting model (WRF) simulation.

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<th>Domain configurations and physics options</th>
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<th>Thompson graupel scheme</th>
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The simulations are taken at the 3 km resolution Weather Researching and Forecasting model (WRF) grid point nearest to the stations.

**Fig. 2** – Time series of observed and simulated (a, d, and g) 2-m temperature, (b, e, and h) 10-m wind speed (m/sec) and (c, f, and i) direction at (a–c) the ShunYi station (116.617°E, 40.117°N), (d–f) the Tongzhou station (116.617°E, 39.917°N), and (g–i) the Guanxiangtai station (116.467°E, 39.783°N). The simulations are taken at the 3 km resolution Weather Researching and Forecasting model (WRF) grid point nearest to the stations.
scheme (Ferziger and Peric, 2001; Miao et al., 2014a) was utilized to iteratively calculate the algebraic system of equations. The RANS equations include a mass equation, momentum equation, and mass transport equation.

\[
\frac{\partial u_j}{\partial x_j} = 0, \quad (1)
\]

\[
\frac{\partial u_i}{\partial t} + \frac{\partial}{\partial x_j} (u_i u_j) - \frac{\partial}{\partial x_j} \left( \nu_{\text{eff}} \frac{\partial u_i}{\partial x_j} \right) = - \frac{\partial p}{\partial x_i}, \quad (2)
\]

\[
\frac{\partial C}{\partial t} + \frac{\partial}{\partial x_j} (u_j C) = - \frac{\partial C}{\partial x_j} = S, \quad (3)
\]

where, \( u_i \) is the \( i \)th velocity component, \( C \) is the pollutant concentration, and \( S \) is the source term of the pollutant. In Eqs. (2) and (3), \( \nu_{\text{eff}} \) and \( v_d \) are the effective kinematic viscosity and diffusion coefficient, which are expressed as:

\[
\nu_{\text{eff}} = \nu_0 + \nu_1, \quad v_d = \nu_1 / S_{\text{ct}}. \quad (4)
\]

where, \( \nu \) and \( \nu_1 \) are the molecular viscosity and turbulence viscosity, \( S_{\text{ct}} \) is the Schmidt number, and \( P_{\text{ct}} \) is a modified mean kinematic pressure. The pollutant dispersion process includes both advection and turbulent diffusion; advection is due to the mean wind fields, while diffusion involves the turbulent mixing of pollutants. In Eq. (3), the second item on the left represents the advection of pollutants, and the third item represents the diffusion process. The validations of OpenFOAM can be found in the previous studies of Miao et al. (2013, 2014a, 2014b).

In this study, the effects of the PBL structure on dispersion processes were examined within different building configurations, including the idealized 2D street canyon, the idealized 3D street canyon and a realistic building cluster. The various boundary conditions (i.e., stable, unstable and extremely unstable) were extracted from the WRF output, and the details of the boundary conditions and building configurations are described in Section 2.

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Fig. 3 – Wind speed profiles of (a) 2D street canyon experiment and (b) 3D street canyon experiment, and the (c) Turbulent Kinetic Energy (TKE) and (d) its dissipation rate profiles of different Planetary Boundary Layer (PBL) structures at 0800 LST (stable), 1100 LST (unstable) and 1400 LST (extremely unstable) on 04 October 2014. The TKE and its dissipation rate profiles are extracted from the Weather Researching and Forecasting model (WRF) simulation at Zhongguancun (116.306°E, 39.978°N).

Fig. 4 – Simulated velocity streamline patterns within 2D street canyon under (a) the stable Planetary Boundary Layer (PBL) condition, (b) unstable PBL condition, and (c) the extremely unstable PBL condition.
2. Results and discussion

In this section, the WRF simulated results are first validated against the measurements from the meteorological stations. Then the effects of the PBL structure on dispersion processes within different building configurations are presented and discussed.

2.1. Evaluation of WRF simulation

The simulated and observed 2-m temperature, 10-m wind speed and wind direction of three meteorological stations are shown in Fig. 2. It is found that the simulated temperature is slightly higher than the observed one around 1400 LST, and a little lower than the observation at night. Despite this discrepancy, the diurnal cycle of surface temperature was well simulated.

As depicted in Fig. 2, although the wind speed at the Guanxiangtai stations (Fig. 2h) was overestimated by the WRF model, comparing the simulations with the measurements, most of the fluctuation characteristics of wind speed at the three stations during the simulation period could be simulated.

In addition, the series of the simulated and observed wind direction exhibits a diurnal pattern that is associated with the mountain-valley breeze circulation of Beijing (Liu et al., 2009; Miao et al., 2015a, 2015b). In the early morning, Beijing is dominated by the cold northern downslope mountain-breeze; and the dominant wind turns into the warm southern upslope valley-breeze during the day; at night, the southern valley-breeze disappears gradually and is replaced by the northern downslope mountain-breeze again. This evolution of the local atmospheric circulation was also well simulated.

In short, the WRF model was capable of simulating the atmospheric conditions from 0000 LST 04 October to 0000 LST 05 October 2010.

The evolution of the 2-m temperature reflects the diurnal variation of surface thermal forcings, and the change of surface forcings (i.e., sensible heat flux and latent heat flux) would affect the vertical structure of the PBL. In the early morning before sunrise a stable inversion layer exists near the surface; after sunrise, as the surface is warmed by the
sunlight, the inversion layer disappears gradually and is replaced by a convective unstable PBL. For instance, at 0800 LST, there is an inversion layer within the surface layer; at 1100 LST, the former stable PBL is replaced by an unstable PBL, and the PBL’s stability becomes more and more unstable as the surface temperature increases; at 1400 LST, the PBL is extremely unstable. Therefore, the WRF-simulated TKE and its dissipation rate at these three moments (i.e., 0800 LST, 1100 LST and 1400 LST) at Zhongguancun of Beijing were extracted out to use as the boundary conditions for the subsequent CFD simulations (Fig. 3).

2.2. Effects of PBL structure on dispersion within 2D street canyon

The first 2D street canyon configuration (Meroney et al., 1996; Rafailidis, 1997; Miao et al., 2014b) consists of six buildings and five parallel street canyons at a scale of 1:500. The buildings are square, with 60 mm width and height, and the line source of tracer is placed on the ground level in the third downstream canyon. All the computational domain set-up and source displacement was the same as in the previous study of Miao et al. (2014b); that is, the computational domain was 600 mm × 480 mm for the X-direction and Z-direction with a finer grid spacing (2 mm) for the third street canyon. The simulated concentration is given in a normalized form as follows:

\[ K = \frac{cULH}{Q} \]  

where, \( K \) is the normalized concentration, \( c \) is the measured concentration, \( U \) is the reference velocity (5 m/sec), \( H \) is the building height, \( L \) is the source length (the y-direction computational dimension) and \( Q \) is the source strength.

To simulate the wind and turbulent fields of different PBL structures, the initial and boundary conditions of TKE and dissipation rate were set by the WRF simulation of different times (i.e., 0800 LST, 1100 LST and 1400 LST), while the inlet velocity was set up by the experimental data of a 2D wind-tunnel experiment (Meroney et al., 1996; Rafailidis, 1997; Miao et al., 2014b). In other words, the different 2D street canyon simulations were conducted by using the same inlet velocity boundary condition (Fig. 3a) with different TKE and dissipation rate boundary conditions (Fig. 3c and d). The WRF-simulated TKE and dissipation rate were downscaled to match the wind-tunnel experiment to drive the CFD simulation. In the following sections, the simulated flow patterns and TKE fields are analyzed to understand the strength of the advection and diffusion processes (Eq. (3)) under different PBL conditions, respectively.

Fig. 4 shows the simulated velocity streamline patterns of different PBL. It is found that the general streamline patterns are almost the same under different PBL conditions, that is, a clockwise vortex is formed right in the center of the 2D street canyon.
canyon. However, the distributions of the velocity show some differences along the building walls and floor within the street canyon; as the instability of the PBL increases, the velocity along the inward walls and floor within the street canyon becomes higher. Compared with the stable PBL case, more momentum can be transported downward from the upper stronger flows above the roof into the street canyon in the unstable PBL cases (Fig. 4). The increment of PBL instability favors the vertical transport of momentum in this 2D street canyon case. As a result, the more unstable PBL is, the stronger the vertical vortex is formed in the street canyon.

As depicted in Fig. 5, under different PBL conditions, the distributions of TKE are quite different. With the extremely unstable PBL, the TKE fields of the street canyon are much stronger than that of the stable PBL. The increment of PBL instability increases the TKE field within the street canyon, as well as the strength of the turbulent diffusion process of pollutants.

From Figs. 4 and 5, it is concluded that the change of the PBL structure cannot change the general pattern of wind field in the 2D street canyon, but can act to modify the strength of the vertical vortex and the turbulent field. And the turbulent field is more sensitive to the PBL structure than the vertical wind field. As a result, the advection process of pollutants driven by the wind field (Fig. 4) and the diffusion of pollutants caused by the turbulent field (Fig. 5) are various under the different PBL conditions, leading to the different simulated pollutant concentration fields within the 2D street canyon (Fig. 5). Among these three cases, under the stable PBL condition, the turbulent mixing within the street canyon is weakest, and the pollutant is transported primarily by advection, resulting in a pollutant plume which could travel vertically a long distance along the building wall without much change in pollutant concentrations (Fig. 5d). On the other hand, under the unstable PBL conditions, when the turbulent diffusion processes within the street canyon are stronger, the pollutants could mix more quickly, resulting in substantial changes to pollutant concentrations in the plume (Fig. 5e, f). The pollution level is heaviest under the stable PBL condition due to the weakest turbulent diffusion process; on the contrary, the lightest pollution is found in the extremely unstable case.

2.3. Effects of PBL structure on dispersion within 3D street canyon

The 3D street canyon configuration consists of two parallel buildings of 0.12 m × 0.12 m × 0.12 m (height × width × length) at a scale of 1:150, which is similar to that of the previous study of Miao et al. (2014b). The cross-sectional dimensions of the computational domain were set equal to the dimensions of the wind-tunnel experiment (Gromke et al., 2008; Moonen et al., 2013), that is, 1 m high and 2 m wide. The computational domain was built using hexahedral elements, and a finer resolution was set for the region close to the parallel buildings (Fig. 6). Four tracer gas emitting line sources were embedded at street surface level in the center of the street canyon, and the simulated concentration was normalized by the following equation:

$$c^+ = \frac{c U_H H}{Q_L}$$

where $c$ is the measured concentration, $H$ is building height, $U_H$ is
is the flow velocity at height $H$ in the undisturbed approaching flow and $Q_L$ is the emission rate of line source.

As depicted in Fig. 6, the isolated street canyon configuration was exposed to a perpendicular approaching flow. Similar to the 2D street canyon case, the inlet velocity was set up by the wind-tunnel experimental data (Fig. 3b), while the initial and boundary conditions of TKE and dissipation rate were set by the simulations of WRF (Fig. 3c, d).

The vertical distributions of flow fields are given in Fig. 7, and similar to the flow patterns of the 2D street canyon (Fig. 4), the flow patterns of different PBL conditions on the vertical planes are almost the same — a clockwise vortex is formed right in the center of the street canyon. However, the strengths of the vertical vortexes are different; the increment of PBL instability favors the vertical transport of momentum from the roof level into the street canyon, and the vortexes in the unstable cases are stronger than that of the stable case. As a result, the horizontal flow fields at the height of 0.1 $H$ show differences under the different PBL conditions (Fig. 8). In the stable case (Fig. 8a), the vertical motion at the height of 0.1 $H$ is significantly weaker than that of the unstable cases, and the horizontal flow pattern of the stable PBL is also different from that of others. For the stable PBL experiment, since the vertical motion is weakest at the horizontal plane, to meet the continuity principle of the fluid dynamics, the horizontal streams on the lateral (shorter) sides ($Y = \pm 5 H$) of the street canyon would flow further into the street canyon than the others’ (Fig. 8).

The vertical sections of TKE fields are presented in Fig. 9. Compared with the flow patterns (Fig. 7), the TKE fields are more sensitive to the change of PBL structure; that is, the TKE field, as well as the turbulent diffusion process, within the

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**Fig. 9** – Simulated Turbulent Kinetic Energy (TKE) fields of vertical planes of the 3D street canyon experiment under (a, d) the stable Planetary Boundary Layer (PBL) condition, (b, e) the unstable PBL condition, and (c, f) the extremely unstable PBL condition.

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**Fig. 10** – Simulated normalized concentration of vertical planes of the 3D street canyon experiment under (a, d) the stable Planetary Boundary Layer (PBL) condition, (b, e) the unstable PBL condition, and (c, f) the extremely unstable PBL condition.
street canyon becomes stronger as the PBL instability increases. From the wind fields and TKE fields, it is obvious that the advection and diffusion processes of pollutants are strongest in the extremely unstable PBL case; on the contrary, those processes of the stable PBL case are weakest. As a consequence, large amounts of pollutants are concentrated in the street canyon of the stable PBL condition, while the pollution levels of the unstable PBL cases are much lower (Fig. 10). Similar to the results of the 2D street canyon, the pollutant plume is transported primarily by advection in the stable PBL experiment, and could vertically travel a long distance along the building wall without much change in pollutant concentrations (Fig. 10a, d); on the contrary, under the unstable PBL conditions, with the stronger turbulent mixing within the street canyon, the pollutants could mix more quickly, resulting in substantial changes to pollutant concentrations in the plume.

In short, it is found that in this 3D street canyon experiment, the change of PBL structure can not only significantly affect the distributions of turbulent variables (Fig. 9), but also modify the general horizontal flow patterns to some extent (Figs. 7 and 8).

Fig. 11 – Simulated (a–c) horizontal wind fields at the height of 2.5 m and (d–f) vertical planes of the realistic building cluster experiment under (a, d) the stable Planetary Boundary Layer (PBL) condition, (b, e) the unstable PBL condition, and (c, f) the extremely unstable PBL condition. The black dot in (a) indicates the location of pollutant source, and the vertical cross section (d–f) is made along the black line in (a–c). The distributions of vertical velocity (w) are presented by the color shade.

Fig. 12 – Similar to Fig. 11, but for the Turbulent Kinetic Energy (TKE) fields under (a, d) the stable Planetary Boundary Layer (PBL) condition, (b, e) the unstable PBL condition, and (c, f) the extremely unstable PBL condition. The vertical cross section (d–f) is made along the black line in (a–c).
2.4. The effects of PBL structure on dispersion within realistic building cluster

For the realistic building cluster simulation, a 10 m horizontal grid spacing computational domain of the Zhongguancun was built (Miao et al., 2013, 2014a), and the buildings’ shapes were simplified to cuboids. In the vertical dimension, there were 50 levels set from the ground to 450 m high; below 150 m height, the vertical grid spacing was set to 5 m, and the rest of the grid was set to a coarser vertical resolution (15 m). For the boundary conditions, the western inlet velocity was set by a similar profile ($H = 100$ m) to that of the 3D street canyon experiment (Fig. 3b), while the initial and boundary conditions of TKE and dissipation rate were also set by the WRF simulations (Fig. 3c, d). A point source of pollutants was set in the center of buildings at ground level (Fig. 11a), continuously emitting during the 10 min dispersion experiment, and the emission rate of pollutants was $10$ g/(m$^3$·sec). Note that the idealized 3D street canyon configuration, with no space in the windward or leeward building along the Y-direction, is much denser than the realistic building cluster configuration.

The horizontal and vertical sections of the simulated wind fields are given in Fig. 11. Unlike the idealized street canyon cases, the flow patterns (both the horizontal and vertical dimension) of different PBL are almost the same, which can be explained by the density of the buildings. For the 3D street canyon experiment, when facing the perpendicular approaching flow (Fig. 6), most of the momentum within the street canyon is transported downward from the stronger flow above the roof, which is quite sensitive to the PBL structure; however, for the realistic building cluster case, there are spaces between buildings perpendicular to the approaching flow direction, and the momentum among buildings could be transported by the horizontal flows.

In addition, the horizontal and vertical resolutions (10 and 5 m) used here could also affect the simulated wind fields; there may be slight differences among these simulated wind fields, while the relative coarse grid spacing used here cannot resolve these differences. Here is worth noting that the wind fields could be more sensitive to the inlet wind speed and direction (Miao et al., 2013; Baik et al., 2009) rather than the PBL structure.

Unlike the wind fields, the simulated TKE fields, as well as the turbulent diffusion process near the surface, are mostly dependent on the PBL structures (Fig. 12); the unstable PBL conditions, corresponding to stronger TKE fields, favor the turbulent diffusion process of pollutants.

The simulated horizontal and vertical concentration fields are demonstrated in Figs. 13 and 14. It is worth noting that the differences of the concentration fields within the building cluster under different PBL are less significant than in the 2D and 3D street canyon experiments, which can be explained by the density of buildings and the simulated wind fields.
discussed above, the density of buildings is a crucial factor to determine the dynamic effects of the PBL structure on flow fields. In short, the distribution of turbulent variables (i.e., TKE and its dissipation rate) is mostly determined by the PBL structure, and the sensitivity of the wind field to the PBL structure is affected by the building density.

To better observe the differences among the simulated concentration fields, the difference between the stable and unstable cases in the horizontal and vertical section is given in Figs. 13d and 14d. It is found that under the unstable PBL conditions, when the turbulent diffusion processes among the buildings are stronger, the pollutants could mix more quickly, resulting in lighter pollution among the buildings (Figs. 13d and 14d). On the other hand, more pollutants are concentrated in the building cluster in the stable PBL experiment because of the weaker turbulent diffusion process. A similar phenomenon could also be found between the stable and extremely unstable cases (Figs. 13e and 14e). Comparing the unstable case with the extreme unstable case (Figs. 13f and 14f), it is found that the increment of PBL instability strengthens the diffusion process of pollutants (Fig. 12), which could lower the pollution among buildings.

In this realistic case with a relatively low density of building, the increment of PBL instability cannot have significant effects on the wind fields and the advection process of pollutants in the building cluster (Fig. 11), but acts to strengthen the diffusion process of pollutants and lower the pollution there.

3. Conclusions

In this study, a CFD study was carried out to examine the effects of PBL structures/conditions on the pollutant dispersion processes within two idealized street canyon configurations and a realistic urban area. To simulate the wind and turbulent fields of different PBL structures, the initial and boundary conditions of TKE and dissipation rate were set by the simulations of WRF at different times (i.e., 0800 LST, 1100 LST and 1400 LST).

From the 2D and 3D street canyon experiments, it was found that the increment of PBL instability favored the vertical transport of momentum in the street canyon. Under the more unstable PBL condition, the stronger vertical vortex would be formed within the street canyon. Similar to the flow fields, the TKE field, as well as the turbulent diffusion process of pollutants, would become stronger as the PBL instability increased. And the TKE field is more sensitive to the change of PBL structure than the wind field. The advection process of pollutants driven by the wind field and the diffusion process of pollutants caused by the turbulent field are various under the different PBL structures, leading to the different pollutant concentration fields. As a consequence, large amounts of pollutants would be concentrated in the street canyon under the stable PBL condition associated with the relatively weak turbulent motion and advection, while the pollution levels of the unstable PBL cases were much lower due to the stronger turbulent mixing and advection processes.

However, in the realistic building cluster case, we found that the differences of the concentration and flow fields within the building cluster under different PBL structures were less significant than that of the 2D and 3D street canyon experiments, which can be explained by the density of buildings. The density of buildings was a crucial factor to determine the dynamic effects of the PBL structure on the flow patterns. In an extremely dense building configuration (i.e., the street canyon with perpendicular approaching flow), the pedestrian level momentum was mostly transported from the upper flows and was sensitive to the PBL structure. In short, the distributions of turbulent variables (i.e., TKE and its dissipation rate) were mostly controlled by the PBL structure, and the sensitivity of the wind field to the PBL structure was
affected by the building density. For the sparse building configurations, the wind fields among buildings could be more sensitive to the inlet wind speed and direction rather than the PBL structure.

Finally, it was recommended to use the MYNN PBL scheme to provide the boundary conditions to the CFD simulation, when using the WRF output to drive the CFD simulation; from the WRF version 3.4, the simulated TKE and its dissipation rate can be explicitly output by the additional option of the MTNN PBL scheme.

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REFERENCES

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