Available online at www.sciencedirect.com

ScienceDirect

www.journals.elsevier.com/journal-of-environmental-sciences

JOURNAL OF ENVIRONMENTAL SCIENCES

www.jesc.ac.cn

Numerical study of the effects of Planetary Boundary Layer structure on the pollutant dispersion within built-up areas

Yucong Miao[1,*], Shuhua Liu[1,*], Yijia Zheng[1], Shu Wang[1], Zhenxin Liu[1,2], Bihui Zhang[3]

1. Department of Atmospheric and Oceanic Sciences, School of Physics, Peking University, Beijing 100871, China
2. International Center of Climate and Environment Sciences, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing 100029, China
3. National Meteorological Center, China Meteorological Administration, Beijing 100081, China

ARTICLE INFO

Article history:
Received 11 September 2014
Revised 28 October 2014
Accepted 29 October 2014
Available online 24 April 2015

Keywords:
Weather Researching and Forecasting model
Planetary Boundary Layer
Computational Fluid Dynamics
OpenFOAM
Dispersion

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

* *Corresponding author*. E-mail: lshuhua@pku.edu.cn (Shuhua Liu), miaoyucong@yeah.net (Yucong Miao).

http://dx.doi.org/10.1016/j.jes.2014.10.025

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).

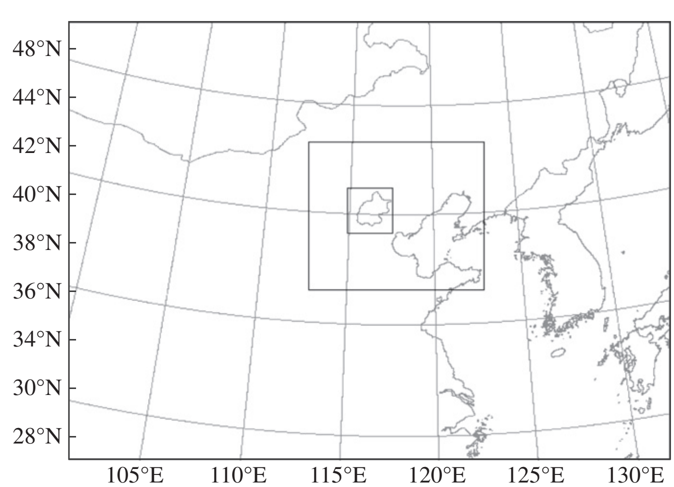

Fig. 1 – Nested computational domains in the Weather Researching and Forecasting model (WRF) simulation.