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NOTES AND COMMENTS

A Mechanical Drag Coefficient Formulation and Urban Canopy Parameter Assimilation Technique for Complex Urban Environments

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Abstract A mechanical drag coefficient formulation was implemented into the Building Effect Parameterization + Building Energy Model system coupled with the mesoscale Weather Research Forecasting model to improve the representation of the wind speed in complex urban environments. Previously, this formulation had been assessed only against spatially-averaged results from computational fluid dynamical simulations in idealized urban configurations. The main objective is to evaluate its performance over a real city. The introduction of a drag coefficient that varies with the building plan-area fraction increases the accuracy of the mesoscale model in predicting surface wind speed in complex urban environments (i.e. New York City) particularly in areas with tall buildings. Additionally, a methodology to implement local building information and a new land-cover land-use distribution is proposed that improves the representation of the urban morphology.

Keywords Drag coefficient · Mesoscale models · Urban canopy parameters · Urban canopy parametrization

1 Introduction

Urban effects in mesoscale numerical models have usually been represented using different techniques and parametrizations. The main goal is to take into account the impact of a city on atmospheric turbulence, and particularly momentum and heat exchange. While some mesoscale models use the Monin–Obukhov similarity theory (Monin and Obukhov 1954) to represent flow dynamics over cities assuming constant turbulent fluxes with height (Bornstein 1975; Chen and Dudhia 2001), a more complex approach employs very high vertical resolution with several levels within the urban canopy where a sink term is introduced into

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the momentum equation to represent the drag induced by buildings (Masson 2000; Kusaka et al. 2001; Martilli et al. 2002; Dupont et al. 2004; Wang et al. 2013). Parametrizations using this approach require an extra set of specific input parameters that describe the complex arrangement of buildings and streets in an urban environment. Simulations using this type of data reproduce fine-resolution features that are not clearly reproducible by traditional methods (Taha 2008; Chen et al. 2011; Salamanca et al. 2011; Gutierrez et al. 2013). However, obtaining these parameters is costly and time consuming limiting the use of mesoscale models with urban canopy parametrizations.

The Weather Research and Forecasting (WRF) model (Skamarock et al. 2008) is a non-hydrostatic, compressible forecasting and regional climate model with a mass coordinate system that includes several options for different physical processes. In order to represent the effects of horizontal and vertical building surfaces in the momentum, heat, and turbulent kinetic energy (TKE) equations, as well as the effect of anthropogenic sensible heat from air conditioning systems, the Building Effect Parametrization and the Building Energy Model (BEP+BEM) (Martilli et al. 2002; Salamanca et al. 2009) have been introduced. In the relevant equations, new terms are included to represent the effects of frictional and drag forces on the mean flow; changes to the potential temperature due to sensible heat fluxes at urban surfaces; and the increase of the TKE between buildings. This scheme assumes a constant drag coefficient that could misrepresent the magnitude of the drag induced by buildings in highly heterogeneous urban environments. In this study, a new formulation has been implemented in the BEP+BEM system to determine the values of the drag coefficient based on the building plan-area fraction so as to improve the airflow prediction inside the urban boundary layer in complex urban areas such as New York City (NYC). Previously, the performance of this drag formulation has been evaluated only in an idealized urban configuration using computational fluid dynamical (CFD) simulations (Santiago and Martilli 2010). Thus, our study investigates the importance of an appropriate drag formulation in mesoscale model simulations over real cities. In order to improve the representation of the city, urban canopy parameters were calculated and assimilated into the WRF model from local building information following a methodology that could be adopted in other complex cities where such datasets may be available. A new land-cover land-use (LCLU) distribution is also proposed. The new implementations were evaluated using rooftop weather data for a 30-day period during the summer of 2010.

2 Mechanical Drag Coefficient Formulation

Impervious vertical surfaces induce a drag force that produces a loss of momentum that alters the flow field in the lower part of the atmospheric boundary layer. The sectional drag-coefficient (C_d) is an important component for estimating the magnitude of the momentum flux induced by buildings in urban canopy models. Martilli et al. (2002) assumed a constant $C_\mathrm{d} = 0.4$ following previous studies over urban environments by Uno et al. (1989), Brown and Williams (1998), and Ashie et al. (1999) and wind-tunnel measurements of Raupach (1992). However, C_d could vary with building packing densities (Santiago et al. 2008). An analytical relation proposed by Santiago and Martilli (2010) has been implemented into the BEP+BEM system to estimate the drag coefficient as a function of the building plan-area fraction as follows,

$$C_{\mathrm{deq}}\left(\lambda_\mathrm{p}\right) = \begin{cases} 3.32x\lambda_\mathrm{p}^{0.47} & \text{for } \lambda_\mathrm{p} \le 0.29 \\ 1.85 & \text{for } \lambda_\mathrm{p} > 0.29. \end{cases} \tag{1}$$

A methodology to determine the building plan-area fraction (λ_{P}) is discussed in the next section. This formulation was based on results from CFD and Reynolds-average Navier–Stokes (RANS) simulations over a staggered array of cubes with constant height. Due to the variability of building heights in a real city, wind speeds at levels between the mean building height and the top of the tallest buildings could be misrepresented by this proposed approach. Nevertheless, this new proposed formulation represents an improvement compared to the current practice of using a constant drag coefficient, and it is necessary to assess this for a real urban scenario.

3 Urban Morphology

3.1 Urban Canopy Parameters

A local tax-lot is defined as a parcel of land identified with a unique borough, block and lot number for property tax purposes. Such lots have different surface areas containing one to several buildings. Buildings are typified according to their gross area, depth, frontage, number of floors and major use. Primary land-use tax-lot output (PLUTO) data from the NYC Department of City Planning were interpolated from an irregular grid with a North American Datum of 1983 New York/Long Island projection to a regular World Geodetic System 1984 Lambert Conformal Conic with a horizontal resolution of 250 m. The interpolation method takes one point from the original grid and calculates the distance to each point in the destination grid. PLUTO parameters were assigned to the closest location, and an average value was calculated from tax-lot data that corresponds to each grid cell. Building heights were determined by multiplying the number of building floors in the tax-lot (N_{fl}) by a floor height of 5 m.

The building plan-area fraction is defined as the ratio of the buildings plan area (A_{P}) to the total surface area of the grid cell (A_{T}) (Burian et al. 2008),

$$\lambda_{\mathrm{p}} = A_{\mathrm{P}}/A_{\mathrm{T}}. \tag{2}$$

The PLUTO database provided total gross area (A_{gross}) for all the structures in a tax-lot including attached and detached garages. The garage floor area was also included as a single parameter (A_{gar}). The surface plan area of only buildings was obtained from

$$A_{\mathrm{p}} = \frac{A_{\mathrm{gross}} - A_{\mathrm{gar}}}{N_{\mathrm{fl}}}. \tag{3}$$

Tax-lots with no information regarding number of floors and/or floor area were discarded, but represented $<1\,\%$ of the total number of lots in the five boroughs of New York City. Assuming a simplified two-dimensional morphology approach (Martilli 2009), the building-surface area to plan-area ratio (λ_{B}) is given by

$$\lambda_{\mathrm{B}} = \frac{2h + b}{w + b}. \tag{4}$$

As mentioned above, building height (h) is obtained from the number of floors and building width (b) is available from the PLUTO database. However, mean street width (w) is an unknown parameter that is obtained by relating λ_{P} and λ_{B} as follows,

$$\lambda_{\mathrm{P}} = \frac{A_{\mathrm{p}}}{A_{\mathrm{T}}} = \frac{b}{w + b}, \tag{5a}$$

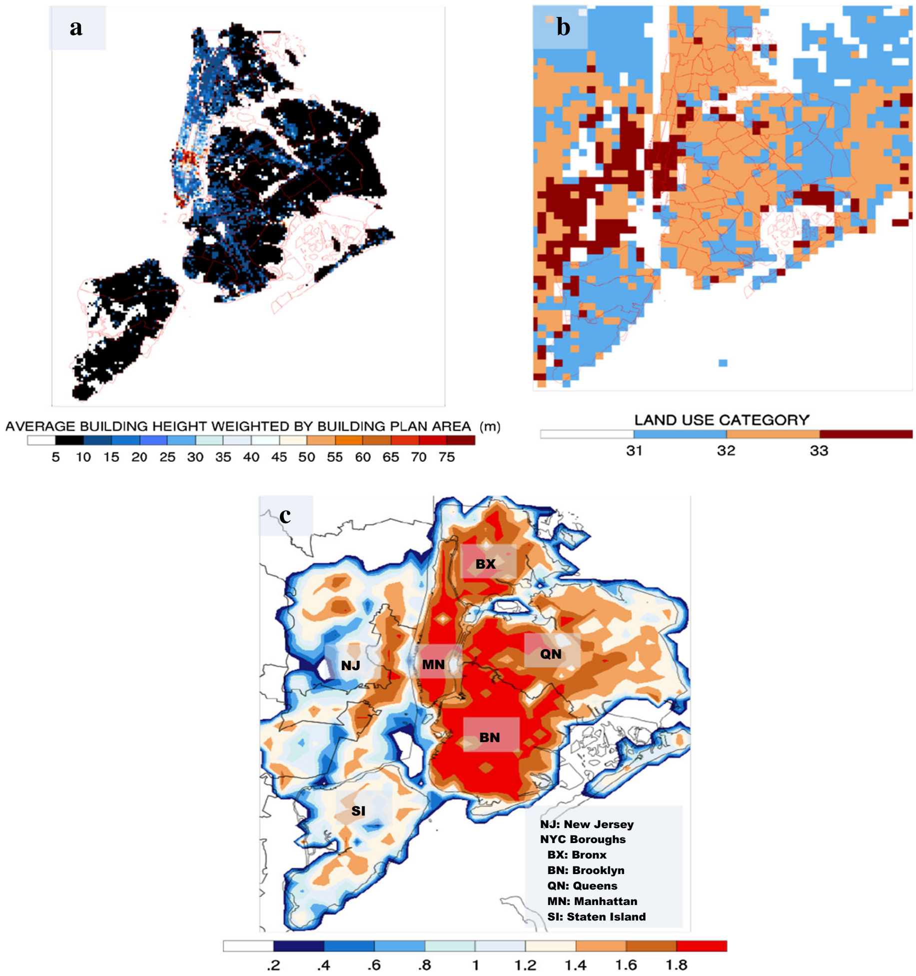

Fig. 1 Mean building height at 250 m. **a** New LCLU distribution at 1 km obtained from tax-lot building information for low residential (31), high residential (32), and commercial areas (33), **b** and drag coefficient as a function of building plan-area fraction C_{deq} (**c**)

$$w + b = \frac{b}{\lambda_P}, \tag{5b}$$

$$\lambda_B = \frac{2h}{w+b} + \frac{b}{w+b} = \frac{2h}{w+b} + \lambda_P, \tag{5c}$$

$$\lambda_B = \left(\frac{2h}{b} + 1\right)\lambda_p. \tag{5d}$$

Even though the finest domain for this study was set to 1 km, PLUTO data were assimilated at 250-m resolution, thus allowing for use in future studies requiring higher resolution. The WRF model preprocessing system performed the extrapolation from 250 m to 1 km. The new average building-height distribution for New York City is presented in Fig. 1a.

3.2 Land-Cover Land-Use Distribution

LCLU is an important component of the BEP + BEM system for simulating urban climate impacts. From the 2006 United States Geological Survey (USGS) national land-cover dataset (Fry et al. 2011), LCLU classification includes three urban classes: low residential, high residential and commercial. The criteria to categorize a region as urban are the same for the entire USA underestimating the spatial variations in highly heterogeneous regions such as New York City. The NYC Department of City Planning developed a land-use classification based on the major use of structures in the tax-lots, and if there are multiple uses or buildings in a tax-lot, the land use describes the use with the greatest coverage.

The NYC Department of City Planning land-use categories are assigned to the three urban classes used by the BEP + BEM system where one or two family buildings are classified as low residential; multi-family walk-up/elevator, industrial and manufacturing buildings belong to the high residential class and mixed residential commercial, commercial/office, transportation/utility, public facilities/institutions are considered commercial areas. Tax-lots classified as open space/outdoor recreation or vacant land are not considered as urban. The most frequent urban class among the tax-lots inside a grid cell determined the land-use category. The new land-cover distribution created from PLUTO data located most of the commercial buildings around midtown and downtown Manhattan while most of the areas in Queens, Brooklyn, and Staten Island are classified as low and high residential (Fig. 1b). This represents an improvement from the USGS database that considers the entire region as commercial.

4 Model Set-Up

The WRF/ARW model version 3.5.1 was used to estimate the impacts of the new implementations during June 2010 over the NYC area. Three two-way nested domains were constructed with spatial grid resolution of 9, 3, and 1 km that contained 120×120, 121×121, and 85×82 grid boxes, respectively, from west to east and north to south. Fifty-two terrain-following sigma levels were defined with the lowest level at 12 m and nine levels in the first 100 m. The BouLac planetary boundary-layer (PBL) scheme (Bougeault and Lacarrere 1989) and single-moment 6-class microphysics (Hong et al. 2004) were used. For longwave radiation, the Rapid Radiative Transfer model (Mlawer et al. 1997) was selected, with the scheme of Dudhia (1989) used for shortwave radiation.

Urban surfaces properties were adopted from Salamanca et al. (2014) and Deru et al. (2011). The initial and boundary conditions were obtained from the North American Regional Analysis datasets in 3-h intervals. Additionally, National Centers for Environmental Predictions Marine Modeling and Analysis Branch data at 0.083° were assimilated to update the sea-surface temperatures every 24 h. Two 30-day simulations were performed; "C_d" and "C_{deq}" refer to the results using constant (equal to 0.4) and variable drag coefficients, respectively. Information from 102 weather stations located at rooftops in different areas of the city was used to evaluate the model results (Fig. 3c,d).

5 Drag Coefficient Formulation Evaluation

The proposed formulation drastically changes the spatial distribution of the drag coefficient throughout the city (Fig. 1c). In highly developed areas such as Manhattan and Brook-

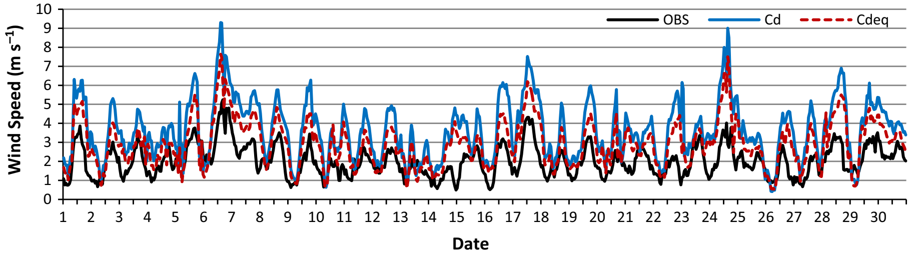

Fig. 2 Average hourly wind-speed time series during June 2010 for observations (OBS), constant drag coefficient (C_d), and variable drag coefficient (C_{deq})

lyn, the drag coefficient acquires a magnitude of 1.85, with C_{deq} in suburban regions such as State Island adopting values above 0.8. Even in low residential areas, the magnitude of C_{deq} at least doubles the constant drag coefficient assumed in the traditional approach. Figure 2 shows the times series of hourly wind-speed averaged over all the stations for observations, constant and variable drag coefficient simulations. Averaged values were calculated from all the stations present in the domain and the nearest grid point to those stations. Observed calm conditions were not included in the calculation of the averages.

In general, results show stronger winds relative to observations regardless of the formulation used. Besides properly resembling the diurnal oscillation with minimum wind speeds during the early morning and maxima during the afternoon, the wind speeds are overestimated with an average positive bias of 1.6 m s^{-1} when a constant drag coefficient is used. Wind-speed overestimation is a common feature reported in different studies with the WRF model over urban areas. In a comparison between different PBL schemes for Oklahoma City metropolitan area (Hu et al. 2013), the BouLac PBL scheme produced the highest surface wind speeds compared to the Mellor–Yamada–Janjic and Yonsei University schemes with a mean bias of 1.3 m s^{-1}. The excessive downward transport of momentum may lead to the overestimation of near-surface wind speeds. For a 48-h heavy rainfall event over the Baltimore-Washington metropolitan area, Li et al. (2013) using a single-layer urban canopy model reported substantially higher wind speeds produced by the WRF model compared to observations. Wind-speed discrepancies produced time lags in the specific humidity peaks. Salamanca et al. (2014) using the BEP+BEM system obtained mean average errors of 1.4 and 1.3 m s^{-1} for rural and urban areas in Phoenix.

The introduction of C_{deq} reduces wind-speed throughout New York City especially in areas with tall buildings (Fig. 3a). In Manhattan, the reduction reached around 1.5 m s^{-1} on average while Staten Island was the area least affected due to the presence of mainly low residential sites. Wind-speed reduction enhanced warming mainly over Brooklyn and Manhattan where ventilation depletion increased air temperatures up to 0.4 °C (Fig. 3b). On the other hand, the advection of heat from urban to rural areas was diminished producing a decrease in the average temperatures over New Jersey. Temperature root-mean-square errors (*RMSE*) slightly decreased by 0.1 °C at the most dense urban areas like Brooklyn where the error was reduced from 2.1 to 2.0 °C. Wind-speed errors were considerably reduced by C_{deq} particularly over Manhattan where *RMSE* values at some stations shifted from 2 m s^{-1} with C_d (Fig. 3c) to 0.6 m s^{-1} (Fig. 3d) with C_{deq}. Errors remained unchanged in areas with low building plan area fractions.

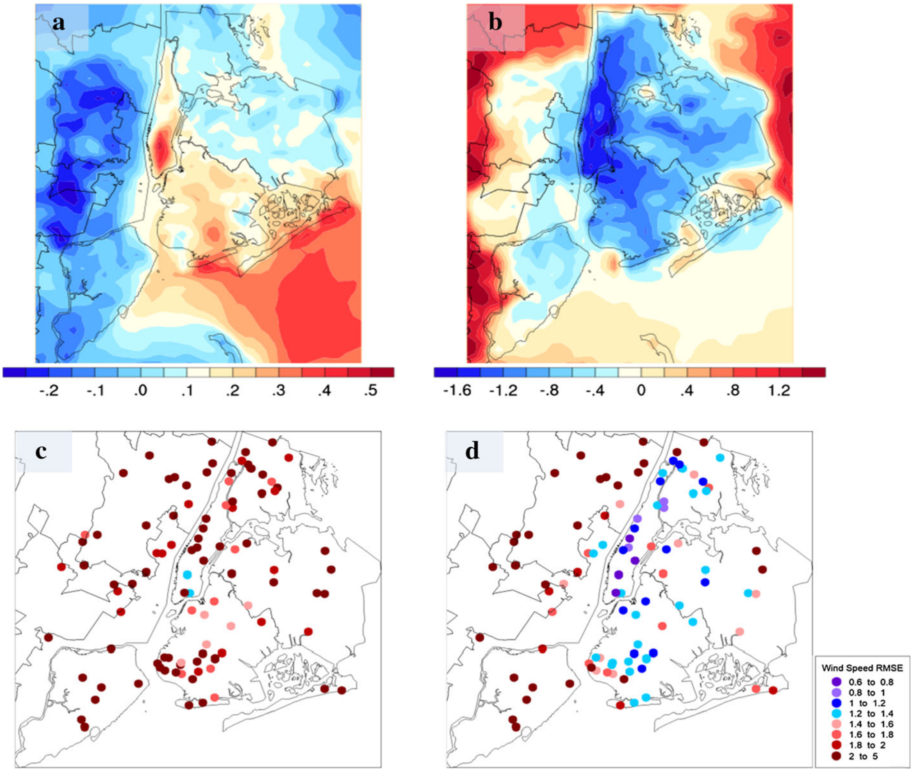

Fig. 3 **a** Average temperature difference between C_{deq} and C_{d} (°C), **b** average wind-speed difference between C_{deq} and C_{d} (m s^{-1}), **c** wind-speed *RMSE* for C_{d} and **d** wind-speed *RMSE* for C_{deq}, all during June 2010. The *dots* represent locations of the surface weather stations

6 Conclusions

A new formulation that calculates the mechanical drag coefficient for complex urban environments is proposed and assessed in New York City. Instead of assuming a constant value that is the common practice in mesoscale models, the drag coefficient introduced in this contribution depends on the magnitude of the building plan-area fraction following Santiago and Martilli (2010) using CFD-RANS simulations over a staggered array of cubes. A 30-day evaluation showed that the urban scheme reduces the wind-speed biases with a substantial improvement in the prediction of the surface wind speed when the proposed formulation is used. Bias reduction was more pronounced in areas where tall buildings are located. In those areas, an increase of air temperature was observed due to the ventilation reduction produced by the increase in mechanical drag.

A methodology for generating and assimilating urban canopy parameters from open source local building tax-lot information was also suggested. For the specific case of New York City, the representation is improved mainly in those areas where gridded building data are not available. The proposed land-cover land-use distribution better reflects the spatial variation of land cover in the city confining commercial areas to Manhattan and classifying the rest of New York City boroughs as low and high residential. This methodology can be adopted in any urban region where tax-lot building information is available to improve the calculation of thermal and mechanical effects of the city on the environment.

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