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Numerical simulation of micro-atmospheric environment by LES in a district of Beijing

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Abstract

The urban atmospheric environment becomes more and more concerned in people life and public safety. One of the environmental issues is the traffic pollution in crowded residence area. This paper investigates field and pollutant dispersion in a local district of Beijing by means of LES. The major difficulties in the prediction of urban atmospheric flows are the appropriate resolution of the complicated underlying buildings and the boundary condition of the local computational domain. In this paper a composite model for the underlying buildings is proposed that buildings and streets are properly resolved with fine grids and immersed boundary method is employed to accurately satisfy the non-slip flow condition at solid wall while in the rest area the buildings are treated as drag elements with coarse grids to reduce computational cost. A coupling method is used in this paper that the boundary conditions of local computational domain is provided by interpolation of pre-computed atmospheric flows by means of a meso-scale model WRF (Weather Research and Forecast) in whole Beijing city with coarse grid. The wind speed, temperature and carbon monoxide concentration fields are computed from 8 am of September 22 2005 to 8 am of the next day and the results show a good agreement with the observation.

The urban atmospheric flow can be considered as incompressible fluid flow governed by Navier-Stokes equation with Boussinesq approximation. The LES equation can be obtained by filtering Navier-Stokes equation as follows

\[
\partial_t \tilde{u} / \partial x_j = 0
\]

\[
\partial \tilde{u}_i / \partial t + \tilde{u}_j \partial \tilde{u}_i / \partial x_j = -\partial p / \partial x_i + \nu \partial^2 \tilde{u}_i / \partial x_j \partial x_j + \partial \tau_{ij} / \partial x_j + \tilde{f}_i
\]

In above equation \( \tilde{u}_i \) is resolved scale velocity, \( \tilde{f}_i \) is an external force, e.g. buoyancy force and building drag force when drag element model is used, and \( \tau_{ij} = \tilde{u}_i \tilde{u}_j - \bar{u}_i \bar{u}_j \) is subgrid stress. The LES equation for pollutant and heat transport can be written as follows

\[
\partial c / \partial t + \tilde{u}_i \partial c / \partial x_i = D \partial^2 c / \partial x_j \partial x_j + \partial \tau_{ij} / \partial x_j + \tilde{S}_c
\]

\[
\partial \theta / \partial t + \tilde{u}_i \partial \theta / \partial x_i = k \partial^2 \theta / \partial x_j \partial x_j + \partial \tau_{ij} / \partial x_j + \tilde{S}_\theta
\]

In above equations \( D \) and \( k \) are the molecular mass and thermal diffusivity respectively; \( \tilde{S}_c \) is the source of pollutant and \( \tilde{S}_\theta \) stands for the heat source. \( \tau_{ij} = \tilde{c}u_i - \bar{c}u_j \) and \( \tau_{ij} = \tilde{\theta}u_i - \bar{\theta}u_j \) are the subgrid mass and thermal flux respectively. The subgrid eddy viscosity and diffusivity models are adopted to close the subgrid stress and subgrid flux and the Lagrange dynamic model is applied to determine the model coefficients. The momentum, mass and thermal transport equations are solved numerically by the finite volume method (FVM) with non-staggered grids and the fourth order Runge-Kutta integration in time advancement is used in computation. The parallel computation based on domain decomposition is used in this paper in order to accommodate the combined model.

The computed area is shown in Figure 1(a) which has a horizontal extent of 2300 meters in \( x \) direction and 1900 meters in \( y \) direction. There are meteorological observation stations in this area, the Baolian station and Chedaogou station, respectively. The Baolian station is located in sub-domain with fine grids, marked by number 1 in Figure 1(a). The computational grid is shown in Figure 1(b) that the area marked with rectangular in figure 1(a) is resolved with grid spacing of 4m in horizontal direction and in the rest area the horizontal grid spacing ranges from 10m to 60m. The domain size in vertical direction is 1000m and the non-uniform grid spacing is 1m near the ground with gradual stretch as the height increases.

The boundary conditions of flow field are provided by interpolation of the pre-computed WRF results on the lateral and top boundaries as mentioned before. The boundary condition at building and street surface in the area 1 is non-slip and the drag element model applied in the rest area.

The boundary conditions for pollutant concentration are as follows. The mass flux is zero at the ground and building surfaces as well as at top boundary whereas the non-reflection condition at rest boundaries. The ground temperature is given by a thermal balance equation (Noilhan et al., 1989). The non-reflection condition is used for the temperature at rest boundaries.

The drag element method is used for buildings outside of area 1 in Figure 1, where the pollutant level is not the major concern. A drag force is inserted in momentum equation as follows

\[
\tilde{f}_i = \rho |\tilde{u}_i| L_c
\]
The length scale $L_c$ is proposed by Belcher et al. (2003).

![Computational domain](image1.png)

Figure 1 (a) Computational domain. A: Baolian observation station B: Chedaogou observation station; (b) Horizontal grids

The traffic exhaust is the major pollution source in Baolian area. The traffic exhaust is considered as a surface source distributed on the first grids over the street ground and the source intensity is calculated from the automobile traffic flow and emission factor. The traffic emission at the main street is taken from the measurements by Meng et al (2004), see Figure 2.

![Emission coefficient of carbon monoxide](image2.png)

Figure 2 Emission coefficient of carbon monoxide

Major results are presented in Figure 3 which shows the comparison with the observed data at Baolian station. The agreement is fairly good between computed and observed results of wind speed and pollutant concentration. The observed concentration CO is zero at 9 am and it is surely incorrect in measurements. The peak values of CO are in good agreement with the emission coefficient shown in Figure 2.

![Numerical results in comparison with observation](image3.png)

Figure 3 The numerical results in comparison with observation at Baolian meteorological station:

The numerical results show that the proposed composite model is appropriate for predicting atmospheric flow and pollutant dispersion in local urban area with complex underlying buildings. It will be also shown in final manuscript that the coupling between WRF simulation and local numerical flow simulation with fine grids is necessary for prediction the hourly distribution of pollutant concentration. More detailed local flow patterns and distribution of pollutant at pedestrians will be also given in the final manuscript.

References

