Environmental Pollution 233 (2018) 782–796

Contents lists available at ScienceDirect

Environmental Pollution

journal homepage: www.elsevier.com/locate/envpol

How tall buildings affect turbulent air flows and dispersion of pollution within a neighbourhood[☆]

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A R T I C L E I N F O

Article history:
Received 13 May 2017
Received in revised form
21 September 2017
Accepted 11 October 2017

Keywords:
Air pollution
Computational modelling
Large eddy simulations
Urban environment
Wind tunnel experiments

A B S T R A C T

The city of London, UK, has seen in recent years an increase in the number of high-rise/multi-storey buildings ("skyscrapers") with roof heights reaching 150 m and more, with the Shard being a prime example with a height of ~310 m. This changing cityscape together with recent plans of local authorities of introducing Combined Heat and Power Plant (CHP) led to a detailed study in which CFD and wind tunnel studies were carried out to assess the effect of such high-rise buildings on the dispersion of air pollution in their vicinity. A new, open-source simulator, FLUIDITY, which incorporates the Large Eddy Simulation (LES) method, was implemented; the simulated results were subsequently validated against experimental measurements from the EnFlo wind tunnel. The novelty of the LES methodology within FLUIDITY is based on the combination of an adaptive, unstructured, mesh with an eddy-viscosity tensor (for the sub-grid scales) that is anisotropic. The simulated normalised mean concentrations results were compared to the corresponding wind tunnel measurements, showing for most detector locations good correlations, with differences ranging from 3% to 37%. The validation procedure was followed by the simulation of two further hypothetical scenarios, in which the heights of buildings surrounding the source building were increased. The results showed clearly how the high-rise buildings affected the surrounding air flows and dispersion patterns, with the generation of "dead-zones" and high-concentration "hotspots" in areas where these did not previously exist. The work clearly showed that complex CFD modelling can provide useful information to urban planners when changes to cityscapes are considered, so that design options can be tested against environmental quality criteria.
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1. Introduction

Optimising the building infrastructure and minimising the effect of emissions of air pollutants within the urban environment requires reliable and accurate predictions of both the turbulent air flows and concentration predictions at high temporal and spatial resolutions. This implies solving the time-dependent, three-dimensional, non-linear Navier-Stokes equations together with the advection-diffusion and chemical reaction equations for the concentration of pollutants, as well as the turbulent diffusion equations on *highly resolved* spatial computational meshes at reasonable computational speeds. In addition, representing and capturing accurately the turbulence and its statistics within the computational domain, thus leading to an enhanced understanding of the physical mixing processes and exchange rates (for both momentum and pollution concentrations) at pedestrian levels and at levels well above the roof tops, is also crucial (Zhou and Hanna, 2007; Solazzo and Britter, 2007). These two aspects: (a) numerical solutions at high temporal and spatial resolutions and (b) accurate as representation of the air flow and turbulence have been the most challenging problems for air quality studies over the last 40 years, leading to the development of both new computational

☆ This paper has been recommended for acceptance by Charles Wong.

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https://doi.org/10.1016/j.envpol.2017.10.041
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methodologies for the representation of turbulence, as well as the implementation of these methodologies on adaptive computational meshes. It is the aim of the research presented in this paper to introduce and show detailed results from a new numerical Large Eddy Simulation (LES) approach within the FLUIDITY software (http://fluidityproject.github.io/) that addresses both challenges. The novelty of the work is based on: (i) the implementation and validation of an innovative LES approach that combines an anisotropic eddy viscosity tensor for the subgrid modelling with adaptive meshes; this allows accurate representation of the turbulence at high spatial resolutions and enables the detailed capture of the turbulent eddies formed within the domain at pedestrian-level scales; (ii) the utilisation of new wind tunnel data for a specific 7-builing configuration representing a real set of buildings in central London; and (iii) the implementation of the software and qualitative assessment of the effect of tall buildings on atmospheric pollution dispersion.

Adaptive meshes began to appear in the early 1990s with the work of Benson and McRae (1991) on structured grids, followed by Odman et al. (1997) utilising an embedded Cartesian grid approach, and Tomlin et al. (1997) with adaptivity on unstructured grids for 2D problems. The adaptive algorithm of Benson and McRae (1991), DSAGA, has since been implemented by several authors in urban pollution problems, with Srivastava et al. (2000) using it in air quality models, capturing the changes in concentration distributions and their gradients due to advection as well as chemical reactions and dispersion of a pollutant puff (Srivastava et al., 2001a,b).

Tackling the second challenge of representing the turbulence within atmospheric flows, traditionally, the k-epsilon turbulence models (Reynolds Averaged Navier Stokes methodology (RANS)) have been implemented for air pollution studies. However, Coirier et al. (2005) and Di Sabatino et al. (2008) emphasised in their studies that underpredicting the turbulent kinetic energy can lead to erroneous concentration predictions, and hence concluded that representing the turbulence accurately within a model is just as important as grid refinement, if not more so. Understandably, the upward/vertical movement of pollution from the lower heights of the street canyons to higher up (through the overlying shear layer and into the boundary layer above) is of major interest in air pollution studies. In the past, for the two-dimensional canyons, this transfer has been assumed to be directly related to the external flow/velocity (http://envs.au.dk/en/knowledge/air/models/ospm/). However, Baik and Kim (2002) showed that not only the vertical mean velocities are important, but also the vertical turbulent velocities, resulting in pollutants escaping through these turbulent processes, whilst the overall effect of the mean flow can lead to the re-entrance of some of the escaped pollutants back into the street. They also confirmed their findings by varying the inlet velocities and turbulence intensities, as well as varying canyon aspect ratios. Caton et al. (2003) carried out a similar study investigating both analytically and experimentally the dispersion mechanisms in two-dimensional canyons. They showed how the turbulent inflow properties influence the vertical transfer of pollutants and are just as important as the external mean flow. Kim and Baik (2003) also discuss how the inlet turbulent intensity conditions affect the dispersion of pollution downstream. In their study, the authors describe how the pollutants are transported upwards or downwards, depending on the strength of the eddy diffusion and advection at different heights, and the influence of the main and secondary canyon vortices. They confirmed that by increasing the inflow turbulent intensities, pollution concentrations within the street decrease, whilst the upward movement of pollution is enhanced. The importance of the inlet turbulent conditions for the accurate prediction of mean concentrations is also highlighted in the study of Milliez and Carissimo (2007). In their study, the authors discuss how the k-epsilon turbulent model parameters affect the predicted concentrations and their associated statistics. Sensitivity studies on the fluctuations in the source emission rate showed little effect. Similarly, the RANS studies carried out by Coirier et al. (2005) and later by Di Sabatino et al. (2008) emphasised the importance of representing as accurately as possible the turbulence characteristics, as underpredictions could lead to erroneous concentration predictions. The authors also make the interesting comment that should the need for short-term responses arise for risk assessment purposes, it would mean that peak concentrations must be evaluated, which can be only achieved more appropriately using methodologies such as the large eddy simulations (LES).

The LES method is currently one of the most favoured and computationally powerful approaches for simulating complex turbulent flows as it enables unsteady flows to be captured at high temporal and spatial resolutions. As such, it provides additional information of both the fine flow structures developed as well as of the turbulence statistics, leading to a greater understanding of the physical processes taking places within street canyons. Its strength lies in its computational efficiency, as it simulates and resolves the larger-scale eddies/turbulent structures explicitly whilst modelling the unresolved/small-scale ones; this leads to faster computations compared to DNS simulations, and more accurate representation of the turbulent fields compared to the RANS approaches. The LES method for atmospheric flows was first proposed by Smagorinsky (1963) and since then it has been facilitated by the rapid growth in computing power, thus enabling it to enter mainstream engineering. Piomelli (1999) summarises the achivements and challenges of the LES method up to the end of the 20th century, whilst Zhiyin (2015) presents a detailed review of the method, outlining its progress since its initial appearance in the 1960s and how it has entered mainstream engineering in the last two decades. In addition, the author describes the challenges, past and present for the LES method, with regards to the range of turbulent length scales it needs to represent during transient simulations, as well as the theoretical developments that have been carried out over the years in order to represent turbulent inlet conditions, and subgrid scale models. Within the LES approach, the smaller eddies have traditionally been modelled with the Smagorisnky eddy viscosity model (Smagorinsky, 1963). In the initial version of the model, the Smagorisnky coefficient required for the determination of the eddy viscosity was kept constant. However, it was later recognised that this assumption may lead to over-dissipation of the sub-grid scale turbulent kinetic energy, and thus efforts since the 1990s have taken place leading to a variety of subgrid scale models based on: (a) an eddy viscosity representation only; (b) the similarity models where filtering methods are used to deduce the subgrid scale model from the resolved stress tensor values; and (c) the mixed models, which integrate the eddy-viscosity approach within the similarity models (Sagaut, 1998).

Apart from the numerous choices of sub-grid scales models within the LES approach, adaptive grids were also implemented, with one of the earliest implementations being the work of Wissink et al. (2005) with a Cartesian Adaptive Mesh Refinement (AMR) capability. This was followed by the work of Ghorai et al. (2000) where we also see an implementation of a three-dimensional, time-dependent gridding technique for dispersion problems in neutral, stable, and unstable atmospheric boundary layers. Walton and Cheng (2002) implemented LES using a structured grid, for street canyons in Hong-Kong, with an aspect ratio (Height/width) of 1.2. A dynamic LES subgrid-scale model was implemented, together with periodic boundary conditions. Based on the comparisons between simulations and wind-tunnel data, the authors

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