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Numerical modeling of passive scalar dispersion in an urban canopy layer

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Abstract

A turbulent dispersion model describing the dispersion of a passive scalar from a localized source released in a built-up environment (urban area) is presented. The proposed model simulates both the flow field in the urban complex using the ensemble-averaged, three-dimensional Navier–Stokes equations with a standard $k-\varepsilon$ turbulence closure model and the turbulent diffusion using transport equations for the mean concentration and concentration variance of the scalar. Two models for the scalar dissipation rate, required to close the transport equation for concentration variance, are investigated. Results of a detailed comparison of the flow and turbulent dispersion between a comprehensive water channel experiment and the model predictions are presented. The water channel experiment is unique in the sense that it includes data obtained from the dispersion of both continuous and nearly instantaneous releases of a tracer from a point source located within a regular array of building-like obstacles, and this data include measurements of both the mean concentration and concentration variance.

Keywords: Reynolds-averaged Navier–Stokes modeling; Urban dispersion modeling; Obstacle array; Mean concentration; Concentration variance; Scalar dissipation; Water channel simulation; Urban canopy flows

1. Introduction

The problem of dispersion, which involves the behavior of a scalar that is diffused and advected by a turbulent velocity field, attracts a great deal of attention due to its

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fundamental scientific significance and practical interest in environmental science and engineering. In recent years, owing to increasing urbanization and an increasing likelihood of an accidental or deliberate release of a hazardous material in an urban (built-up) area, the understanding of the wind flow statistics in an urban area and the concomitant dispersion of material released in that flow is gaining importance. Consequently, considerable attention has focused recently on the development of models to predict the dispersion of toxic materials released into the urban environment. Dispersion models, which predict the concentration distribution of pollutant in an environmental flow, can provide useful information to assist emergency responders in the delineation of hazard zones (toxic corridors) resulting from the contaminant release. Nevertheless, owing to its intrinsic complexity, the "correct" prediction of urban flow and dispersion is currently an unresolved issue due to the inherent difficulties in formulation of physically sound turbulence models within a complex array of structures (viz., within an urban canopy composed of an arbitrary configuration of groups of buildings and street canyons).

Computational fluid dynamics (CFD) has recently been applied to simulate the dispersion of contaminants in an urban canopy. The two basic methodologies in CFD that have been applied here are a Reynolds-averaged Navier–Stokes (RANS) modeling and a large-eddy simulation (LES) of the mean flow and turbulence structure, each augmented with models for the corresponding passive scalar transport within and above an urban canopy. Previous modeling studies of scalar dispersion in an urban canopy (usually limited to a simple street canyon geometry) using either RANS or LES include Johnson and Hunter (1995), Sini et al. (1996), Baik and Kim (1999), Kim and Baik (1999), Huang et al. (2000), Liu and Barth (2002), Walton and Cheng (2002), Chang and Meroney (2003) and Hanna et al. (2002).

Currently, LES of general urban flow and dispersion is unaffordable, although it is useful for fundamental studies of flow and scalar transport in simple geometrical urban configurations (e.g., a single street canyon flanked by buildings on either side). In more geometrically complex urban canopies, RANS models (and, in particular, the two-equation k–ε turbulence closure model) are frequently used. These models provide lengthscale and timescale information that can be utilized in the modeling of additional processes. More specifically, the unclosed turbulent scalar fluxes in the scalar transport equation (ensembled-averaged advection–diffusion equation) are usually expressed in terms of an eddy diffusivity that is assumed to be proportional to the eddy viscosity (specified using the relevant turbulence lengthscale and timescale information) representing the turbulent momentum transport through the conventional Boussinesq assumption.

Virtually all the research effort on modeling of dispersion in urban canopies has focused exclusively on prediction of the ensemble mean concentration. The only notable exception to this situation is the numerical modeling effort of Liu and Barth (2002) who applied LES to study scalar transport in a street canyon. In particular, these researchers used this methodology to investigate the distribution of concentration variance in a modeled street canyon with a building-height-to-street-width ratio of unity in order to obtain deeper insights into the physical mechanisms responsible for turbulent mixing of the scalar in the canyon. The paucity of effort in the modeling of concentration fluctuations in a plume or cloud dispersing through an urban canopy is a rather surprising state of affairs, given that concentration fluctuations are a ubiquitous feature in a dispersing plume or cloud and the recognition that this feature has practical significance in a number of engineering and technological applications. These applications include screening obscurant studies, the