ABSTRACT: The predictive capabilities of a building-resolving prognostic numerical simulation model (urbanSTREAM) for small-scale (microscale) atmospheric flows in an urban environment will be evaluated based on detailed comparisons between the predictions and measurements of various flow quantities obtained in the Joint Urban 2003 (JU2003) field experiment in Oklahoma City. The prognostic model for the wind field in a cityscape is obtained by solving the unsteady Reynolds-averaged Navier-Stokes (URANS) and partially-resolved Navier-Stokes (PRNS) equations. For URANS, a two-equation $k$-$\varepsilon$ turbulence closure model is used. However, in contrast to conventional large-eddy simulation (LES), which is based on spatial filtering of the NS equation, PRNS solves the time-filtered NS equation. The latter approach provides a unified framework for the numerical simulation of turbulent flows, and includes URANS, LES and direct numerical simulation (DNS) as special cases, depending on how the cut-off frequency of the filter is chosen. A two-equation $k$-$\varepsilon$ PRNS is adopted here, with the eddy viscosity being multiplied by a resolution control parameter function which is dependent on the cut-off wave number (or, equivalently, the cut-off frequency) of the filter.

KEYWORDS: unsteady RANS, PRNS, urban flow, drag-force approach

1 INTRODUCTION

Our current understanding of the flow in an urban environment is still very limited. The main motive for studying turbulent flows in the urban atmosphere is to understand the processes governing the exchanges of momentum, heat and mass between the urban surface and the atmospheric flow above it. Apart from this basic interest, there are several crucially important “real world” applications where such knowledge is critical. At the top of the list (especially in a post September 11, 2001 world) is the need to understand and model the dispersion of pollutants (e.g., chemical, biological and radiological (CBR) warfare agents) in the urban environment, which strongly depends on the meteorological conditions and how they are modified by the urban complex. However, prediction of the nature of turbulent flow through the urban environment is in principle pre-requisite to the prediction of the simpler (but itself complex) problem of contaminant dispersion in the urban complex.

To address the urgent problem of modeling the dispersion of CBR warfare agents in the urban complex, we require physically-based urban wind models that will be able to provide the needed spatial pattern of wind statistics. A reassessment of wind models is timely because atmospheric physicists and micro-meteorologists are increasingly forced to accept that the idealization of horizontal uniformity in terrain is too obviously wrong to be ignored. However, the modeling of flow in the urban complex is a difficult problem that is characterized by extremely diverse length and time scales and complex geometries and interfaces.
A possible solution to this problem is to use large-eddy simulation (LES) for prediction of urban flows [1], which provides a higher-level of description of the flow than unsteady RANS (URANS) models. In LES, the equations are filtered so that the larger-scale motions are explicitly resolved and the smaller, high-frequency motions (which are more universal) are represented by a subgrid model. This method can produce results that are more reliable than RANS-based closure models, and are less sensitive to the subgrid model used. Unfortunately, the “rigor” associated with LES comes at the expense of a high computational requirement. It is, therefore, imperative to seek a solution for the flow that is intermediate between the RANS and LES methodologies in order to obtain a compromise between efficiency and accuracy – an approach commonly referred to as the hybrid RANS/LES approach [2]. In the present paper, the concept of partially resolved numerical simulation (PRNS) [3] is employed. In contrast to [3], in which \( C_\mu \) is assumed to be a constant (\( \approx 0.035 \) for LES) in the eddy viscosity when a two-equation \( k-\varepsilon \) model is used, a generalized expression for the eddy viscosity (in which \( C_\mu \) is multiplied by a function of the cut-off wavenumber of the filter) is proposed here and tested on several urban flows.

2 PARTIALLY RESOLVED NUMERICAL SIMULATION (PRNS)
The occurrence of a non-physical buffer-like layer in the vicinity of the interface location when hybrid RANS/LES is adopted is due to the flow quantities in the RANS and LES regions being defined differently: namely, quantities in the LES region are based on spatial filtering, whereas those in the RANS region are based on statistical averaging. To avoid this conceptual difficulty, [3] proposed to filter the NS equations in time rather than space. If the cut-off frequency \( f_c \) is set to the reciprocal of the Kolmogorov time scale (i.e., \( f_c = 1/\sqrt{\nu/\varepsilon} \)), PRNS reduces to DNS. On the other hand, PRNS becomes RANS if \( f_c \) is set equal to zero. For URANS and LES, \( f_c \) of the temporal filter must be chosen to lie at the range of frequencies corresponding to the energy-containing and inertial subrange scales of turbulence, respectively.

If the two-equation \( k-\varepsilon \) model is used as the basis for the PRNS framework, the turbulent (eddy) viscosity can be expressed as

\[
\nu_t = F_{\text{RCP}}(f_c)C_\mu \frac{k^2}{\varepsilon}
\]

Here \( C_\mu = 0.09 \) is a closure coefficient and \( F_{\text{RCP}}(f_c) \) is the resolution control parameter function. It can be readily seen that for RANS and URANS, \( F_{\text{RCP}}(f_c) \to 1 \) as \( f_c \to 0^+ \) and for DNS, \( F_{\text{RCP}}(f_c) \to 0^+ \) as \( f_c \to 1/\sqrt{\nu/\varepsilon} \). However, temporal and spatial filtering operations are intimately linked which follows from the following argument. Let \( \Delta_c \) be the cut-off length associated with the spatial filtering operation used in LES (in most applications of LES, \( \Delta_c \) is related to the grid spacing used in the discretization of the flow domain). Then the cut-off wave number of the spatial filter is \( \kappa_c = \pi / \Delta_c \). If \( E(\kappa) \) is the spectral energy density of the velocity fluctuations, then the kinetic energy associated with \( \kappa_c \) is \( \kappa_c E(\kappa_c) \). The kinetic energy at \( \kappa_c \) is associated with a cutoff velocity scale given by \( v_c = \sqrt{\kappa_c E(\kappa_c)} \). In view of this, the cut-off time scale \( t_c = 1/ f_c \) must be related to \( \Delta_c \) through \( t_c = \Delta_c / v_c \). Hence, in the present study \( F_{\text{RCP}} \) will chosen to be \( F_{\text{RCP}}(l_i,l_c,l_k) \), where \( l_i,l_c,l_k \) are the integral, cutoff and Kolmogorov length scales, respectively. These are defined as
\[ l_i = k^{3/2} / \varepsilon, \quad l_c = 2 \max \left[ (\Delta_i, \Delta_j, \Delta_k) \right]^{1/3}, \quad l_k = (v^3 / \varepsilon)^{1/4} \]  

Let us assume the energy spectrum \( E(\kappa) \propto \kappa^{-5/3} \) and \( \kappa \propto l^{-1} \). The proposed \( F_{RCP}(\kappa_i, \kappa_c, \kappa_k) \) is

\[ F_{RCP} = \left[ \frac{\int_{\kappa_c}^{\kappa_k} E(\kappa) d\kappa}{\int_{\kappa_c}^{\kappa_k} E(\kappa) d\kappa} \right]^n = \left[ \frac{\kappa_k^{2/3} - (r\kappa_k - r\kappa_i + \kappa_i)^{2/3}}{(r\kappa_k - r\kappa_i + \kappa_i)^{2/3} (\kappa_k^{2/3} - \kappa_k^{2/3})} \right]^n \]  

where \( r = (\kappa_c - \kappa_i) / (\kappa_k - \kappa_i) \). Note that in practice \( \kappa_i \) is replaced by \( \max[\kappa_i, \min(\kappa_c, \kappa_k)] \) in order to satisfy the condition \( F_{RCP} = 0 \) when \( \kappa_c \leq \kappa_k \), and \( F_{RCP} = 1 \) when \( \kappa_c \geq \kappa_k \). The optimal value of the exponent \( n \) will need to be determined by testing the proposed model over a range of flow conditions. In the present study, \( n=2 \) is employed although more testing will be required to determine if this value for \( n \) is optimal.

3 TEST PROBLEMS

3.1 Regular Array

The first calculations were performed on a mesh of 340,000 nodes for the disturbed flow over a regular (aligned) array of \( 16 \times 16 \) obstacles, each with a square cross-section of side length \( H \) and height \( 2H \) as shown in Figure 1 (left panel). As seen in Figure 1 (middle panel), the streamwise velocity profile predicted by PRNS agrees slightly better with the experimental data than the URANS prediction. The \( F_{RCP} \) contours in Figure 1 (right panel) show that \( F_{RCP} \approx 1 \) close to walls and along the shear layer emanating from the upstream corner of the obstacle. \( F_{RCP} \approx 0.2 \) is observed at or near the center of street canyon and in the free-stream region above the rooftop. This result generalizes Shih & Liu’s early work [3], in which \( F_{RCP} \) was simply set to a constant (\( \approx 0.4 \)).

3.2 Oklahoma City

A major field experiment, Joint Urban 2003 (JU2003), was conducted in Oklahoma City from June 28 to July 31, 2003 to collect meteorological and tracer data sets for evaluating dispersion models in urban areas. Various meteorological instrumentation and tracer samplers were installed at various locations throughout and around the city in order to track the air movement of safe, non-toxic tracer gases. The purpose of this study is to provide a better understanding of pollutant dispersion in an urban environment, and the data can be used to develop and validate urban models for flow and dispersion. Further details of the experiment can be found at https://ju2003-dpg.dpg.army.mil/.

The computational domain consists of an “inner region”, in which all buildings are explicitly resolved as shown in Figure 2 (left panel), and an “outer region” in which the effect of an aggregation of groups of buildings are treated as a porous barrier [4]. The inlet condition was estimated based on the field measurements of mean velocity and turbulence kinetic energy at a location with coordinates 35.45° N and 97.53° W. Sample results in terms of a vertical profile of the horizontal velocity magnitude measured at a location with coordinates 35.48° N and 97.52° W are shown in Figure 2 (right panel) and compared with the URANS and PRNS predictions (based on a grid of 1 million nodes).

3.3 Conclusions and Future Work

Preliminary results obtained with the proposed PRNS approach are encouraging. However, further optimization for the free parameter \( n \) in Equation (3) over a wide range of flows is still re-
quired. Coupling between urbanSTREAM and the “urbanized” Global Environmental Multi-
scale/Limited Area Model (GEM/LAM), developed by Environment Canada, is currently under
investigation.

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Figure 1. Regular array: (left) a regular and aligned array of obstacles; (middle) vertical profiles of streamwise mean
velocity predicted and measured at a location on the vertical center plane in the wake region between the 6th and 7th
rows of obstacles; (right) contours of $F_{\text{BCP}}$ on the vertical center plane between the 6th and 7th rows of obstacles.

Figure 2. Oklahoma city: (left) contours of log(C) where C is the concentration; (right) vertical profile of horizontal
velocity magnitude at a location with coordinates 35.48° N and 97.52° W.