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Advanced turbulence models and boundary conditions for flows around different configurations of ground-mounted buildings

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ABSTRACT

When dealing with Atmospheric Boundary Layer (ABL) simulations, commercial computational fluid dynamics (CFD) acquires a strategic resonance. Thanks to its good compromise between accuracy of results and calculation time, RANS still represents a valid alternative to more resource-demanding methods. However, focusing on the models' performances in urban studies, LES generally outmatches RANS results, even if the former is at least one order of magnitude more expensive. Consequently, the present work aims to propose a variety of approaches meant to solve some of the major problems linked to RANS simulations and to further improve its accuracy in typical urban contexts. All of these models are capable of switching from an undisturbed flux formulation to a disturbed one through a local deviation or a marker function. For undisturbed flows, a comprehensive approach is adopted, solving the issue of the erroneous stream-wise gradients affecting the turbulent profiles. Around obstacles, Non-Linear Eddy-Viscosity closures are adopted, due to their prominent capability in capturing the anisotropy of turbulence. The purpose of this work is then to propose a new Building Influence Area concept and to offer more affordable alternatives to LES simulations without sacrificing a good grade of accuracy.

1. Introduction

Atmospheric boundary layer simulation over complex terrains (both in rural and urban contexts) is a crucial juncture for the correct estimation of flow-field in urban canopy; wind load on turbines and buildings; and pollutant dispersion. It is also employed for the safe siting of facilities manufacturing or dealing with hazardous gases. Within this context, the forecast accuracy is of paramount importance to draw conclusions that can support policy maker decisions. In recent years, these specific subjects have been examined and studied mostly through Reynolds-Averaged Navier-Stokes by several research groups (i.e. Castro et al., 2003; Blocken et al., 2007a; Pontiggia et al., 2009; Balogh et al., 2012; Parente et al., 2017). As demonstrated by Xie and Castro (2006), Large Eddy Simulation (LES) can offer improved performance for ABL flows, provided an acceptable characterisation of the inflow conditions. However, due to the large scales encompassed by ABL flows, LES methods are considerably more honerous than RANS (Rodi, 1997). Consequently, simulations of ABL flows are often carried out using RANS in conjunction with two-equation turbulence models, with the aim of providing fast and feasible answers to the various design requests. That notwithstanding, there are two non-negligible drawbacks linked to RANS simulations: the well-known horizontal inhomogeneity affecting the profiles, and the inconsistency between wall functions and turbulence models. Blocken et al. (2007a) and, subsequently, O'Sullivan et al. (2011) further improved the original Richards and Hoxey (1993) near-wall treatment. They also focused on how excessive stream-wise gradients can be influenced by an inappropriate wall-function formulation, as well as roughness height and boundary conditions. When taking into account the decrease of shear stress together with height, the horizontal inhomogeneity was quantitatively estimated by Juretic and Kozmar (2013). Recently, Gorlé et al. (2009) introduced a new formulation for the C_μ constant, and for the turbulent dissipation Prandtl number, σ_ϵ, in order to achieve homogeneity with the k profile proposed by Yang et al. (2009). An analogous approach is further validated and extended in Parente and Benocci (2010), through a proper modification of the $k-\epsilon$

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turbulence model according to the set of inlet conditions by Yang et al. (2009). This turbulent kinetic energy definition also proved to be valid for accurate modelling of the atmospheric dispersion, i.e. Riddle et al. (2004), Pontiggia et al. (2009) and Gorlé et al. (2009). The restriction of the former approach is represented by the unsatisfactory inlet profile adopted for turbulent kinetic energy which is not able to satisfy all the governing simulations involved in the problem. As a consequence, Parente et al. (2011a, 2011b) proposed a comprehensive approach consisting of a new set of fully developed inlet turbulent conditions for the neutral ABL. As an alternative, Yan et al. (2016) developed a modelling methodology for the simulation of horizontally homogeneous flows, with the adoption of an arbitrary shear stress approach inside the RNG $k - \epsilon$ model. As for the correct representation of the turbulence properties in disturbed flows (namely in the vicinity of obstacles), a building influence area (BIA) has been developed (Parente et al., 2011a) and further perfected in the last few years. Such a transition is generally referred to as "blending" and inside the BIA, specific turbulence models are applied.

Despite these remarkable improvements, the modelling accuracy of the flow-field around bluff bodies, where the standard two-equation turbulence models keep on failing (Durbin, 1996), still remains problematic and, at least, a challenging task. First of all, this kind of flow-field is quite sensitive to the incoming boundary layer properties, as stated by Porté-Agel et al. (2014). Moreover, correct prediction of the size, shape and position of the separation bubble on the building and of the recirculation/stagnation zones – both upwind and in the wake - is not straightforward (Gorlé, 2010). In order to firmly improve the performance of the standard two eqs. models in proximity of obstacles, one possible path is to adopt higher order term closures for the stress-strain relation. Different quadratic stress-strain relations have been proposed to improve the applicability of linear eddy-viscosity models at an acceptable computational cost (Shih et al., 1993). However, different comparisons proved that no one quadratic relation guarantees significant improvement in performance. Following this trend, Craft et al. (1996) proposed a cubic relation between the strain-rate and vorticity tensors and the stress tensor, which behaves much better than an ordinary eddy-viscosity model, being also able to properly reproduce the effects of stream-line curvature. According to the same recursive cubic formulation, Lien et al. (1996) and Ehrhard and Moussiopoulos (2000), also edited and tuned this type of model through a proper definition of the coefficients for the non-linear terms.

Merci et al. (2004) further investigated cubic models, proposing a new formulation for the non-linear closure. Furthermore he claimed C_μ to be the only relevant parameter – especially in respect to the non-linear coefficients - for all the flows characterized by reduced swirl and vorticity.

The present paper, moving from an assessed verification of the proposed turbulence models in open-field simulations, is centred around both the **CEDVAL A1-1** (displaying a scaled single ground-mounted building, as shown in Fig. 1 on the left) and the **CEDVAL B1-1** (displaying an array of 7×3 A1-1 buildings, on the right) test cases available from the BLASIUS Wind Tunnel of the Environmental Wind Tunnel Laboratory of the Meteorological Institute of Hamburg University (CEDVAL at Hamburg University).

As a consequence, it focuses on the topical challenges linked to the flow-field simulation in a typical urban context.

The aim of this study is somewhat multifaceted, but the main targets are:

- to demonstrate the relevance of using a **Building Influence Area** both for improved results and for reducing the computational resources required all over the domain;
- to further improve the detection of an obstacle and to investigate the effect of the BIA definition on the results;
- to develop a new Building Influence Area formulation based on a marker which measures the local deviation from a parallel shear flow;
- to employ different **NLEV** (non-linear eddy-viscosity) closures with the aim of investigating the influence of both the modified value of C_μ and the non-linear terms;
- to finally point out which model combination results in a better representation of the ground and obstacles' influences on the flow-field.

2. Governing equations and implementation

In RANS simulations fully developed profiles of velocity and turbulence characteristics are generally imposed. As previously mentioned, a crucial problem witnessed when applying RANS methodologies to ABL flows, deeply related to a proper selection of boundary conditions, is represented by the undesired changes (stream-wise gradients) that occur in the vertical profiles of mean wind speed and turbulence quantities as they travel from the inlet of the computational domain to the outlet.

This problem has been described in detail (Blocken et al., 2007a) and it can dramatically affect the overall quality of the simulations.

2.1. Comprehensive $k - \epsilon$ model

Typically, inlet profiles of mean longitudinal velocity and turbulent properties under neutral stratification conditions are defined according Richards and Hoxey (1993) formulation:

$$U = \frac{u_*}{\kappa} ln\left(\frac{z + z_0}{z_0}\right), \tag{1}$$

$$k = \frac{u_*^2}{\sqrt{C_\mu}}, \tag{2}$$

$$\epsilon = \frac{u_*^3}{\kappa(z + z_0)}. \tag{3}$$

In order to make Eqs. (1)–(3) analytical solutions of the standard $k - \epsilon$ model, following Pontiggia et al. (2009) and Parente et al. (2011a), the following source term has to be added to the dissipation rate eq.:

$$S_\epsilon(z) = \frac{\rho u_*^4}{(z + z_0)^2}\left(\frac{(C_{\epsilon 2} - C_{\epsilon 1})\sqrt{C_\mu}}{\kappa^2} - \frac{1}{\sigma_\epsilon}\right). \tag{4}$$

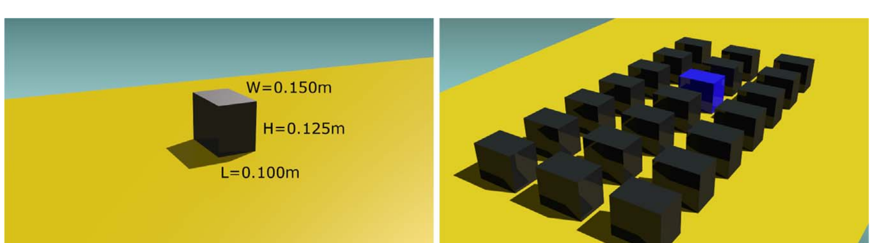

Fig. 1. Cedval A1-1 (on the left) and B1-1 (on the right) test cases, rendered in Blender.