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Large-eddy simulation of thermally stratified forest canopy flow for wind energy studies purposes

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Abstract

A Large Eddy Simulation (LES) code using Lagrangian Dynamic Smagorinsky subgrid models was developed for the simulation of atmospheric stratified flows over topography for wind energy assessment purposes. In this article, the code, which uses separated dynamic procedures for the calculation of eddy diffusivities of momentum and heat, was used to simulate horizontally homogeneous flow in forest canopies, for both unstable and stable regimes. The results were in good agreement with both numerical and experimental results for stable stratified wind regimes but, as far as unstable regimes are concerned, there are still unresolved issues to be addressed.

Keywords: Atmospheric wind flow, forest canopy, lLarge-eddy simulation, LES, wind energy

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1. Introduction

Computer simulation of fluid flows (CFD) has been extensively used in many engineering fields, of which wind energy is no exception. CFD tools have indeed become the conventional tool in recent years for for the study of the wind behaviour in the vicinity of wind farms. Different Reynolds Averaged Navier-Stokes (RaNS) models have been used for this purpose though, as computer capabilities increase, more sophisticated models, such as Large Eddy Simulation (LES), are being increasingly used for this purpose.

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The presence of different kinds of terrain canopies, namely forests, induce complex behaviour and turbulence in the wind flow and its models have been included in CFD tools [1]. In this work, the presence of forest canopy in a thermally stratified flow is modelled using a LES code with Lagrangian Dynamic Smagorinsky models. Results are compared with experimental and numerical results presented in the study [2].

2. Mathematical model

2.1. Governing equations and turbulence modelling

For the present work, the continuity, transport of linear momentum and dry temperature/potential temperature equations were simplified using the anelastic and Boussinesq approximations. The Large Eddy Simulation (LES) filtered fundamental equations used in the presented code are,

$$\frac{\partial\left(\rho\tilde{u}_j\right)}{\partial x_j}=0, \tag{1}$$

$$\frac{\partial\rho\tilde{u}_i}{\partial t}+\frac{\partial}{\partial x_j}\left(\rho\tilde{u}_i\tilde{u}_j\right)=-\frac{\partial\tilde{p}'}{\partial x_i}-\frac{\partial\sigma_{ij}}{\partial x_j}+\frac{\partial\varsigma_{ij}}{\partial x_j}+f\epsilon_{ij3}\tilde{u}_j+\rho g\frac{\tilde{\theta}-\langle\tilde{\theta}\rangle}{\theta_0}\delta_{i3}+F_i, \tag{2}$$

$$\frac{\partial\rho\tilde{\theta}}{\partial t}+\frac{\partial}{\partial x_j}\left(\rho\tilde{u}_j\tilde{\theta}\right)=-\frac{\partial\rho q_j}{\partial x_j}+\frac{\partial}{\partial x_j}\left(\frac{\mu}{\Pr}\frac{\partial\tilde{\theta}}{\partial x_j}\right)+S_h, \tag{3}$$

with

$$\sigma_{ij}=\rho\tau_{ij}=\rho\left(\widetilde{u_iu_j}-\tilde{u}_i\tilde{u}_j\right), \tag{4}$$

$$\varsigma_{ij}=\mu\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right) \tag{5}$$

$$q_i=\widetilde{u_i\theta}-\tilde{u}_i\tilde{\theta}, \tag{6}$$

where (˜) represents the filter operation, ρ is the horizontally averaged fluid density of a background reference state (z-dependent in case of a stratified flow), u_i is the i-component of the instantaneous velocity field, p' the deviation of pressure from the reference state, θ the dry temperature/potential temperature field, $\langle\rangle$ represents average over horizontal planes, θ_0 the reference value of θ, g the magnitude of gravity acceleration, f the Coriolis parameter, μ the molecular viscosity, Pr the Prandtl number, δ_{ij} the Kronecker tensor and F_i, S_h the drag force and heat source in the forest canopy, respectively.

The subgrid-scale stresses and heat fluxes were obtained using scale dependent eddy-viscosity dynamic Smagorinsky models (see [3], [4], [5], [6]) with Lagrangean averaging over pathlines [7]. In these subgridscale models the deviatoric part of the subgrid-scale kinematic stress tensor and the subgrid-scale heat fluxes are calculated using

$$\tau_{ij}-\frac{1}{3}\tau_{kk}\delta_{ij}=-2\nu_T\tilde{S}_{ij} \tag{7}$$

and

$$q_i=-\alpha_T\frac{\partial\tilde{\theta}}{\partial x_i} \tag{8}$$