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Simulations of separated flow over two-dimensional hills

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ABSTRACT

Simulations of separated flow over smooth two-dimensional sinusoidal hills were performed, for hills of varying aspect ratio, using the atmospheric model Regional Atmospheric Modeling System (RAMS) and the engineering model Fluent. This was done with the intent of testing the performance of RAMS when applied to simulations of resolution ~ 1 m. For certain cases, RAMS and Fluent produced mean velocity fields which differed substantially from each other and from wind tunnel observations. The difference in large-scale flow features is believed to be a result of the models' different representation of the hill surface.

1. Introduction

High-resolution atmospheric models can be used to estimate wind fields in high detail. This helps to inform the placement and operation of wind turbines, power stations and airports, potentially improving energy yield, emissions control and aircraft operations.

To cover a large area in detail, models must be computationally efficient. This requirement is balanced by the need to handle the complex flow phenomena, such as separation, that are resolved at high resolution. Two-equation turbulence models are presently a popular compromise between fidelity and computational expense. In order to further reduce computational requirements, the grid resolution can be dramatically reduced away from the area of interest; nesting the high-resolution grid within a regional atmospheric model is a convenient method of achieving this. The procedure is simplified if the same model is capable of both regional and high-resolution simulations.

The Regional Atmospheric Modeling System (RAMS, version 6.0, Pielke et al., 1992; Cotton et al., 2003) has been widely used for regional weather and climate modeling (Gero and Pitman, 2006) and recent development efforts have led to a high-resolution capability. This capability implies a problem domain that overlaps with models used widely in computational fluid dynamics (CFD) for engineering problems, such as Fluent (version 6.1.18, ANSYS Inc.), which has also been applied to atmospheric flows (Kim and Boysan, 1999).

The aim of the present work is to compare RAMS and Fluent when applied to an idealized flow, but one that is representative of the type of situation that would be encountered in a high-resolution simulation over complex terrain. The case that forms the basis of this comparison is the separated flow over a steep two-dimensional hill.

As well as being representative of a realistic flow problem, flow over a hill is interesting in its own right. Flow separation from a smooth body poses major challenges to numerical models (Leschziner, 2006) and, partly because of this, a wide body of literature is devoted to flow over hills. Linear theory is used to predict the speed-up over low hills (Jackson and Hunt, 1975; Hunt et al., 1988) and wavy surfaces (Poggi et al., 2007), while steep hills have been modeled numerically and studied experimentally (Bitsuamlak et al., 2004; Ayotte and Hughes, 2004; Gong and Ibbetson, 1989; Ross et al., 2004; Loureiro et al., 2007). The continued research activity is indicative of the complexity of the flow, despite the simple geometry. In the context of previous work, the hills considered in this paper are very steep; the steepest of the cases more closely resembles an artificial, rather than natural, obstacle.

In the following sections of this paper, the configuration of RAMS and Fluent is described, with particular focus on the surface treatment and grid, the results of simulations are presented and compared with experimental work, reasons for differences are discussed, and conclusions are summarized.

2. Model configuration

The numerical models were configured to match previously reported separated flows (Ferreira et al., 1991, 1995; Lun et al.,

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2003). Four configurations match the work of Ferreira et al., namely hills A–D, and a single configuration matches that of Lun et al. (2003). In all of the cases coriolis frequency was zero and the flow was unstratified.

2.1. Turbulence model

Both RAMS and Fluent were configured to use the same turbulence model, the standard k–ε turbulence model (Launder and Spalding, 1974). The model is named the E–ε turbulence model in meteorological literature (Detering and Etling, 1985) and the latter convention is followed here.

In this model, the effect of turbulence is felt in the mean flow via an eddy viscosity term in the momentum equation. Eddy viscosity acts in a similar manner to molecular viscosity, but is much larger and has a value that depends on flow properties. For heat and momentum, the eddy viscosity is

$$K = c_0^4 \frac{E^2}{\varepsilon} \tag{1}$$

where E is turbulence kinetic energy, ε its dissipation rate and c_0 is an empirical constant. Eddy viscosity for turbulence energy, K_e, and dissipation, K_ε, are assumed to be proportional to K with $K_e = \alpha_e K$ and $K_\varepsilon = \alpha_\varepsilon K$, where α_e and α_ε are empirical constants.

The evolution of turbulence energy, E, expressed in tensor notation is

$$\frac{dE}{dt} = K\left(\frac{\partial U_i}{\partial x_k} + \frac{\partial U_k}{\partial x_i}\right)\frac{\partial U_i}{\partial x_k} + \frac{\partial}{\partial x_k}\left(\alpha_e K \frac{\partial E}{\partial x_k}\right) - \varepsilon \tag{2}$$

where U_i is the i th component of the velocity vector and x_i is the i th component of the displacement vector. The evolution of turbulence dissipation rate, ε, is

$$\frac{d\varepsilon}{dt} = c_1 K \frac{\varepsilon}{E}\left(\frac{\partial U_i}{\partial x_k} + \frac{\partial U_k}{\partial x_i}\right)\frac{\partial U_i}{\partial x_k} - c_2\frac{\varepsilon^2}{E} + \frac{\partial}{\partial x_k}\left(\alpha_\varepsilon K \frac{\partial \varepsilon}{\partial x_k}\right) \tag{3}$$

where c_1 and c_2 are empirical constants.

In total, the turbulence model requires the specification of five empirical constants. These were set to the commonly used values of

$$c_0 = 0.55, \quad c_1 = 1.44, \quad c_2 = 1.92, \quad \alpha_e = 1.0, \quad \alpha_\varepsilon = 0.77 \tag{4}$$

Eq. (4) is derived from wind tunnel measurements; other values are used for a better match with field measurements (Detering and Etling, 1985; Trini Castelli et al., 2001; Xu and Taylor, 1997; Richards and Hoxey, 1993).

In Fluent, these constants are defined differently, following Launder and Spalding (1974), and relate to the present definition as

$$c_0 = C_\mu^{1/4}, \quad c_1 = C_1, \quad c_2 = C_2, \quad \alpha_e = 1/\sigma_k, \quad \alpha_\varepsilon = 1/\sigma_\varepsilon. \tag{5}$$

Further details are provided by Trini Castelli et al. (2001, 2005) and Fluent Inc. (2004).

2.2. Boundary conditions

In all model runs, the surface boundary was a smooth sinusoidal hill with elevation

$$z_s = \begin{cases} (H/2)[1+\cos(\pi x/2L)], & -2L < x < 2L \\ 0, & |x| \geq 2L \end{cases} \tag{6}$$

where H is the hill height and L is the hill half-width at half-maximum. The aspect ratio of the hill was varied, with $H/L = 0.75, 1, 2$, and 4, for hills A, B, C and D respectively as well as $H/L = 1.33$ to match Lun et al. (2003). Model runs were carried out with hill heights of 60 m for model intercomparison, and 60 and 120 mm, as appropriate, for direct comparison with experiments.

The hill surface was aerodynamically smooth in all cases, and the surface stress was calculated using wall functions. The wall function definitions differ between the models, RAMS follows the method of Detering and Etling (1985) whereas Fluent follows Launder and Spalding (1974).

In RAMS, the velocity at the grid point nearest the wall, $U(z_p)$ at location z_p, is used to calculate the friction velocity, u_*, assuming a logarithmic velocity profile between z_p and the wall. For an aerodynamically rough horizontal wall, this is

$$U(z_p) = \frac{u_*}{\kappa}\log(z_p/z_0), \qquad z \geq z_0 \tag{7}$$

where the constant z_0 is the roughness length.

For this work, the RAMS wall function was extended to include smooth walls. For a smooth wall, z_0 is replaced by the displacement length $\nu/(Cu_*)$, where $C = 9.793$ is an empirical constant (Fluent Inc., 2004) and ν is kinematic viscosity, so that

$$U(z_p) = \frac{u_*}{\kappa}\log(C z_p u_*/\nu) \tag{8}$$

The stress on the fluid, τ, is found from Eq. (8) and the definition $u_* \equiv (\tau/\rho)^{1/2}$, where ρ is the fluid density.

The RAMS wall functions for E and ε are based on the assumption that, between z_p and the wall, turbulence production and dissipation are in equilibrium and the velocity profile is logarithmic. Following Detering and Etling (1985)

$$E(z_p) = u_*^2/c_0^2 \quad \text{and} \quad \varepsilon(z_p) = u_*^3/(\kappa z_p) \tag{9}$$

The boundary conditions in RAMS imply that u_*, E, and ε at the boundary depend only on the near-surface velocity, but a different approach is taken in Fluent.

In Fluent, $E(z_p)$ is calculated from the transport equation, Eq. (2), in the same manner as interior points, assuming zero flux of E into the wall. The stress on the fluid is calculated from $U(z_p)$ and $E(z_p)$ by

$$\frac{U(z_p)}{u_*^2} c_o E^{1/2} = \frac{1}{\kappa}\log(C z_p c_0 E^{1/2}/\nu) \tag{10}$$

where $C = 9.793$ is an empirical constant, which is often denoted E elsewhere. Turbulence dissipation near the wall is

$$\varepsilon(z_p) = c_0^3 E^{3/2}/(\kappa z_p) \tag{11}$$

assuming that turbulence production is in local equilibrium with dissipation.

The difference between the wall functions of RAMS and Fluent arises from the assumption of one velocity scale in the derivation of the former and two velocity scales in the latter (Lacasse et al., 2004). In Eq. (10), a length scale based on turbulence, $c_o E^{1/2}$, is included in addition to the friction velocity, u_*. This allows for non-zero E, and therefore non-zero scalar fluxes, at stagnation points.

In parts of the flow where an equilibrium boundary layer really is present, Eq. (2) simplifies to $E(z_p) = u_*^2/c_0^2$. Then the Fluent boundary conditions, Eqs. (10) and (11), reduce to the RAMS boundary conditions, Eqs. (8) and (9). If E is larger than the equilibrium value, Eq. (10) implies a larger surface stress for the Fluent boundary.

The next important boundary condition is at the inlet to the domain. This was a fixed velocity profile, therefore setting up a pressure gradient and driving the flow through the model domain. For cases A–D the inlet velocity, U, was chosen to have the form of a turbulent boundary layer double the thickness of the hill height; $U/U_0 = (z/\delta)^\alpha$ with $U_0 = 20\,\text{m s}^{-1}$, $\delta = 2H$ and $\alpha = 0.16$. This profile matches previous measurements (Ferreira et al., 1995), but is not itself a solution to the governing equations of an E–ε model. As a