H14-153
EVALUATION OF WIND FIELD AND DISPERSION MODELS IN THE PRESENCE OF COMPLEX TERRAIN

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Abstract: The simulation of high resolution complex terrain effects (grid resolution of about hundred meters) is of great importance to model atmospheric dispersion at local scale (simulation domain less than 10 km), for air quality assessments. These effects include acceleration at the lee side and over the hill top, deceleration downstream of the hill and an eventual separation depending on the steepness and roughness of the hill.
This paper investigates the performances of two air flow models, a linearizeddiagnostic model (Flowstar) and a CFD code (Fluent), in capturing complex terrain effects. We compare these two codes with measurements from two wind tunnel experiments in the presence of hills and valleys of different shapes and roughness (Khurshudyan *et al*., 1981, and Almeida *et al*., 1992). Results are presented in terms of wind, turbulence and relative acceleration (speed-up). We also focus on the ability of these models to simulate recirculation regions downstream of the valleys and steepest hills.Overall, we find a better prediction with Fluent, especially for rough and steep hills and in recirculation regions. We also present a limit of applicability for each code.
Furthermore, the air flow simulated by the two codes is used to drive the Safety Lagrangian Atmospheric Model (SLAM) developed at EcoleCentrale de Lyon. The impact of the precision of the simulated air flow is evaluated and an intercomparison with the Gaussian plume dispersion model ADMS, using the Flowstar wind field, is presented. Finally, we find considerable improvement when we use the coupling of a CFD wind field code with a Lagrangian dispersion model, especially in highly complex terrain simulations.

Key words: *Complex terrain, evaluation of wind flow models, evaluation of dispersion models*

INTRODUCTION

In regions of complex terrain, such as those in the presence of valleys, hills and rough terrain, a proper modeling of the air flow is required in order to correctly predict air quality and dispersion of pollutants in these regions. The flow in complex terrain presents local characteristics such as strong acceleration or deceleration of the flow, zones of recirculations, and considerable changes in turbulent quantities.The aim in this paper is a thorough comparisonof two wind flow models, an analytical model and a Computational Fluid Dynamics model (CFD), and the study of their capability in simulating these effects. The linearized analytical model chosen for this study is Flowstar, i.e. the meteorological pre-processor of the Gaussian plume dispersion model ADMS, which is largely used in the atmospheric dispersion community. The CFD code chosen is the well-known Fluent. We will compare these two codes with measurements from wind tunnel experiments in the presence of hills and valleys and identify the limitation of each code. The two experiments considered in this study are Khurshudyan *et al*., 1981 (known as the RUSHIL experiment), and Almeida *et al*., 1992.

In the second part of this paper, the air flow simulated by the two codes will be used to drivethe Safety Lagrangian Atmospheric Model (SLAM), a dispersion model developed at EcoleCentrale de Lyon (SLAM), in the presence of a steep hill. This Lagrangian model has been configured to use wind flow data both from Flowstar and Fluent. We will also perform an intercomparison with the Gaussian plume dispersion model ADMS using the wind field provided by the analytical model Flowstar. The general scheme of the work is presented in Figure 1.

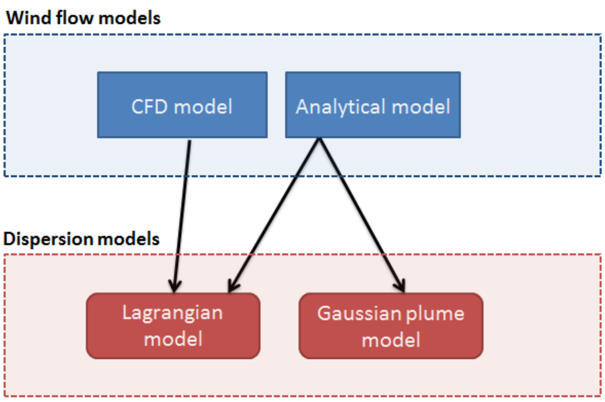

Figure 1 Schematic representation of work presented

DESCRIPTION OF THE EXPERIMENTS

The RUSHIL experiment

The Khurshudyan *et al*.(1981)orEPA (Environmental Protection Agency) RUSHIL experiment, was conducted in a wind tunnel immersed in a neutral boundary layer. Three 2D symmetrical hills withvarious ratios of height h over length Lwere considered. The hill height, length and roughness are all expressed in Table 1 where the dimensions have been multiplied by a certain factor in order to correspond to real hills.Their shape is given by a parametric expression but it iseasily approximated by a cosine expression. Reversed flow was observed in the wake of thetwo steeper hills.

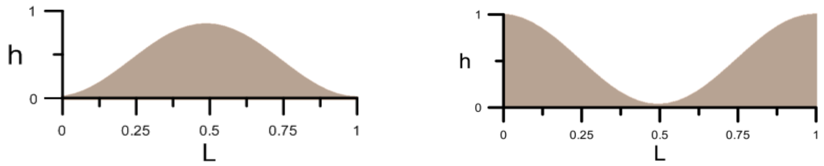

Figure 2 Schematic representation of the dimension of a 2D hill and valley

The Almeida et al. (1992) experiment

The Almeida *et al*. (1992) experiment (termed Almeida in the remaining of this paper) considers two configurations. The first case is in the presence of a single 2D hill, while the second oneconsiders several consecutive 2D hills, thus leading to the creation of valleys (Figure 2). The experiment is in the presence of neutral atmospheric conditions. The shape of the hills is given by a fourth order polynomial, although it is close to having a cosine form, similarly to the previous experiment. All hills have the same shape. Due to their steepness, large regions of reversed flow are created in the wake of the single and consecutive hills. Using the data provided by the experiment in the recirculation zones, we will focus on the ability of our models to reproduce the flow in this region.

The main characteristics of the upwind flow in the two experiments, as well as the characteristics of the hills (dimensions, roughness lengths) whichwill be later used in the wind flow models in the following sections, are expressed in Table 1.

Table 2 Summary of main characteristics of the flow and hills. The dimensions have been multiplied by 10^3 and 10^4respectively for the RUSHIL and Almeida hills.$u_*$is the friction velocity, $u_\infty$the free-stream velocity and $z_0$the roughness length.

Hill	**h (m)**	**L (m)**	**h/L**	u_* **(m/s)**	u_∞**(m/s)**	z_0 **(m)**
RUSHIL H8	117	1872	0,0625	0,178	4	0,157
RUSHIL H5	117	1170	0,1	0,178	4	0,157
RUSHIL H3	117	702	0,166	0,178	4	0,157
Almeida	280	1080	0,259	0,079	2,147	0,015

PARAMETRISATION OF THE WIND FLOW MODELS

CFD Wind flow model (Fluent)

The turbulence model chosen in the CFD code is the RANS k-ε model with the modified Duynkerke constants. Concerning the boundary conditions, theoretical profiles in neutral atmospheric conditions (equations 1) are specified at the inlet of the domain. We note that κ is the Von-Karman constant and is equal to 0.4 and C_μ is equal to 0.033.The theoretical wind profile approximates very well the upstream profile of the two experiments.We impose a wall condition at the ground with a specified roughness length, a symmetry condition at the top (the top being at a height of 3km), and a uniform pressure profile at the outlet of the domain.

$$u(z) = \frac{u_*}{\kappa} ln\left(\frac{z}{z_0}\right) \quad ; \quad k(z) = \frac{u_*^2}{\sqrt{C_\mu}} \quad ; \quad \varepsilon(z) = \frac{u_*^3}{\kappa z} \tag{1}$$

Analytical wind flow model (Flowstar)

Flowstar is a linearized analytical model based on the theory developed by Jackson and Hunt (1975) and Hunt *et al.* (1988), which is based on the fact that different processes influence the flow dynamics in layers according to the height above the ground.As input for Flowstar, we specify data about wind velocity profiles by means of a .prf file at various heights, and also information about the fluctuating terms when data is available. A uniform roughness length is also specified at the ground.

MODEL RESULTS

The RUSHIL experiment

We will focus in this part on the ability of our models to predictacceleration on the upwind part and top of the hill, depending on the steepness of the hill. The ability of the generation of a reversed flow will be discussed in the Almeida experiment, where additional data exists in this region. We will therefore express here our results in terms of the speedup (ΔS), defined as the relative difference between the hilltop velocity u_p and the upstream velocity u_0 (equation 2), z being the vertical coordinate.

$$\Delta S = \frac{u_p(z)-u_0(z)}{u_0(z)} \tag{2}$$

As shown in Figure 3, both models over-predict the experimental profile of the speed-up for the lowest hill (H8). In this case, the acceleration at hilltop is decreased due to the rough terrain ($z_0 = 0{,}157m$), and the maximum of speed-up observed during the experiment is situated at 25m above the ground. This is approximately the height predicted by Fluent, whereas Flowstar predicts that the maximum is situated at ground level. Although the known limitation of Flowstar is for hills with slopes no greater than 1 to 3 or ah/L ratio of 0.167, the roughness of hill H8 induces considerable error in this case.

For the steeper hill, Fluent is in very good agreement with experiment data, even for the steepest hill (H3). On the contrary, Flowstar over-predicts the speed-up in the three cases, and the error increases with the steepness of the hill. However, the minimum error displayed by Flowstar is in the case of the H5 hill. All in all, CFD models should be preferred to linearized models when the hill is low and rough, or when it is steep.

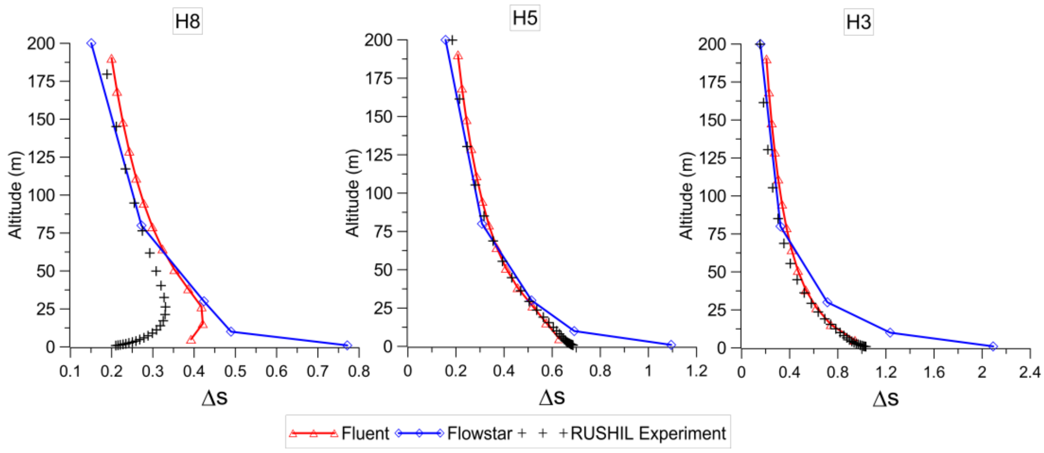

Figure 3 Profiles of speed-up for different steepness of the hills

We now perform a sensibility test of our models by changing the roughness length for the lowest hill H8. We change $z_0$from its value during the experiment (0.157m) to three different values of z_0 ranging from smooth to rough (0.005m, 0.25m and 0.5m). Figure 4 shows that as the roughness increases, Fluent predicts thatthe maximum of speed-up decreases and its location increases in height. The speed-up profile of Fluent can eventually fit to the experimental data if a value of the roughness length is chosen between 0.25m and 0.5m. On the contrary, Flowstar predicts that themaximum speed-up is situated at ground level for all of the roughness length. In fact, there seems to be no sensitivity to the value of z_0 when the terrain becomes rough (no changes forz_0 ranging from 0.157 to 0.5m).A limitation of Flowstar has therefore been identified.

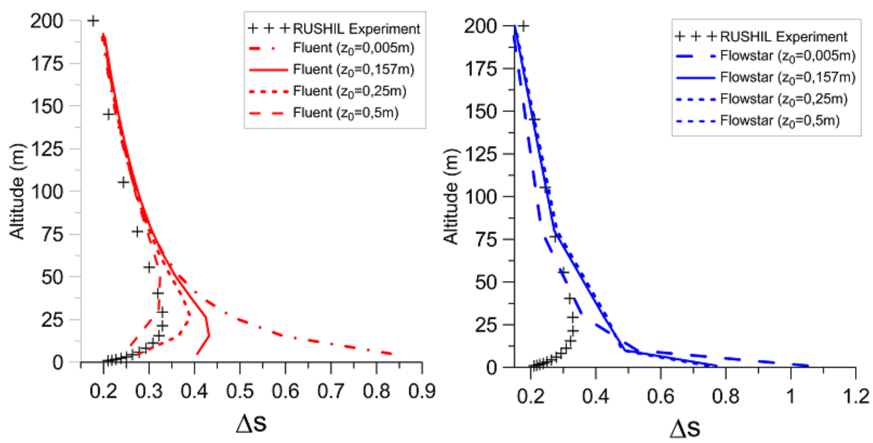

Figure 4 Profiles of speed-up for different roughness lengths for the H8 hill

The Almeida *et al.* (1992) experiment

The single hillcase

On Figure 5, the data provided by the experiment indicates that in the case of the single hill, the mean flow is strongly decelerated on the upward part at x=0,315L (see Figure 2). This is very well predicted by Fluent. On the other hand, the effect of the high steepness of the hill on the mean flow is not correctly taken into account in Flowstar. The speed-up at 70m above the ground is 0.563 according to the experiment, whereas it is 0.724 in Fluent and 0.961 in Flowstar. This relatively large difference between Fluent and the experiment is due to the high steepness. At the lee of the hill (x=0.963L), both the experiment and Fluent simulate a region of reversed flow with an approximate height of 120m, i.e. a ratio of 0.43 of the total hill height. The total length of the recirculation region in the experiment is approximately 1,3L and 1,2L in Fluent. Flowstar fails to predict a recirculation region above a few meters.

The multiple hill case

Contrary to the previous section, we are in the presence of a reversed flow both in the upward and leeward part of the hill, according to the experiment (see Almeida*et al.*, 1992) and to Fluent. Actually, the recirculation region extends almost to the whole of the valley region between the two hills. On the whole, the results with Fluent are very good (Figure 5). On the contrary, Flowstar fails to capture the valley effect and displays results quite similar to those in the presence of a single hill seen in the previous section. Therefore, wehave identified here another limitation of the analytical model. Concerning the turbulent kinetic energy k, both models under-predict the values of the experiment, though Fluent gives better results, especially regarding the height of the maximum of k due of the nature of the k-ε turbulence model. We can also note that the k-ε model induces a greater vertical diffusion of turbulence, as compared to the experiment. This is generally encountered when using this type of turbulence model.

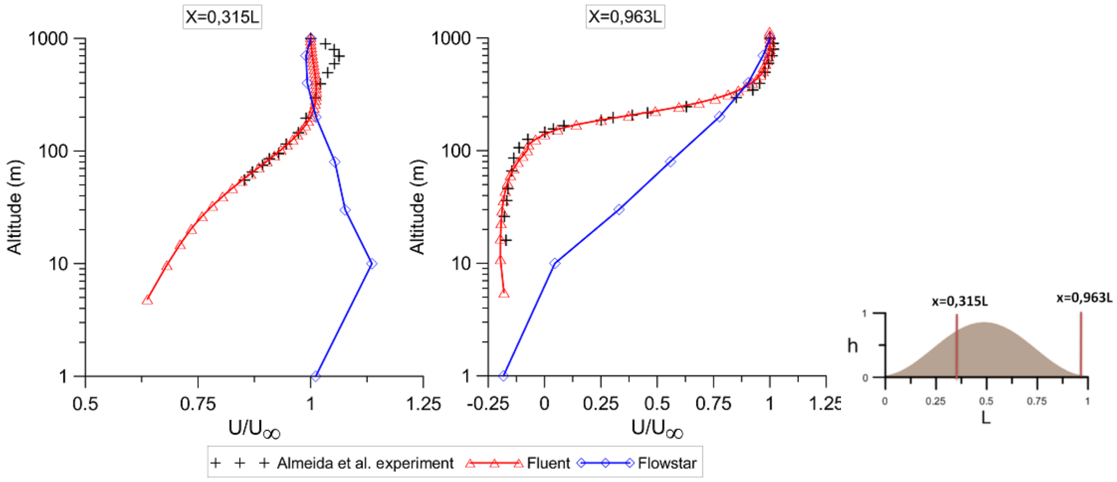

Figure 4 Profiles of horizontal wind velocity U for the single hill

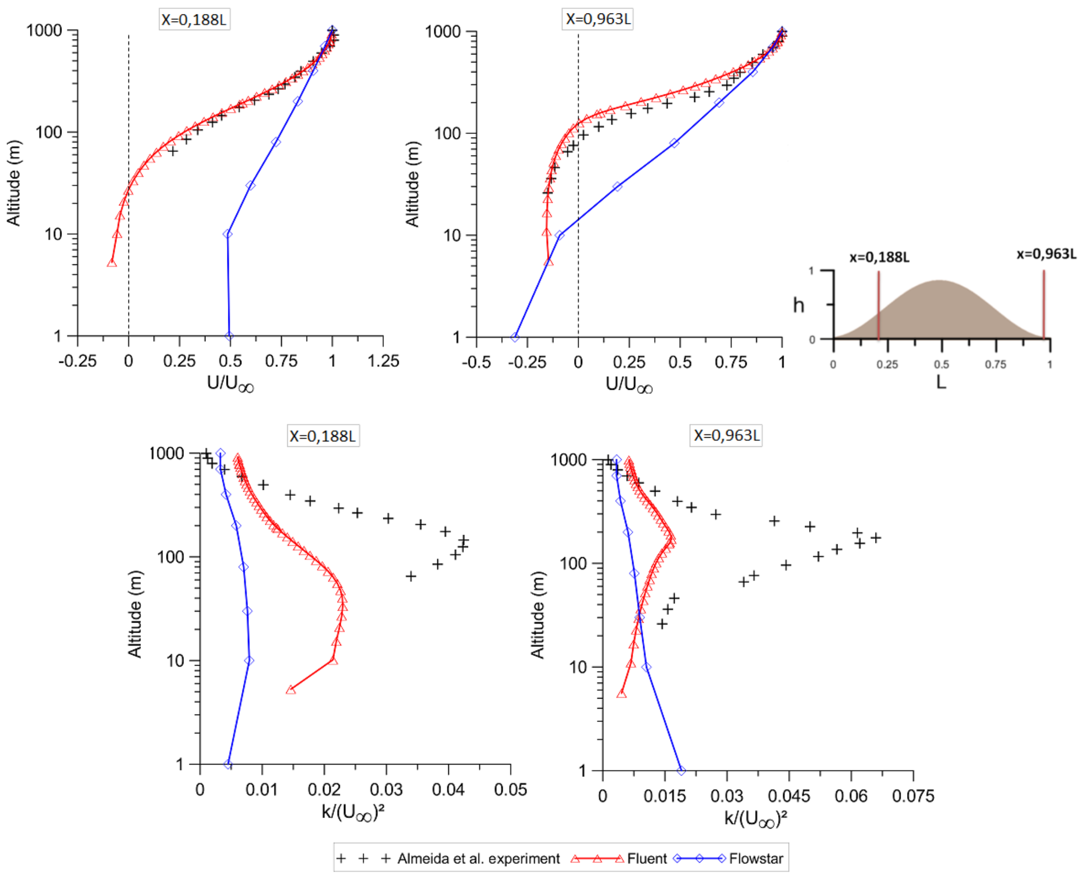

Figure 5 Profiles of horizontal wind velocity U and turbulent kinetic energy k for the multiple hills (between the third and the fourth hill)

Study of the dispersion of a pollutant

We are interested in this section in the coupling between the wind flow and the dispersion model. The methodology of the coupling is explained in Figure 1. We therefore take into consideration two dispersion models (SLAM and ADMS). SLAM is a Lagrangian dispersion model (Vendel*et al.*, 2011), which uses the Langevin equation in order to model the advection of particles in the atmosphere; whereas ADMS is a Gaussian plume model, thus assuming that the pollutant dispersion has a Gaussian distribution. Wetherefore present in this section the study of the dispersion of aNO_2 pollutant in the single Almeida hill domain. The source is located at x=L/4 at 20m above ground level, and it emits at a rate of 10 g/s. We choose an averaging time of 15 minutes for ADMS.Consequently, and in order to compare between the two dispersion models, we simulate with SLAM an one-hour long emission of NO_2, which is sufficient to give a quasi-stationary state. In SLAM, 1000 particles are emitted every 5s, so there are approximately 200,000 particles in the domain, at a given moment.

At hilltop, the concentration levels at the groundcalculated by the Analytical-Gaussian coupling method (Flowstar-ADMS) are the highestof the three methods (Figure 6). The largest vertical dispersion is displayed by the CFD-Lagrangian approach, mainly because of the higher values of k calculated with the CFD code, as seen in Figure 5. In the wake of the hill, (at x=3L/4 and x=L), results with the CFD-Lagrangian method are very different from the other two methods because of the reversed flow calculated by Fluent, which leads to the pollutants going generally above the recirculation zone. This induces ground level concentrations much lower than the ones appearing when using a Flowstar flow (approximately 10 times lower).On the whole, the results using a Flowstar flow (with either ADMS or SLAM)calculate approximately the same concentrations, although with a higher vertical dispersion displayed by the Lagrangian model, whereas the concentrations are very different in the wake of the hills when using a CFD flow.

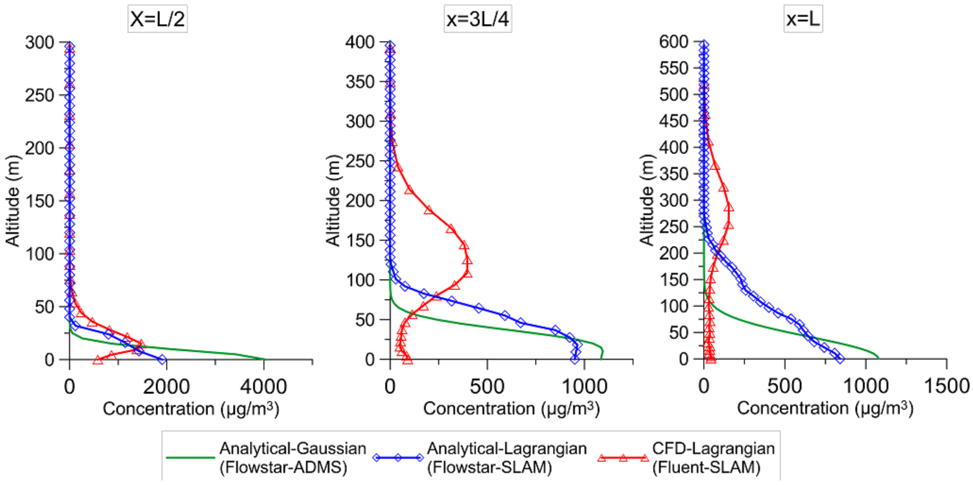

Figure 6 Profiles of NO2 concentrations at different locations, following the direction of the flow, in the presence of the Almeida single hill

CONCLUSION

The unquestionable advantage of the linearized models over the CFD models lies in the fact that the former has a negligible CPU time as compared to the latter. Nevertheless, in the examined cases, we demonstrated that the validity of the Flowstar model is not satisfactory and that there is a need to use a CFD code in modelling the wind flow not only in the presence of steep hills, but also in rough low hills.

Concerning the atmospheric dispersion of pollutants, in this paper we wish to underline the high impact of the choice of the wind flow. The coupling approaches using a linearized model as wind flow data, along with either a Gaussian plume or a Lagrangian dispersion model, calculated approximately the same rate of concentrations in the studied case, whereas results where highly different when a CFD flow was used, especially in the wake of the hill. The necessity of the use of a CFD model flow as input for the dispersion models has therefore been demonstrated. Nevertheless, additional comparisons, especially with results of experiments in the presence of dispersion in the case of complex terrain, need to be carried out.

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