4.3 A LARGE EDDY SIMULATION STUDY OF POLLUTANT DISPERSION IN URBAN AREAS

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1. INTRODUCTION

It has been estimated that in 2008 for the first time in history, the urban population surpassed the rural one (United Nations Report (2007)). Hence, it is of fundamental importance to acquire a deep understanding of the pollution risks related to urban areas where the air quality is nowadays a critical environmental problem. The flow and dispersion in these regions are driven by a multiplicity of factors (meteorological forcing, antrophic activities, building heating) and involve phenomena which span over a wide range of scales (from regional to city, to neighborhood, to building scale). A new multidisciplinary focus area, called urban fluid mechanics after Fernando (2001), developed in the last years to study the complex flow motion in cities. In this field a big help can be given by numerical simulations and in the last years, with the increasing computer power, it has been possible to apply more sophisticated numerical techniques to urban studies. This is the case of the large-eddy simulation approach (LES), that, in the last decades, has been applied to a number of urban studies (e.g. the studies from Brown et al. (2001), Stevens (2004), Mahura et al. (2005), Grinstein et al. (2007), Lundquist et al. (2010)).

In this paper a new large-eddy simulation model, called LES-AIR, developed for the study of flow and dispersion at neighborhood scales, is presented. The LES-AIR, whose description will be given in section 2, is able to recreate the urban geometries with great details through the combined usage of a curvilinear grid to take into account the macroscopic obstacles like hills, and of the immersed boundary (IB) method for the smaller obstacles like buildings. It has been extensively validated reproducing various test cases with increasing degree of complexity. Results from the validation procedure will be discussed in section 3, while in section 4 its application to the study of flow and dispersion in the Servola-Valmaura suburban area of the city of Trieste is presented. Lastly in section 5 the conclusions will be reported.

2. MODEL DESCRIPTION

The model resolves the incompressible continuity, momentum and scalar transport equations under the Boussinesq approximation over curvilinear coordinates. A body fitted grid is used to reproduce the macroscopic terrain slopes while the immersed boundary method of Roman et al. (2009) is used to reproduce complex geometric features, like buildings. Wall shear stresses are reproduced using two different approaches depending on the kind of solid wall (body fitted grid or IB). An equilibrium-stress wall-layer model together with a modification of the Smagorinsky SGS model is employed at the body-fitted walls, whereas the equilibrium-stress model of Roman et al. (Phys. Fluids, 2009b) has been set over the immersed boundaries. A standard Smagorinsky model is used in the flow field. The governing equations are solved by means of the fractional step algorithm of Zang et al. (1994). The pollution dispersion is treated in an Eulerian way, solving a number of transport equations equal to the species (pollutants) whose dispersion is studied. The advective terms of momentum equation and advection-diffusion equation of the pollutant concentration are treated using two different strategies. First we use centered second order accurate scheme together with explicit high-order filter to remove spurious wiggles arising close to the sharp corners of the buildings (F-simulations). Second we used a quadratic upwind interpolation (Q-simulations). The first strategy has the advantage to preserve the correct level of turbulent kinetic energy in the flow field, while removing small scale unphysical wiggles. The main drawback of this procedure stands in the empirical calibration required for the frequency of filtering. The second strategy does not require calibration but has the drawback to remove a large amount of turbulent kinetic energy.

3. MODEL VALIDATION

The model has been massively validated against numerical and experimental literature data. Tests have been performed reproducing cases with increased complexity. First a

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bottom Ekman layer archetypal of a neutral atmospheric boundary layer has been reproduced and results compared with those of Moeng and Sullivan (1994). Successively a wind tunnel experiment of the flow around an isolated obstacle (CEVDAL database) has been reproduced. In this test, emission of a dilute concentration in the downwind side of the obstacle has been also simulated. Third, the flow around an array of low-rising buildings (MUST experiment) has been reproduced with an incidence angle of 41°.

Overall, the validation phase has shown that the Q simulations overestimate the average velocity when held at a constant driving force because of suppression of a noticeable amount of turbulent kinetic energy and a consequent underestimation of the friction coefficient. This problem is less evident when the simulations are carried out at constant flow rate. In this case the average velocity is well predicted while the underestimation of the wall shear stress affects less the characteristics of the mean velocity field. The main drawback of Q simulations was the prediction of a too low level of turbulent kinetic energy when compared to the reference data.

4. REPRODUCTION OF FLOW AND DISPERSION IN A SUBURBAN AREA OF THE CITY OF TRIESTE IN ITALY

As an applicative example we studied pollutant release in a residential area of the city of Trieste in Italy. The simulated area has the shape of a valley which is confined on one side by the sea (see fig.1 where a schematic of the domain is reported). The area covered by the simulation has horizontal extensions of Lx=1500m and Ly=1000m and vertical extension Lz=600m thus, following the distinction proposed by Britter and Hanna (2003), it falls into the category of the neighborhood scale simulations. 256x256 equi-spaced grid nodes were used in the horizontal directions while in the vertical one 60 points were used. They were clustered near the ground with a maximum resolution of 1m. The flow is directed along the x direction, mimicking a south-west sea breeze. The inflow planes at x=0 were generated by a LES pre-simulation over a periodic domain, while at the outflow plane located at x=Lx a zero gradient condition was used together with a damping region to avoid spurious reflections in the domain. At the lateral and at the upper sides free slip conditions were set. The base of the body fitted grid was derived through an interpolation of the terrain elevations on the grid base nodes while the buildings were reproduced by means of the IB method using their actual height and position. The velocity at the nodes placed close to the fluid IB interface, called IB nodes, has been derived through a linear interpolation of the velocities from the projection nodes. Both F and Q simulations were performed.

The first analysis concerned the bulk quantities in the canopy region. The average velocities were evaluated in three different regions of the domain, A, B, and C, having different terrain and building characteristics (see Figure 2). Region A has few tall building and an almost flat terrain; in region B the terrain has a slope aligned with the main flow direction and there are many regular buildings; region C has a big amount of small irregular houses with a strong terrain slope occurring transversely to the flow direction. The profiles have been compared with the exponential formula proposed by Macdonalds (2001) to describe the canopy layer velocities:

$$u(z) = u_H \exp(a(z/H - 1)) \qquad (1)$$

where H is the average building height, a is a constant related to H, to a mixing length-scale inside the canopy and to the friction coefficient, u_H is the velocity at z=H. There are few differences between the F and Q profiles. The A and B profiles have been fitted to the theoretical exponential profile of (1) using a value of a=0.8 and a good match was found. The C profile presents lower values of u/u_H and the exponential profile gave a good fitting for a value of a=1.5. We will not enter too much in details about all the factors that determined the changes of a. What it is possible to conclude is that in A and B areas, the average canopy velocities present more similar exponential profiles. This is a good example which introduces the problem that the same values of the a constant of (1) could be found for very different canopy layers.

The instantaneous contour plots of the vertical velocity component of F and Q simulations have been compared in Figure 3. It is possible to detect differences between the shape and the sizes of the instantaneous turbulent structures in the two type of simulations. In simulation Q the structures are more elongated, and smeared while in case F smaller spots are present. This is a symptom of the larger dissipation present in the QUICK scheme that it is not able to reproduce the smaller structures of the turbulent field. In other words, the LES cut off is shifted to lower wave numbers.

To simulate pollutant dispersion from urban vehicular traffic, a line source has been placed in the central street of the domain (see Figure 1) in the F simulation. The concentration has been emitted over four cells along the x directions for a total source length of Ls=24m. In the source area a concentration C=1 was imposed. At the starting emission time the background concentration was set to zero. Also the emitted scalar has been filtered like the flow velocity components. From Figure 4, where the instantaneous concentration pattern on a curvilinear plane placed at z=0.5m is reported, it is possible to see that the dispersion plume is mainly channeled in the large central street of the domain. Some deviations occur whenever the flow finds large lateral streets. Lastly in Figure 5 the concentration pattern on a vertical plane is reported. High concentration spots, that are driven by the turbulent ejection events are clearly visible. These results, although preliminary, were inserted in the thesis to give an example of the LES-AIR code capability to deal with the contaminant dispersion also in case of very complex geometries. Indeed such a detailed flow and domain reproductions are a very powerful tools and could be used for many practical applications.

5. CONCLUSIONS

A new large eddy simulation model, called LES-AIR, suited for urban simulations at neighborhood scales has been presented.

In the LES-AIR, the combine usage of body fitted grid and of the IB method is used to reproduce the urban geometries with great detail. Two simulation strategies, consisting in a different treatment of the advective terms, have been followed in order to remove spurious wiggles arising close to the sharp corners of the buildings. In F simulations a centered second order accurate scheme is used together with explicit high-order spatial filtering; in Q simulations a quadratic upwind interpolation is applied.

The results have shown that in Q simulations the dissipative scheme produced a flow field in which the size of the smallest turbulent structures was considerably larger than in the F simulations. The latter ones seem to be preferable since are able to suppress the oscillations and at the same time they furnish a more detailed representation of the small turbulent structures acting at the building scales. Preliminary results for the scalar concentration showed the great capabilities of the code to represent the dispersion pattern in the very complex urban geometries.

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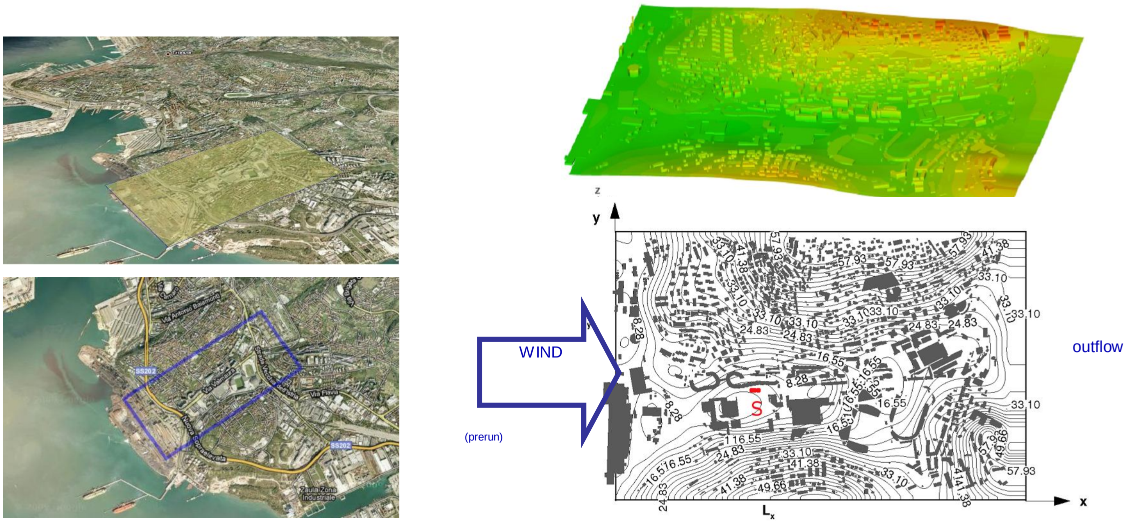

Figure 1. Left panels: top views of the Servola-Valmaura quarters of Trieste in Italy; right panels: schematic of the LES-AIR simulation domain.

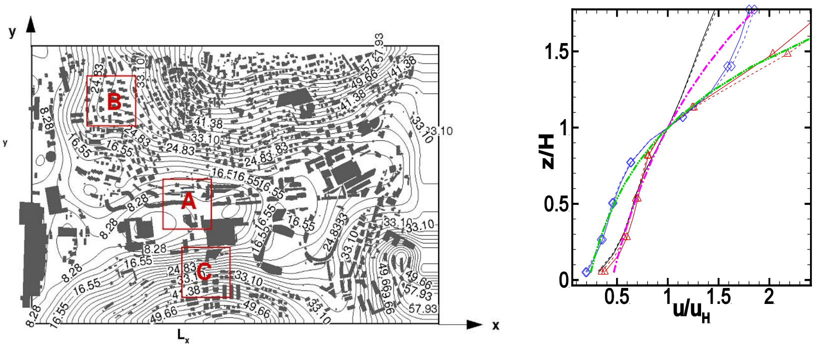

Figure 2. Inner scaling in the three regions of the domain having different orographic and topographic characteristics. Solid lines R-F simulations; dashed lines R-Q simulations. Black lines without symbols zone A; red lines with open triangles, zone B; blue lines with open diamonds, zone C. The pink dash dot line and the green dash dot lines have been derived from eq. 1 using a=0.8 and a=1 respectively.

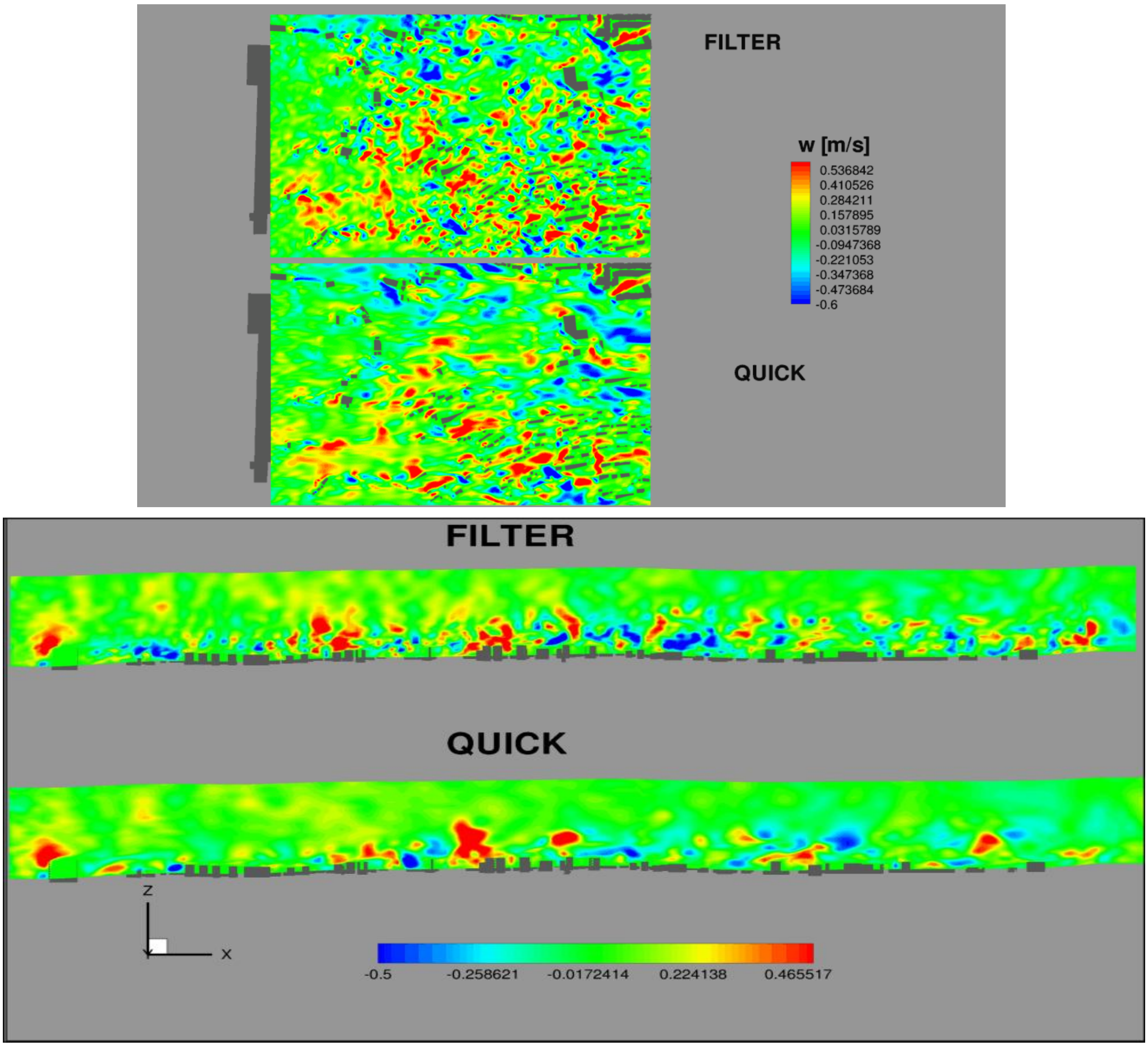

Figure 3. Instantaneous contour plots of the vertical velocity component for the F and Q-Simulations. Upper panel: curvilinear surfaces placed at z=8m from the ground; lower panel x-z planes.

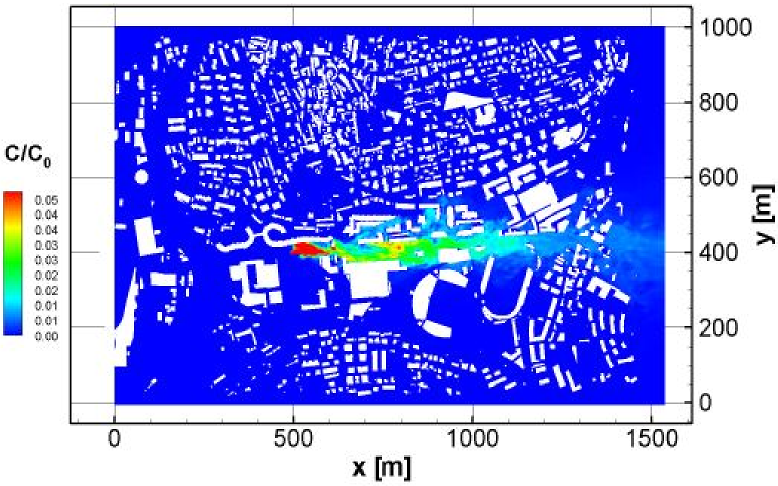

Figure 4. Top view of the instantaneous concentration plot on a curvilinear surface placed at z=0.5m from the ground after 1.4h from the initial emission time.

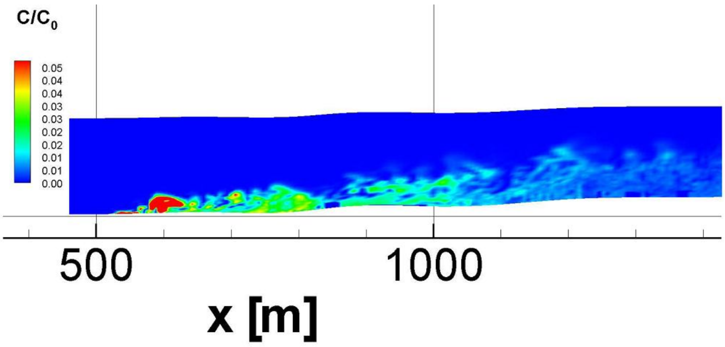

Figure 5. Lateral view of the instantaneous concentration plot on a x-z plane located in correspondence of he line source after 1.4h from the initial emission time.