Numerical study of the wind patterns inside and around buildings and urban blocks of different topologies

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1. Introduction

A wide diversity of urban fabrics exists around the world, especially in traditional neighborhoods. They are generally linked with typical spatial configurations of buildings. In particular, open, compact and attached forms were developed depending on the local geography, climate and culture. The different levels of porosity that characterize these urban forms involve different very-local micro-climates and internal wind patterns. Indeed, the very-local interactions between mean winds and the shape and layout of urban structures determine to a large extent the flow structures that develop in the urban canopy layer. These aerodynamic phenomena affect in turn, among other things, urban ventilation processes, wind and thermal comfort as well as the climate at the upper scale of the city.

At the spatial scales of the building and street canyon, specific air flow structures develop within courtyards and other urban outdoor spaces linked with constructions. They depend on the orientation of these outdoor spaces in relation to the mean wind incidence, as well as openness, i.e. whether these outdoor spaces are external, partially or totally surrounded by a building or contained inside a building group.

This paper presents a numerical study performed to analyze and better understand the aerodynamic processes leading to these flow structures developing around buildings and inside urban blocks depending on their topological features. Only forced convection processes are considered. The effects of the horizontal openness of courtyards and internal open spaces of urban blocks are more specifically examined. Providing information on the wind conditions next to buildings and on ventilation processes, such observations linking urban morphological properties to physical phenomena would support a better understanding of the urban heat island phenomenon on larger urban scales, as well as a more integrated and bio-climatic design of buildings and urban areas on smaller scales.

2. Computational model

2.1 Validation study

The study is based on numerical experiments, which are performed using computational fluid dynamic (CFD) models and the commercial software Ansys Fluent, versions 14.5 and 15 (Fluent inc. 2013). A Reynolds averaged Navier-Stokes (RANS) method is used. The model was preliminarily validated by comparison with high quality reduced-scale experimental data from wind-tunnel tests (CEDVAL, Meteorological Institute of Hamburg 2013) as well as detailed numerical predictions obtained using the lattice Boltzmann Method and a large eddy simulation approach (LBM LES, Obrecht et al. 2014). The accuracy of steady RANS predictions was evaluated in cases of an isolated and a regular array of rectangular obstacles. More specifically, the performance of two turbulence models, namely the realizable k-ε model (Rk-ε) and the Reynolds stress model (RSM), was evaluated. In comparison with k-ε turbulence models, the RSM accounts for anisotropic effects of turbulence on the mean flow. For more details about the validation study, please refer to Merlier (2015).

On the one hand, the Rk-ε model was found to predict flow structures that better match experimental data very close to the isolated obstacle. On the other hand, the RSM better predicts the recirculation in the cavity zone downstream the rectangular block. In addition, this later model better reproduces the vortical structure developing between obstacles in the multi obstacle case, whereas no recirculation is predicted by the Rk-ε. RSM predictions are also generally in better agreement with the LBM LES results than the Rk-ε results are. Nonetheless, note that the flow intermittence probably affects RSM results. No clear stabilization of the mean flow profiles could be achieved where the flow is reported very unsteady by the experimental documentation.

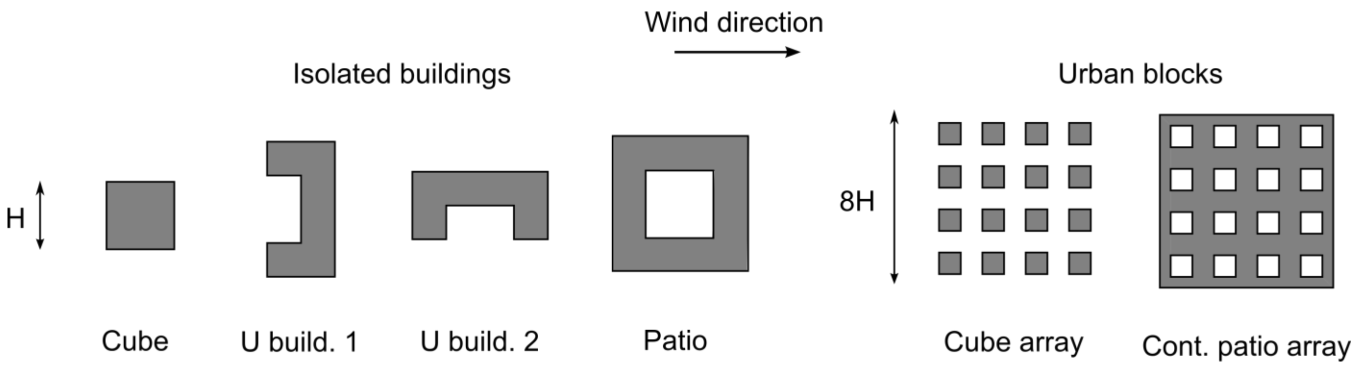

Figure 1: Case studies

Hence, according to the validation study, the steady RANS RSM is able to reproduce the main physical phenomena, although imperfectly being a steady RANS model. As a consequence, actual simulations were performed using the steady RANS RSM.

2.2 Settings of the computational model

CFD simulations were performed for different building and urban block generic types, which were specifically designed for that purpose. These morphological types are based on an analysis and abstraction of urban textures that exist in different regions of the world, as well as an identification of the urban morphological factors that affect aerodynamic processes that develop in the urban canopy layer. Examples of the analyzed urban patterns can be found in Firley et Stahl (2011) and Salat (2011). To examine the effects of the topological properties of built structures, a cubic, a U, and a patio buildings as well as a cube and a continuous patio arrays are focused on. The height of each construction is H = 10 m. Figure 1 illustrates the different case studies currently considered.

The approach flow was designed using a preliminary simulation of a virtual 10 km long empty tunnel. According to the Davenport's classification, the resulting mean wind profile corresponds to an intermediate roughness class between an open and a roughly open landscape (Wieringa et al. 2001). The mean velocity speed at 10 m high equals 4.3 $m.s^{-1}$. The computational domain respects the recommendations of Tominaga et al. (2008) in terms of size and spatial discretization. Cell dimensioning down to 15 cm was used for complex cases. Mesh sensitivity was verified for the isolated building types but not for the arrays because of the mesh size already involved (> 15-25.10^6 cells). The numerical schemes used are second order at least. Convergence was verified by monitoring mean velocity and turbulent properties profiles for several lines along the domain and by checking the overall evolution of the simulation residuals. Note that no stabilization of the profiles could be achieved for the continuous patio array case. Numerical instabilities periodically occurred. This might be explained by the physical complexity of the flow field, which might not show clear and stable recirculation zones. For this case, results were taken after 2.10^3 iterations during which no numerical instability occurred.

3. Results and analysis

Figure 2 - Figure 15 show the 3D mean velocity streamlines as well as the 3D mean vorticity contours[1] around the generic constructions and within courtyards. Simulation results were post processed using the free and open source software ParaView. Typical flow structures around sharp edged obstacles basically develop:

- the horseshoe vortex which begins upwind and extends downstream on the sides of obstacles
- the separated bubbles after the leading edges of obstacles
- and the arch vortex downstream obstacles.

Recirculation phenomena located in under-pressure zones generally correspond to low velocity zones. On the contrary, corner streams show high velocities. Within courtyards and canyons, vortical recirculation phenomena develop. Their features depend on the openness of the court or canyon involved, its orientation with respect to the wind incidence and its location with respect to the upstream leading edge of the built structure in case of arrays.

[1] Blue : 0.5 rad. s^{-1} ; green : 1.5 rad ;s^{-1}, red : 5.5 rad.s^{-1}.

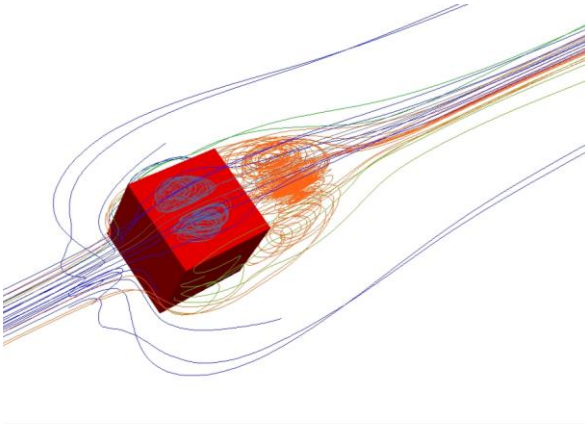

Figure 2: Flow structures around the cube

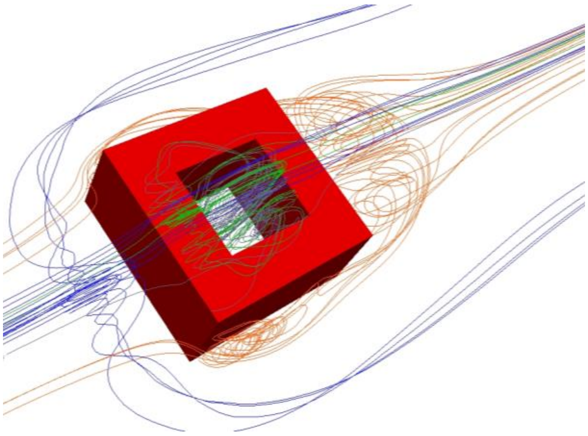

Figure 3: Flow structures within and around the patio

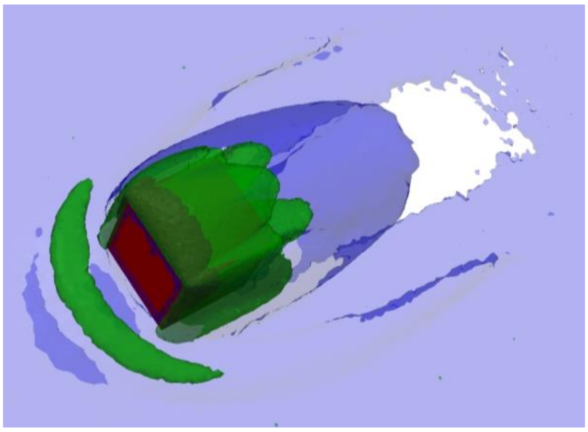

Figure 4: Mean vorticity contours around the cube

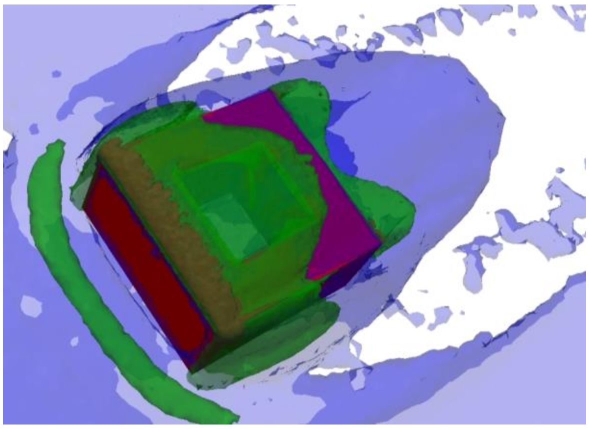

Figure 5: Mean vorticity contours around the patio

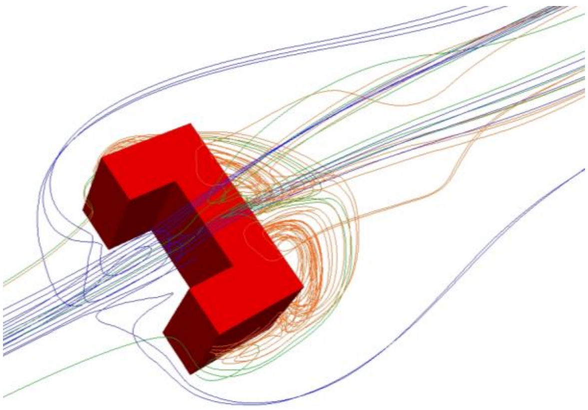

Figure 6: Flow structures around the U building standing perpendicular to the incident flow

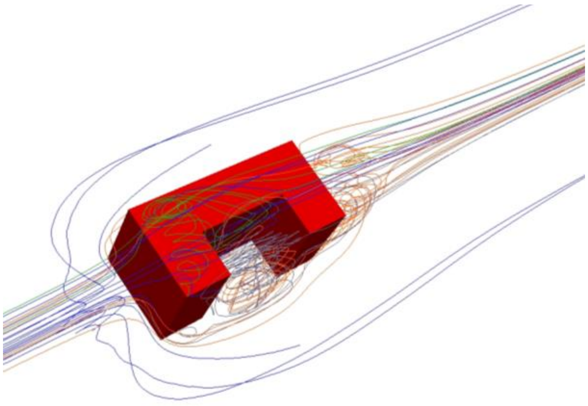

Figure 7: Flow structures around the U building standing parallel to the incident flow

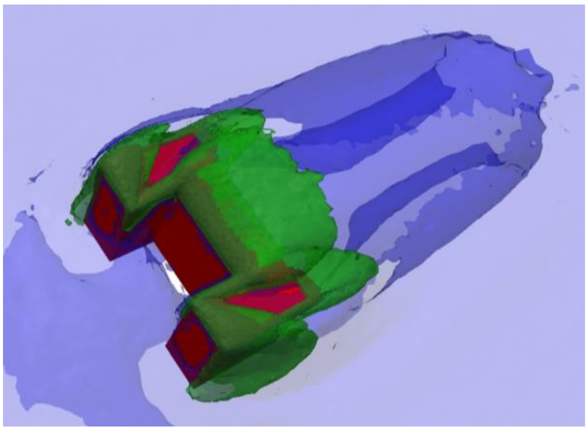

Figure 8: Mean vorticity contours around the U building 1

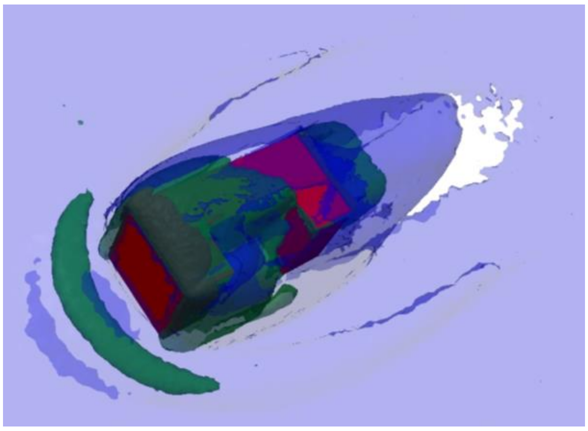

Figure 9: Mean vorticity contours around the U building 2

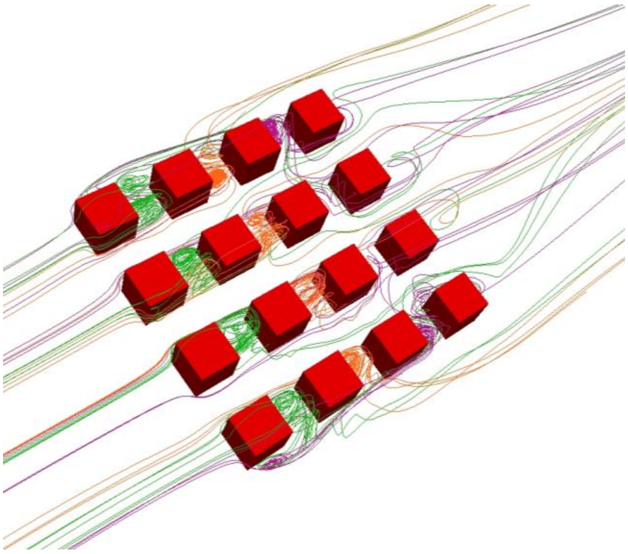

Figure 10: Flow structures within the cube array

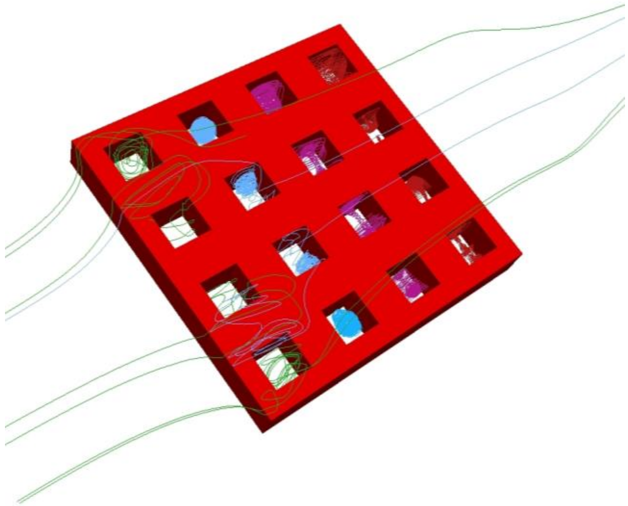

Figure 11: Flow structures within the patio array

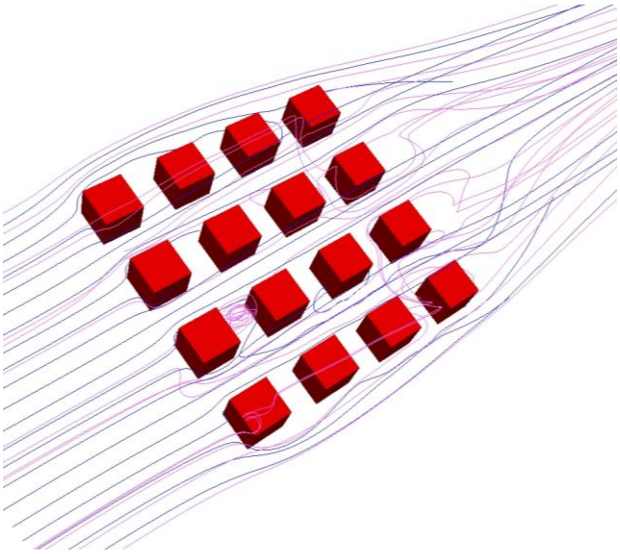

Figure 12: Flow structures around and through the cube array

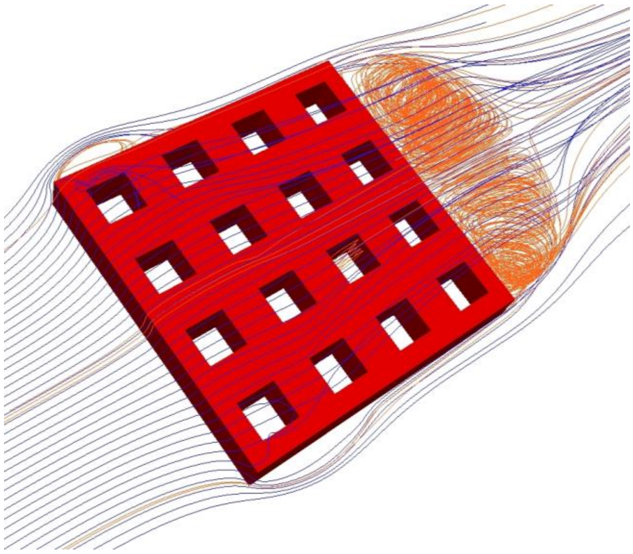

Figure 13: Flow structures around the continuous patio array

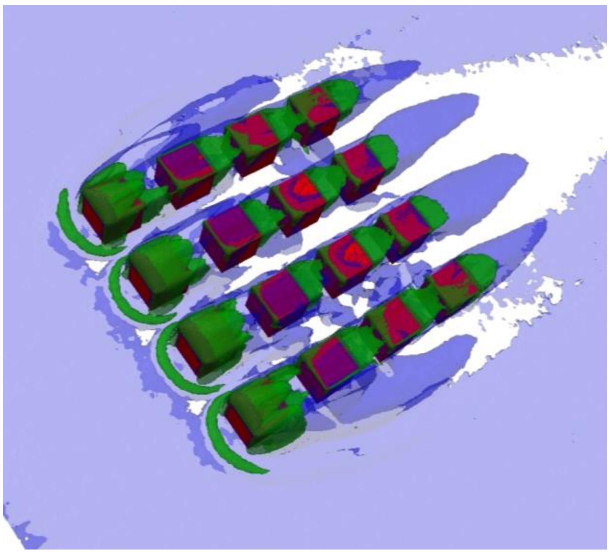

Figure 14: Mean vorticity contours around and through the cube array

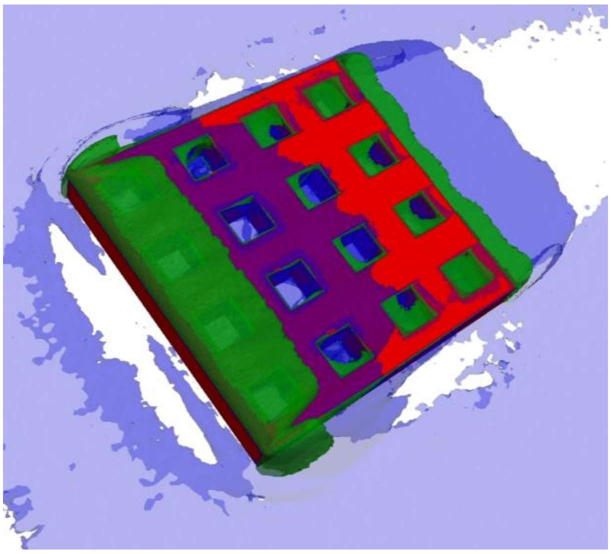

Figure 15: Mean vorticity contours around and through the continuous patio array

In cases of isolated buildings, results show quite different flow patterns and recirculation phenomena in courts depending on their horizontal openness and orientation in relation to the approach flow. Regarding semi-open courts, the internal flow recirculation is often merged with the surrounding flows. Typically, the court of the U building 1 modifies the basic standing vortex as part of it is entrapped inside. A recirculation shaped as a semi arch vortex develops in the court of the U building 2 driven by the above and lateral flows. Note that such flow structures are observed because of the small depth of courts. When deeper, a self-contained vertical structure, which resembles to that developing within the patio, may develop (Merlier, 2015).

The flow patterns developing within the open spaces of urban blocks show flow paths or recirculation phenomena, which more or less interfere with the surrounding flows. These different flow patterns are characterized by different levels of vorticity and mean velocities, creating higher wind speeds or rather sheltered zones in flow recirculation regions. Such vortical recirculation regions develop in courts, canyons and downstream obstacles. In comparison with the flow structures developing around corresponding isolated building types, the flow structures developing in arrays are altered because of the presence of the additional constructions. These constructions directly affect the basic recirculation phenomena or create a general group effect which modifies the driving aerodynamic forces. Essentially, corner streams are altered in the first line of cubes and the general recirculation that develops above the upstream part of the continuous patio array affects the vortical structures within the underlying patios. Two structures occur inside: one related to the top separated bubble and the second below. The different flow structures then evolve streamwise showing less defined shapes in the cube array because of the sheltering provided by the upstream obstacles and the convergence of lateral flows, and showing more usual shapes in patios.

3. Conclusion

This study uses CFD to analyze the flow structures that develop around built structures depending on their topological properties. A steady RANS approach is implemented. Generic case studies and forced convection processes are considered.

The presence of courts or surrounding constructions modifies flow structures with respect to the basic structures usually observed around isolated sharp-edged obstacles. The different basic flow structures are intensified; reduced or may even be prevented depending on the topology of the built structure. Hence, the built design appears to be critical in defining urban air flows and therefore urban microclimates. The different flow patterns created may affect the pedestrian wind comfort, the convective cooling of surfaces, the turbulent heat removal as well as the building energy loads due to air infiltration and heat transmission through the building envelope. Nevertheless, to evaluate these effects in details, a more detailed computational approach is required.

References

Firley, E., Stahl, C., 2011. *The urban housing handbook*. 1st ed. John Wiley & Sons.

Fluent inc. 2013. "Fluent release 14.5 user guide".

Meteorological Institute of Hamburg. 2013. "Compilation of Experimental Data for Validation of Microscale Dispersion Models". *CEDVAL*. http://www.mi.uni-hamburg.de/CEDVAL_Validation_Data.427.0.html.

Merlier, L., 2015. *On the Interactions between Urban Structures and Air Flows: A Numerical Study of the Effects of Urban Morphology on the Building Wind Environment and the Related Building Energy Loads*. Ph D thesis, CETHIL UMR 5008, INSA Lyon, CSTB, submitted.

Obrecht, C., .Kuznik, F., Merlier, L., Roux, J.J., Tourancheau, B., 2014. "Towards Aeraulic Simulations at Urban Scale Using the Lattice Boltzmann Method". *Environmental Fluid Mechanics*.

Salat, S., 2011. *Cities and Forms: on sustainable urbanism*. Hermann CSTB.

Tominaga, Y., Mochida, A., Yoshie, R., Kataoka, H., Nozu, T., Masaru Yoshikawa, M., et Shirasawa, T., 2008. "AIJ Guidelines for Practical Applications of CFD to Pedestrian Wind Environment around Buildings". *Journal of Wind Engineering and Industrial Aerodynamics* 96 (10-11): 1749‑61.

Wieringa, J., Davenport, A. Grimmond, C.S.B., Oke, T.R., 2001. « New revision of Davenport roughness classification ». In *3rd European and African Conference on Wind Engineering*. Eindhoven, Netherlands.