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A two-stage CFD method for wind microclimate studies coupling large-scale topography and local urban regions

N.P. O'Sullivan[a], E. Cardone[b], U. Ikono, A.W. Rofail

[a]*Windtech Consultants, London, United Kingdom, niall@windtechglobal.com*
[b]*Windtech Consultants, London, United Kingdom, edoardo@windtechglobal.com*

SUMMARY

This paper presents a two-stage Computational Fluid Dynamics (CFD) approach for modelling urban wind microclimate conditions in areas impacted by complex surrounding terrain. Gibraltar is considered as a case study providing an example of a dense urban environment affected by a large topographic feature. In the first stage, CFD simulations are performed over a broad terrain domain (5km diameter) containing only topographic features. Flow fields from these simulations are sampled on a cylindrical surface enclosing a smaller, refined urban region (475m radius). These sampled data are subsequently used as boundary conditions for the second stage of CFD simulations that incorporates the full urban morphology. This workflow enables terrain-informed boundary conditions for multiple local urban studies, while requiring the computationally expensive large-scale topography simulation to be performed only once. This provides an efficient, repeatable framework for assessing wind microclimates in regions dominated by strong orographic effects.

Keywords: *CFD, Wind Microclimate, Topography, Mapping, Gibraltar*

1. INTRODUCTION

Pedestrian-level wind microclimate assessments are required in urban environments to evaluate comfort and safety conditions. These studies are commonly performed using Computational Fluid Dynamics (CFD), where the atmospheric boundary layer (ABL) is represented using idealised inlet profiles based on terrain roughness classifications and empirical laws (Blocken et al., 2007; Richards and Norris, 2011). While this approach is widely accepted for relatively homogeneous surroundings, it can become uncertain in regions dominated by large and complex topographic features, where strong orographic effects significantly modify the approaching flow.

Gibraltar represents a particularly challenging case, as its dense adjacent urban area is directly influenced by the Rock of Gibraltar, a steep limestone ridge rising over 400m above sea level. The interaction between approaching winds and the Rock produces flow acceleration, separation, and directional distortion that cannot be adequately captured through standard terrain-category-based ABL profiles alone (Franke et al., 2011; Castro and Apsley, 1997). As a result, conventional CFD approaches either simplify the upstream flow or require very large computational domains that include both the extended surroundings topography as well as the detailed local urban geometry, leading to high computational costs.

This paper presents a two-stage CFD methodology designed for pedestrian wind microclimate studies in topographically complex regions. The method decouples the large-scale terrain simulation from the local urban simulation, allowing boundary conditions to be reused across multiple local studies. A case study focusing on an area near Queens Hotel in Gibraltar is used to demonstrate the approach and to compare its performance against a conventional single-step simulation including both terrain and urban geometry.

2. METHOD

2.1. Overview of the Two-Stage Approach

The proposed workflow consists of two sequential CFD stages:

- Stage 1, Large-Scale Topography Simulation: CFD simulations are performed over a broad domain (5km in diameter) including the Rock of Gibraltar and surrounding orography.
- Stage 2, Small-Scale Urban Simulation: Flow data extracted from the first stage are sampled on a cylindrical surface enclosing a smaller, refined urban region (475 m radius). These data are mapped onto the boundaries of a second CFD model that includes full urban morphology.

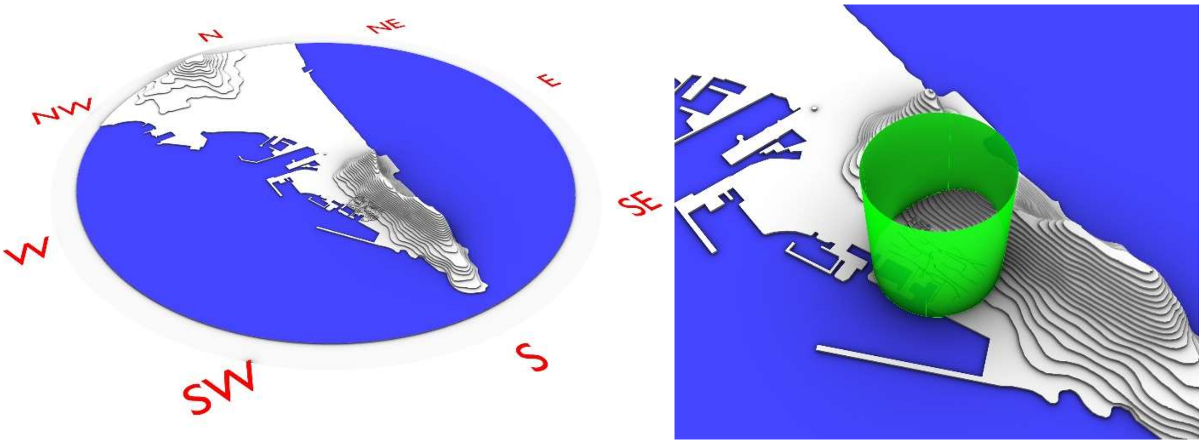

Figure 1: Large-scale Topography Domain of Gibraltar (left) and close-up of small-scale urban area with cylinder surface (in green) used for mapping of boundary conditions (right).

2.2. Numerical Setup

All simulations were performed using the Reynolds-Averaged Navier-Stokes (RANS) modelling, implemented in HELYX®, based on OpenFOAM. The governing equations for incompressible flow are:

$$\nabla \cdot \mathbf{U} = 0 \tag{1}$$

$$\rho \frac{\mathrm{D}\mathbf{U}}{\mathrm{Dt}} = \rho g - \nabla p + \mu \nabla^2 \mathbf{U} \tag{2}$$

where **U** is the mean velocity vector, p is pressure, ρ is the density and μ is viscosity coefficient.

Turbulence closure is achieved using the k-ω model, which has been shown to perform robustly for urban flow applications when appropriate near-wall treatment is applied (Blocken et al., 2007; Tominaga et al., 2008). The turbulence model coefficients were calibrated against Windtech’s boundary-layer wind tunnel measurements for pedestrian wind comfort assessments.

2.3. Boundary Conditions and Wind Assessment

One critical wind direction was considered, that is the East-North-Easterly (ENE) wind. For Stage 1, inlet boundary conditions consist of neutral ABL profiles defined using standard logarithmic formulations above the terrain:

$$U(z) = \frac{u_*}{\kappa} \ln\left(\frac{z + z_0}{z}\right) \tag{3}$$

where u_* is the friction velocity, κ is the von Kármán constant, and z_0 is the surface roughness length (Blocken et al., 2007; Richards and Norris, 2011).

For Stage 2, inlet boundary conditions are mapped using the sampled velocity and turbulence fields extracted from the cylindrical surface in Stage 1. This ensures that local simulations are driven by terrain-modified flow rather than ABL assumptions, addressing limitations of conventional inflow profile definitions in complex terrain (Franke et al., 2011; Castro and Apsley, 1997).

Pedestrian level wind conditions were evaluated using the wind speed ratio:

$$\eta = \frac{U_i}{U_{ref}} \tag{4}$$

where U_i is the mean wind speed at 1.5 m above ground level, and U_{ref} is the reference wind speed at a specified height above terrain.

To evaluate the accuracy of the two-stage method, a reference simulation was conducted in which the local urban geometry was directly embedded within the large-scale terrain domain. This single-step model follows conventional best-practice guidance for pedestrian wind CFD simulations and serves as a benchmark for comparison (Franke et al., 2011; Tominaga et al., 2008).

3. RESULTS

3.1. Wind Speed Ratios

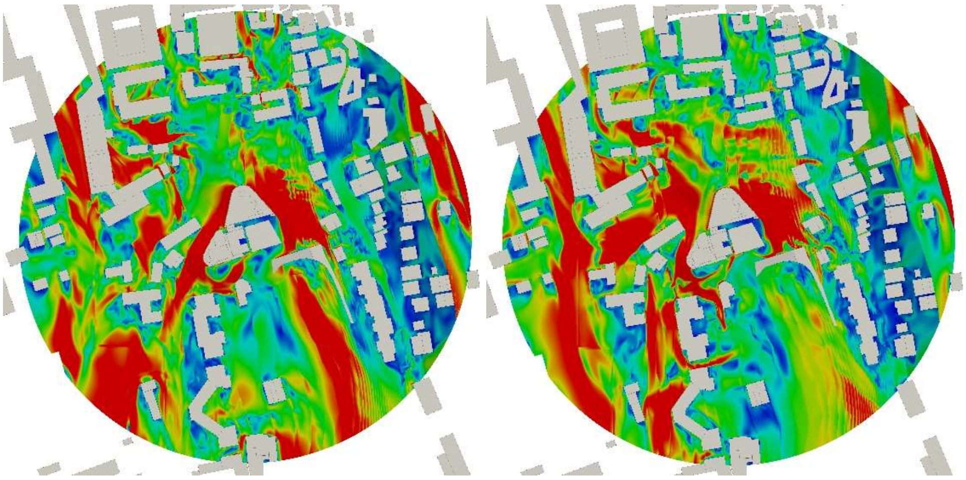

Figure 2: Ground level ENE wind speed-up results for the two-stage (left) and single-step approach (right).

Spatial distributions of wind speed ratios obtained from the two-stage approach show strong agreement with the single-step reference simulation (Figure 2). Localised acceleration zones near street corners and building edges are consistently reproduced, indicating that the sampled boundary conditions preserve key flow features induced by the surrounding topography.

4. DISCUSSION

The results demonstrate that the two-stage methodology captures the dominant flow features influencing pedestrian wind conditions in several areas of the site. By transferring fully developed, terrain-modified flow fields to the local domain, the method objective is to avoid uncertainties associated with terrain-category selection and empirical orographic adjustments (Blocken et al., 2007; Richards and Norris, 2011).

Compared to the single-step approach, the two-stage method offers substantial computational savings when multiple local urban areas are expected to be assessed within the same topographic context. The method maintains sufficient accuracy for pedestrian wind microclimate studies, which primarily rely on mean flow statistics rather than detailed transient turbulence structures (Britter and Hanna, 2003).

5. CONCLUSIONS

A two-stage CFD framework for pedestrian wind microclimate assessment in topographically complex regions has been presented using a Gibraltar case study. The key conclusions are the following:

- Terrain-induced flow effects can be captured and reused through a large-scale topography simulation.
- Sampled and mapped boundary conditions provide accurate inflow for local urban CFD models.
- The approach potentially enables repeatable and consistent wind microclimate assessments without reliance on simplified ABL assumptions.

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