Urban canopy wind flow in Genoa: implementing transfer coefficients to integrate CFD-derived patterns into NWP forecasts

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SUMMARY
Accurate prediction of near-surface wind flow in complex urban environments remains a challenge for operational forecasting. In cities such as Genoa, steep terrain and dense urban infrastructure strongly modify the mesoscale wind field, producing localized accelerations and directional shifts. This study employs a static downscaling methodology based on transfer coefficients derived from pre-computed CFD simulations. Empirical relationships are established between upper-layer and near-surface flow. These relationships are then applied to mesoscale NWP forecasts to generate morphology-aware surface wind predictions. Initial results show the emergence of terrain-driven patterns and enhanced spatial detail relative to the original mesoscale forecast. Ongoing work addresses validation and optimization of the method.

Keywords: urban canopy wind flow downscaling, transfer coefficients, NWP-CFD coupling

1. INTRODUCTION

Accurate prediction of near-surface (urban canopy) wind flow is essential for civil protection, air-quality management, renewable energy assessment, and infrastructure resilience. In coastal and topographically complex cities such as Genoa (Italy), strong wind events are frequent and often amplified by orographic channeling and urban morphology. Forecasting these near-surface flows remains a key challenge in applied meteorology and urban climate research (Fernando, 2010; Blocken, 2015).

Numerical Weather Prediction (NWP) models provide a physically consistent representation of atmospheric processes at mesoscale and synoptic scales. However, their horizontal resolution (typically 1–3 km in convection-permitting configurations) limits their ability to explicitly resolve flow distortion induced by complex terrain and urban obstacles. Urban canopy parameterizations partially address these effects but remain simplified (Joshi et al., 2025). In contrast, the Computational Fluid Dynamics (CFD) technique computes the wind flow by explicitly accounting for complex geometries; however, its high computational cost prevents the operational forecasting use over large domains (Blocken, 2015).

Hybrid approaches have emerged to bridge the scale gap between mesoscale forecasting and microscale urban flow modeling. One strategy consists of precomputing CFD simulations under standardized inflow conditions and using them to downscale mesoscale wind forecasts (e.g., Barcons et al., 2018; Ricci et al., 2022). This study follows such approach by deriving transfer coefficients from CFD simulations to improve the representation of Genoa's urban wind field. These coefficients are integrated into NWP model outputs to generate near-surface wind forecasts that account for morphology-driven flow distortions.

2. NWP-CFD COUPLING AND WIND FIELD DOWNSCALING

Numerical procedure is summarized as follows. Wind fields are obtained from pre-computed CFD simulations for 12 inflow wind directions at two heights: (*a*) 100 m above ground level (AGL), above the urban boundary layer (UBL), and (*b*) 10 m AGL, representative of the urban canopy. These fields are used to compute transfer coefficients. From the NWP model, the wind forecast at 100 m AGL is extracted. The transfer coefficients are then applied to the forecasted flow, leading to a near-surface wind prediction based on the CFD simulations. The workflow of this process is depicted in Figure 1. Model configuration and transfer coefficients formulation are described in subsections 2.1 to 2.3.

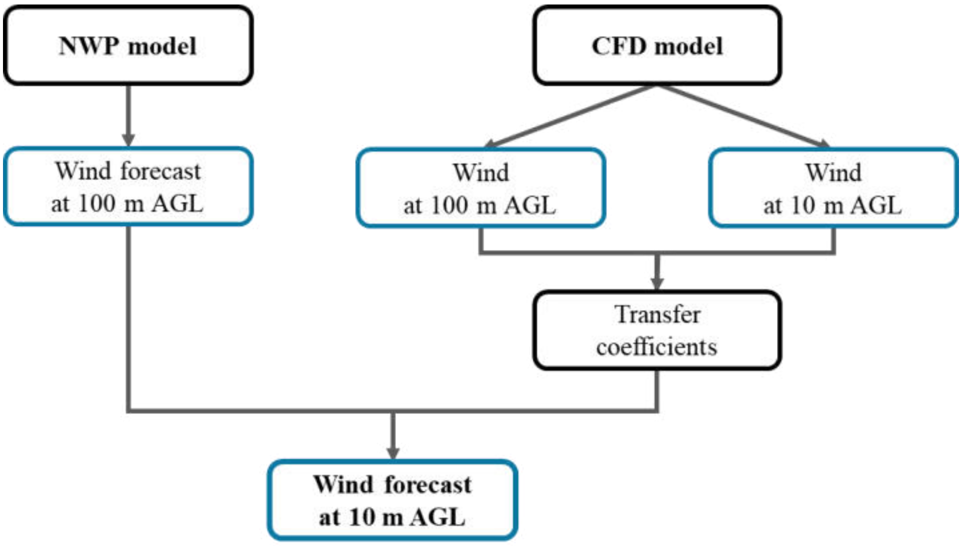

Figure 1. Workflow of the procedure used to downscale the NWP wind forecast at 100 m AGL to 10 m AGL within the urban canopy.

2.1. NWP Model Settings

The forecasted flow in the upper UBL is obtained from MOLOCH (LOCal MOdel in Hybrid Coordinates), the last component of the operational atmospheric modeling chain used at the Meteo-Hydrological Center of the Liguria Region (ARPAL). MOLOCH is a non-hydrostatic, convection-resolving model, implemented at horizontal resolution of about 1.5 km and using 60 vertical levels over a domain that covers Italy. A hybrid terrain-following vertical coordinate, which gradually relaxes to horizontal surfaces away from the ground, is employed (Sacchetti et al., 2023). The dynamical and physical schemes of MOLOCH are described in Buzzi et al. (2014) and Trini Castelli et al. (2020).

2.2. CFD Model Settings

CFD simulations were performed over the entire area of the city (37 × 18 km^2) as part of a previous project aimed at developing a digital twin of the city, using the open-source CFD library OpenFOAM. The complex model geometry accounts for both terrain topography and urban infrastructure, with different roughness parameters for sea, urban, and rural areas, as described by Žužul et al. (2024). Simulations were performed for 12 inflow wind directions (α = 15°, 45°, …, 345°).

2.3. Downscaling strategy

Transfer coefficients defined in Eq. (1) provide an empirical relation to downscale wind intensities from each point *j* at 100 m AGL (coincident with the NWP model grid points) to each point i within the urban canopy at 10 m AGL, for all simulations and corresponding inflow directions α_g.

$$k_{ij}(\alpha_g) = \frac{U_{i\,10m}(\alpha_g)}{U_{j\,100m}(\alpha_g)} \tag{1}$$

Correspondingly, the shift in wind direction between the upper layer and the urban canopy is obtained from CFD outputs, as expressed in Eq. (2).

$$\Delta_{ij}(\alpha_g) = \theta_{j\,100m}(\alpha_g) - \theta_{i\,10m}(\alpha_g) \tag{2}$$

where U and θ are wind intensities and directions from the CFD model. To downscale the NWP wind field to the urban canopy, the transfer coefficients are chosen according to the inflow direction. The final downscaled field is obtained by combining contributions from each NWP point at the 100 m layer, weighted by the normalized horizontal distance d_{ij} between the source and target points:

$$U_{i\,10m} = \sum_j d_{ij} * U_{j\,100m}(\alpha) * k_{ij}(\alpha_g) \tag{3}$$

$$\theta_{i\,10m} = \sum_j d_{ij}[\,\theta_{j\,100m} - \Delta_{ij}(\alpha_g)] \tag{4}$$

Ricci et al. (2022) verified the validity of similar transfer coefficients using anemometric observations collected near the port of Livorno, another city in northern Italian. Their study analyzed the relationship between wind at 100 m AGL, assumed to be undisturbed by the surface, and wind at 6 m AGL, within the urban canopy, at two sites horizontally separated by 1.5 km. Results showed good correlation between the downscaled and observed wind speed and direction.

3. PRELIMINARY RESULTS

An example of the wind flow in the upper UBL forecasted by MOLOCH and the corresponding downscaled near-surface flow for midday of an unstable summer day (12 UTC on 06 July 2025) is shown in Figure 2. Few hours after the represented flow a mesoscale convective system formed. The resulting wind field exhibits enhanced spatial detail compared with the original mesoscale forecast. Topography-based patterns emerge, with stronger wind flow over mountain ridges.

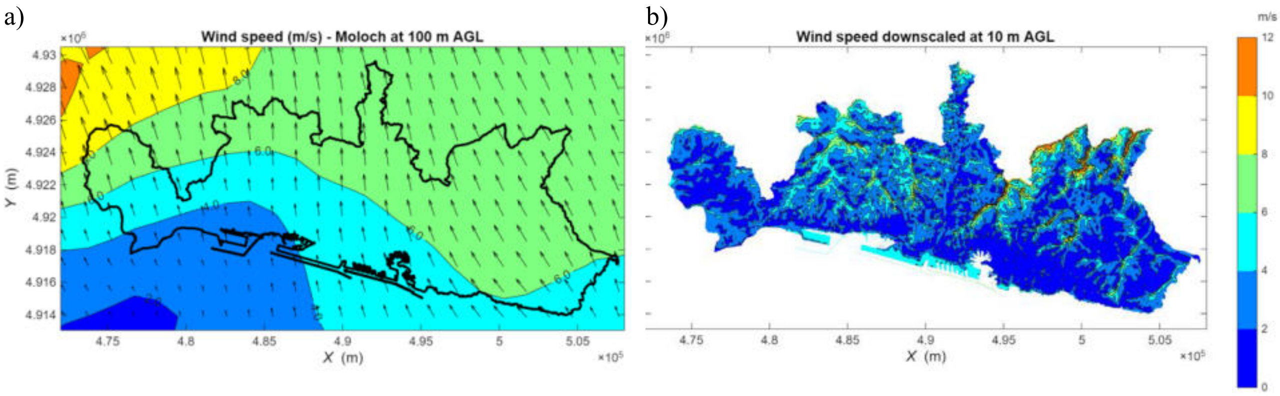

Figure 2. Example of input (left) and downscaled (right) flow forecast for 12 UTC on 06 July 2025.

4. DISCUSSION AND ONGOING WORK

The preliminary results exhibit realistic flow patterns, suggesting that the proposed method effectively captures terrain-driven wind features. On a standard laptop, the computation for a single forecast time requires around 10-30 minutes based on the number of used NWP grid points, significantly less than the runtime of full CFD simulations using HPC resources. Ongoing work focus on improving the method, probably by reducing the selection of input points and refining the reference height used in the downscaling procedure to reduce computational cost while maintaining forecast accuracy. More on this optimization process will be discussed during the conference.

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