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From validation to application: standardizing LES for realistic urban aerodynamics

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SUMMARY

Large eddy simulations (LES) hold substantial promise for wind engineering, yet their practical use remains limited by two unresolved challenges: the dependence of validation on specific wind-tunnel sensor locations and the lack of procedures ensuring that a validated LES setup generalizes to unseen urban configurations. This work introduces a two-part framework to address these limitations. First, a validation technique via streamline-driven Lagrangian Spectrum Analysis is proposed. Since streamlines capture turbulent interactions between wind and the built environment, they reveal flow regions where LES must accurately match experimental data. These regions are application-specific yet configuration-independent, enabling a unified validation approach for environmental and structural wind engineering. Second, urban morphology indicators from 75 global cities are clustered into groups with similar aerodynamic behaviour, providing representative configurations for evaluating the robustness of LES setups across diverse built environments. Together, these contributions create a transferable and aerodynamically grounded pathway toward standardized LES validation.

Keywords: *large eddy simulation, validation and verification, dynamic terrain, urban morphology indicators, langrangian spectrum analysis*

1. INTRODUCTION

Wind flow in the low atmospheric boundary layer is governed by high turbulence features that interact with buildings leading to case specific wind patterns. Large Eddy Simulation (LES) have proven necessary to model this complex interaction accurately (Potsis et al., 2023). One of the biggest problems with application of LES at the current moment is that a specified numerical set up (boundary conditions, domains size, mesh, inflow turbulence etc.) can work accurately only for a specified configuration, for which usually experimental data are available. This makes a great negative impact in the generalizability of LES for a case where wind tunnel data are not existent. Besides that, experimental benchmarks on the literature focus on case specific applications (usually pedestrian level winds) on limited number of sensors, for whom there is not information a priori for their aerodynamics relevance.

To progress the applicability of CWE in urban configuration, this paper introduces a novel database of experimental wind flow measurements in four representative urban benchmarks. In such as way, practitioners can rely on their numerical results for an unseen case, after a thorough validation is conducted based on a similar representative benchmark urban configuration. Similar efforts on codification of LES for wind engineering have already initiated (Potsis and Stathopoulos, 2025) and these results can aid to develop them further and solidify them. In Section 2 the validation framework is presented, in Section 3 the specific case study of Montreal is used as an example, while Section 4 concludes the paper and mentions the future steps before the CWE2026.

2. VALIDATION OF AERODYNAMIC INTERACTION

The lack of LES guidelines for the interaction of wind flow in the ABL and urban configurations limits tremendously the practical applications on wind engineering. The underline issue is that LES modelling is a complicated numerical process, and various methods and approaches have proven to provide accurate results when validated against wind tunnel measurements. For example, various computational domain size, inflow turbulence generation methods, subgrid models and mesh configurations have proven to be effective in capturing mean and turbulence properties of wind flow as well as peak wind induced pressures. A key parameter to accurately capture the natural interaction of wind and structures is the incident flow modelling as discussed thoroughly in Potsis and Stathopoulos, 2026. This should be the first validation in the framework – the ability of the set up to represent the natural ABL without any structures yet, based on comparisons with experiments and code-defined wind profiles (from ASCE 49-21 or similar). These types of validation results are presented are omitted by this abstract for clarity, but they have been previously conducted and discussed in Potsis and Stathopoulos, 2024, 2026 and Potsis et al., 2024.

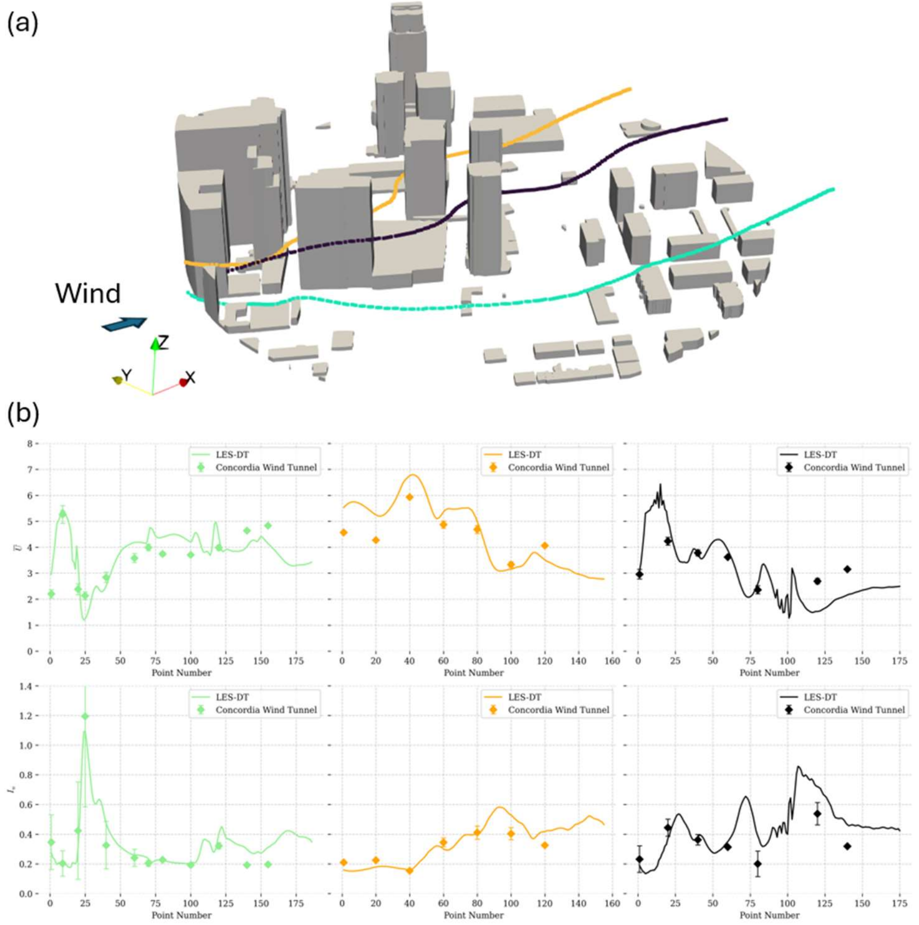

Figure 1: (a) Urban configuration of downtown Montreal with three streamlines (b) validation of mean (first row) and turbulence intensity (second row) on the three streamlines

After the first validation metrics are produced and the flow matches the target wind exposure, the urban configuration should be placed in the domain to interact with the wind flow. As mentioned, validation studies in specific sensors, limit tremendously the generalizability of LES to other configurations and other applications, thus here a novel validation process is presented. This regards validation of the wind flow on streamlines paths that extend into the entire urban configuration and vary in height from pedestrian winds to locations where wind patterns can be dominated by acceleration (good for ventilation) or stagnation (bad for urban heat islands). Three representative streamlines were calculated based on refined stratified sampling (Shields et al., 2015) of the mean magnitude of velocity and presented in Figure 3a.

Furthermore, an inherent advantage of using streamlines for this validation regime lies behind the fact that Langrangian Spectrum Analysis (LSA) metrics can be calculated for each streamline. Those metrics can shed light into which locations of the urban flow are easier to replicated and where the turbulence regime is more dominant – thus limiting the accuracy. Further discussion on LSA metrics will be presented in the presentation during the conference, with a discussion on how to leverage them to enhance the reliability of LES even further.

3. TOWARDS A STANDARDIZED VALIDATION FRAMEWORK

Urban morphologies are inherently diverse around the globe, but when carefully observing UMI some patterns can emerge, that can aid into identifying similar aerodynamic behaviours. In this study, UMI were extracted for 55k grids of 1 km x 1km resolution from 75 cities worldwide – presented in Fig2a. They regard aggregated building-level morphological characteristics computed from OpenStreetMap. Similar results have been presented in Biljecki and Chow, 2022. This novel database was used to cluster urban morphologies based on 22 different UMI. The clustering was conducted based on K-means, and more details will be discussed during the conference presentation. From the clustering four representing urban morphologies were extracted and are presented in Fig 2b.

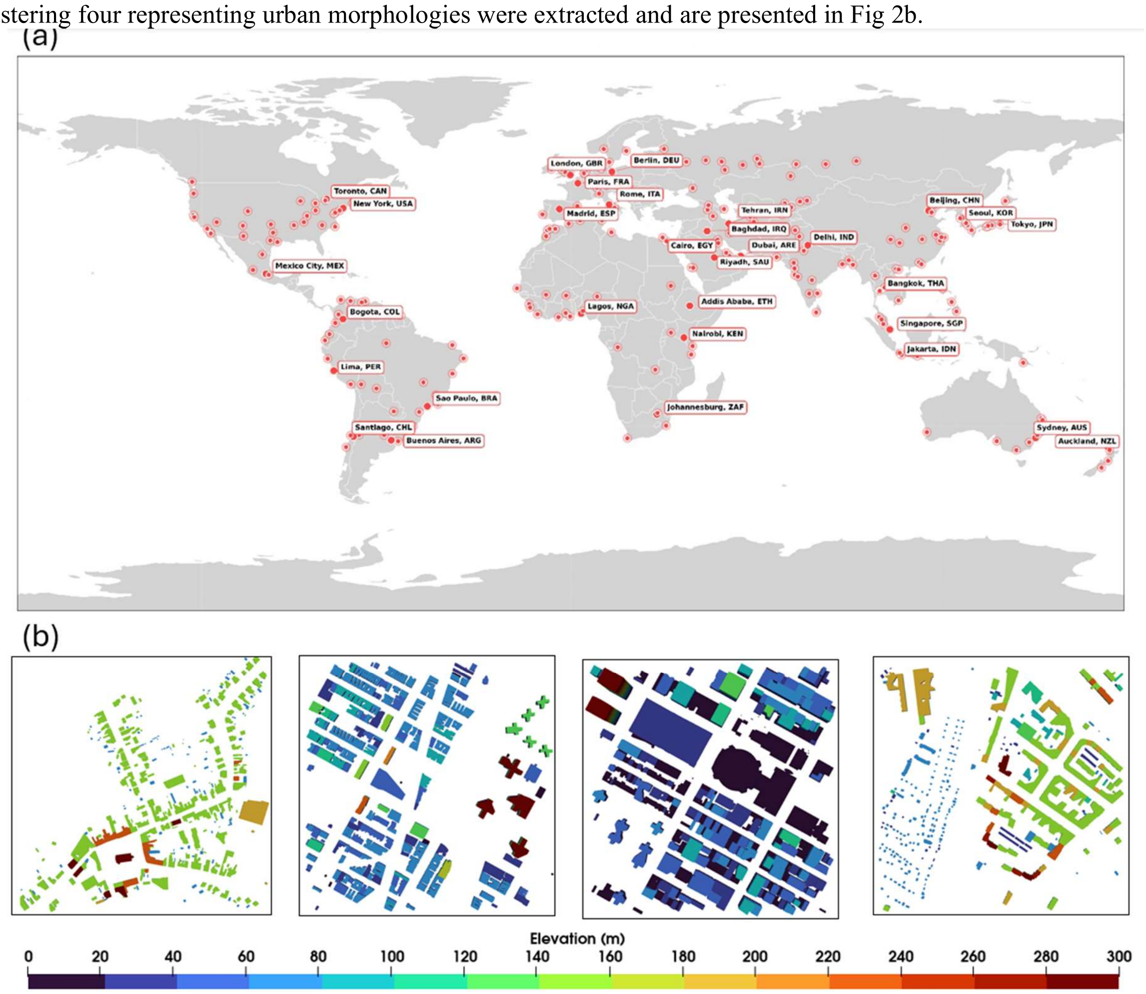

Figure 2: (a) Map of the globe with the cities in the database pointed out with red dots (b) four representative clusters based on the preliminary results

In the basis of the above, this work proposed a standardize validation framework presented in Fig. 3. Initially, the target area should be selected, that next will be integrated into the dataset and identify the representative case that it is closer to. For each of cluster cases an experimental wind tunnel study is currently being conducted, and the dataset is expected to be done by the conference date. This way, the LES results can be validated based on the procedure presented in Section 2 and the validation metrics can prove the abilities of the set up to capture various range of wind flow patterns based on the LSA. If the targets of the validation are not achieved, then the physical domain and modelling parameters, numerical parameters, inflow/boundary conditions, simulation control parameters and post-processing techniques must be checked/modified. The test case should be rerun until the validation metrics are achieved. In this way, this set up can be applied to an unseen configuration with increased reliability via aerodynamic similarity of the urban morphology.

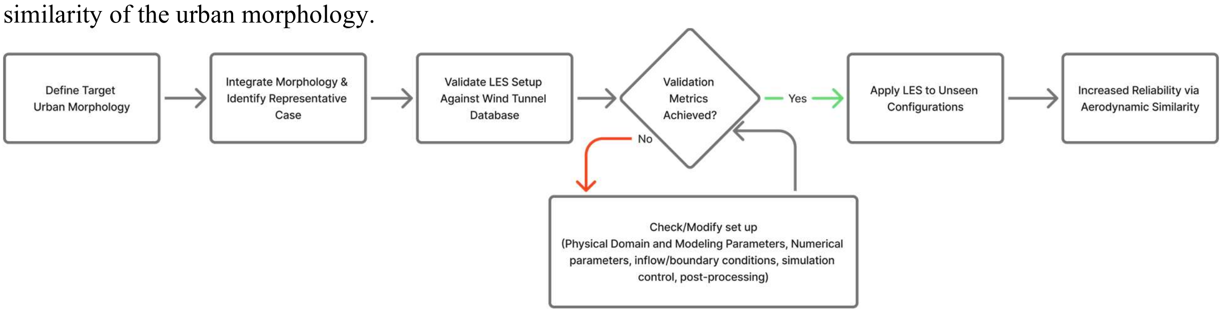

Figure 3: Proposed validation framework

4. CONCLUSION – FUTURE STEPS

This paper presents two novelties that aim to improve the current state of applicability of LES in the built environment for environmental and structural applications. The first one regards a validation process based on streamline paths, that go beyond fixed sensor locations that are credible only for limited wind engineering applications. In the near future, leveraging of LSA metrics to further enhance the credibility of LES will be conducted and presented during the conference. The second novelty regards a standardized validation framework for reliable LES in unseen cities i.e cities without experimental data for validation. By utilizing UMI, the framework establishes similarities between a given location of interest (e.g. an area of a city of interest) and four benchmark configurations. For each of those, an open database of wind flow and pressures properties is constructed, and details will be presented in the conference. This way, an LES set up can be validated into similar aerodynamic conditions, before used in an unseen city, thus improving its credibility for engineering usage.

During the conference more details on LSA validation metrics and their connection with target applications (pedestrian winds, natural ventilation, UHI or wind loads) will be presented and proof that urban morphology similarities can lead to similar aerodynamic LSA characteristics. This will strongly support the proposed framework that can be further developed for codes and standards with scientific clarity and practical relevance.

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