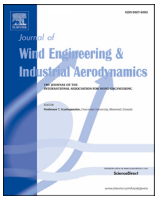
Journal of Wind Engineering & Industrial Aerodynamics 176 (2018) 87–97

Contents lists available at ScienceDirect

Journal of Wind Engineering & Industrial Aerodynamics

journal homepage: www.elsevier.com/locate/jweia



# Uncertainty quantification for microscale CFD simulations based on input from mesoscale codes

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## ARTICLE INFO

*Keywords:*
Askervein hill
Joint urban 2003
Inflow conditions
Mesoscale simulations
RANS
Uncertainty quantification

## ABSTRACT

Accurate predictions of wind and dispersion in the atmospheric boundary layer (ABL) can provide essential information to support design and policy decisions for sustainable urban areas. However, computational fluid dynamics (CFD) predictions of the ABL have several sources of uncertainty that can affect the results. An important uncertainty is the definition of the inflow boundary condition, which is influenced by larger scale weather phenomena. In this paper, we propose a method to quantify the effect of uncertainty in the inflow boundary conditions using input from an ensemble of mesoscale simulations. The mesoscale mean velocity and turbulent kinetic energy at the inflow of the CFD domain are used to define probability density functions for the uncertain wind direction and magnitude. A non-intrusive method is used to propagate these uncertainties to the quantities of interest. The methodology is applied to two different cases for which field experimental data are available: the Askervein hill and the Joint Urban 2003 measurements. For the latter case, the results are similar to those of a previous study that characterized the uncertain input parameters based on measurements. Hence, the results show that the proposed mesoscale simulation-based approach provides a valuable alternative in absence of sufficient measurement data.

## 1. Introduction

Computational fluid dynamics (CFD) predictions of atmospheric boundary layer (ABL) flows can be used for a variety of sustainable design problems, ranging from assessing air quality and wind energy resources, to calculating wind loads on buildings. However, CFD results can be compromised by several sources of uncertainty. Common examples are uncertainties in the turbulence or subgrid turbulence model, in the geometrical characterization, and in the boundary conditions. For example, the inflow boundary condition, which is determined by the larger scale ABL flow characteristics, can significantly influence the CFD result.

Several previous studies have focused on including the effects of the larger scale atmospheric flows by coupling numerical weather prediction codes with microscale CFD (Yamada, 2010; Wyszogrodzki et al., 2012; Nozawa and Tamura, 2012; Wang et al., 2013; Van Beeck and Benocci, 2013; Farella et al., 2013; Zhen et al., 2015; Temel and van Beeck, 2016). However, several challenges arise when coupling meso- and microscale codes. First, numerical weather prediction codes include physical processes, e.g. transport of moisture and radiation, that are generally not represented in the CFD models. Second, when both codes do represent the same physics, such as turbulence, there are considerable differences in the parametrizations used. Lastly, numerical weather predictions are inherently uncertain, and when coupling the codes these uncertainties are directly propagated to the microscale simulation.

The objective of the present work is to present an alternative approach that uses the mesoscale model to characterize uncertainties in the inflow boundary conditions for microscale Reynolds-averaged Navier-Stokes (RANS) simulations. The inflow boundary conditions for the CFD model have the form of the standard neutral surface layer profiles (Richards and Hoxey, 1993; García-Sánchez et al., 2014), which are fully consistent with the RANS model used. We define three uncertain parameters used to specify these profiles: the roughness length, $z_0$, and the wind velocity magnitude and direction, $U$ and $\theta$, at a reference height. The characterization of the uncertainty in the roughness length is based on empirical data, while the uncertainty in the wind velocity magnitude and direction is characterized using an ensemble of mesoscale simulations. A non-intrusive stochastic expansion method is used to propagate

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https://doi.org/10.1016/j.jweia.2018.03.011
Received 6 November 2017; Received in revised form 22 February 2018; Accepted 8 March 2018

these uncertainties to the quantities of interest, i.e. microscale predictions of the wind or concentration field. Previous work on quantifying uncertainties in inflow boundary conditions (García-Sánchez et al., 2017; Sousa et al., 2018) used a similar approach, but relied on the availability of high frequency wind velocity measurements near the inflow boundary to characterize the uncertain parameters; the lack of accurate inflow measurements for many cases of interest motivated the current study.

The predictive capabilities of the method are evaluated by comparing the results of the uncertainty quantification (UQ) study to full scale experimental data for two test cases. The first test case, representative of an ABL flow over natural terrain, considers the flow over Askervein hill, for which wind measurements are available (Taylor and Teunissen, 1983, 1985). The second case, representative of the flow in an urban environment, is the Joint Urban 2003 (JU2003) field experiment performed in Oklahoma City (Allwine and Flaherty, 2006), which includes wind and sulfur hexafluoride ($SF_6$) concentration measurements. By using field measurement data sets for validation we intend to demonstrate the method's capabilities for representing the uncertainty present in reality.

The paper is organized in six main sections. First, we introduce the two test cases and corresponding experimental campaigns. In the following two sections we describe the numerical set-up of the RANS and the mesoscale simulations for both test cases. In the fourth section, we explain the uncertainty quantification (UQ) methodology, including the methods to characterize the uncertain inflow parameters based on the mesoscale simulations. Lastly, we compare the UQ results to the field measurements and present the conclusions together with some directions for future research.

## 2. Introduction to the experimental data

To assess the predictive capabilities of the proposed UQ approach, we evaluate the results by comparing with two full scale experimental campaigns: the Askervein hill experiment, representing flow over natural terrain, and the Joint Urban 2003 experiment in Oklahoma City, representing flow in an urban canopy. In the following we briefly summarize the measurements from both experiments that will be used for validation.

### 2.1. Askervein hill experimental campaign

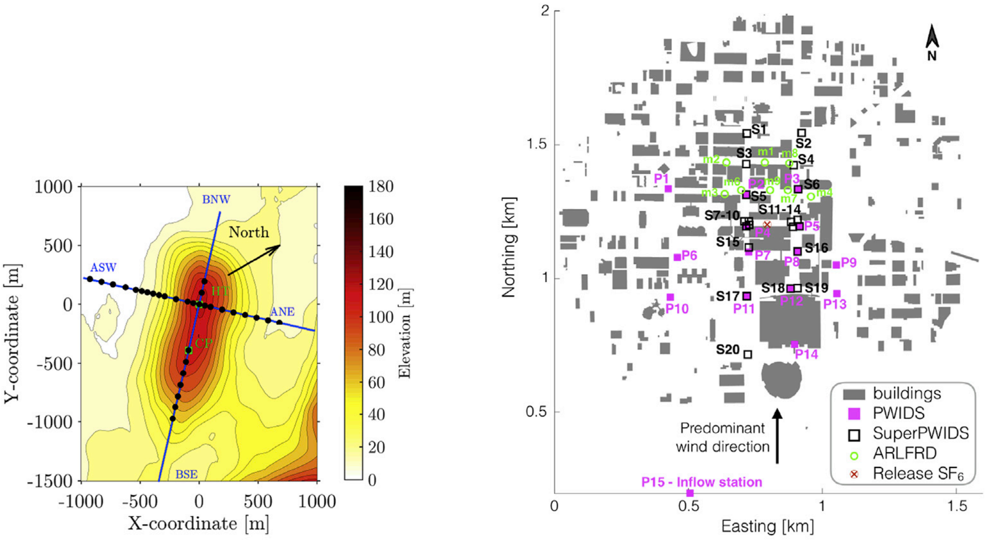
Askervein hill is an isolated 126 m hill located close to the west coast of South Uist, in the Outer-Hebrides of Scotland. Two experimental campaigns were performed in 1982 and 1983, with the objective of gathering field measurement data for an atmospheric boundary layer flow over natural terrain. The measurements were first published in two different reports by Taylor and Teunissen, 1983, 1985. They present all the experimental data in tabular form, organized in sets of runs based on the type of data collected.

Fig. 1a, reproduced from (Paci et al., 2015–2016), presents the geometry of the hill, and indicates the hill top (HT), the approximate geometrical center point (CP), and the lines along which measurements were performed. The work presented here focuses on the measurement period TU03ab, which took place on the 3rd of October 1983. The winds were mostly south oriented, and the Richardson numbers corresponded to fairly low numbers ($-0.0038 < Ri < -0.0074$), which supports the neutral stratification assumption of the atmospheric boundary layer. The measurements focused on collecting wind velocity and direction, as well as turbulence intensities. We will consider the data recorded with cup anemometers along line ASW-ANE in Fig. 1a.

### 2.2. Joint Urban 2003 experimental campaign

The Joint Urban 2003 (JU2003) measurements consist of a full month of experimental data collected in downtown Oklahoma City (Allwine and Flaherty, 2006). The main objective of the campaign was to gather sufficient information to improve our knowledge on modeling urban flow and dispersion phenomena. To quantify dispersion, scientists released and measured sulfur hexafluoride ($SF_6$) during so-called Intensive Observation Periods (IOP). During each IOP, puff and continuous releases were performed. In this paper, we use the data recorded during a 30-min continuous release performed during IOP9 (Storwold, 2003).

The numerical results for the mean velocity field will be compared to data obtained from 15 portable weather information display system (PWIDS) sensors and 20 super portable weather information display system (SuperPWIDS) sensors (Allwine and Flaherty, 2006). The locations of these sensors are shown in Fig. 1b; the height of the sensor was 8 m above ground level, with the exception of P14, located on a building roof, and P15, located at 30 m height. The PWIDS sensors measured the velocity magnitude and direction each second, and averaged the values over a 10 s interval before recording. The SuperPWIDS sensors measured with a sampling frequency of 10$Hz$, and saved the data instantaneously



(a) (b)

**Fig. 1.** (a) Askervein Hill elevation map. HT: hill top; CP: geometrical center point; ASW, ANE, BNW, BSE: measurement locations. (b) Measurement locations in downtown Oklahoma City (García-Sánchez et al., 2017).