Journal of Physics: Conference Series

A nested multi-scale model for assessing urban wind conditions : Comparison of Large Eddy Simulation versus RANS turbulence models when operating at the finest scale of the nesting.

To cite this article: Mandar V Tabib *et al* 2021 *J. Phys.: Conf. Ser.* **2018** 012039

EERA DeepWind'2021 IOP Publishing
Journal of Physics: Conference Series **2018** (2021) 012039 doi:10.1088/1742-6596/2018/1/012039

A nested multi-scale model for assessing urban wind conditions : Comparison of Large Eddy Simulation versus RANS turbulence models when operating at the finest scale of the nesting.

Mandar V Tabib [1], Knut Helge Midtbø [3], Adil Rasheed[1,2],Trond Kvamsdal[2,4],Tor Skaslien [3]

[1]Department of Engineering Cybernetics, NTNU, Trondheim, Norway
[2]Mathematics and Cybernetics, SINTEF Digital, Trondheim, Norway
[3]Meteorologisk institutte, Oslo, Norway
[4]Department of Mathematical Sciences, NTNU, Trondheim, Norway

E-mail: `mandar.tabib@sintef.no, adil.rasheed@ntnu.no, trond.kvamsdal@sintef.no`

Abstract. Good understanding of micro-scale urban-wind phenomena is needed for optimizing power generation capabilities of building-integrated wind turbines and for safety of futuristic urban transport involving drones. The current work involves development of a multi-scale methodology for obtaining wind fields in an urban landscape. The multi-scale methodology involves coupling three models operating on different scales namely an operational meso-scale numerical weather prediction model HARMONIE, a micro-scale model that captures terrain-induced wind influence and a super-micro scale Computational Fluid Dynamics model using large eddy simulation and RANS model to capture the building-induced wind flow. Here, we present a comparison of the wind velocity predicted by two different turbulence models (LES and RANS) that are operating at the finest scale with the measured experiment data for a realistic case of flow in vicinity of the Oslo university hospital. The reasons behind the observed better prediction of LES model are outlined, and use of such models is advocated to improve accuracy.

LES, multi-scale, wind, urban climate, drones, wind energy

1. Introduction

Optimal wind turbine siting and power production forecasting for building integrated wind turbine require accurate knowledge of local wind field. Similarly, other areas where accurate knowledge of building induced flows are relevant are Unmanned Aircraft Systems (UAS) applications at urban hospitals. However, for use in emergency medical purposes, the expectations are a drone should be available for at-least 95% of the time (if not 24-by-7 a year) to be deemed reliable. The weather challenge is likely to be the factor that threatens the UAS service availability the most. Low cost and small, reliable systems have not yet been developed to be used in all-weather conditions with a high level of safety and availability. The current knowledge of the impact of wind and turbulence on drone flight safety is scarce. Thus, to obtain accurate knowledge of building-induced flows is important. Generally, measurement campaigns are undertaken to obtain an insight into the prevailing wind conditions at a particular site. These campaigns are expensive, and yield very coarse resolution wind data. Numerical simulation is therefore, an attractive alternative to the measurement campaigns. For development of this knowledge, tools that can predict urban micro-scale climatology accurately are needed. Recently, micro-scale modelling using conventional CFD code has come up with an alternative and researchers have been able to simulate full cities [Tabib *et al.*(2017), Tabib *et al.*(2020)] with promising results. However, such micro-scale models need accurate boundary conditions to work. In this direction, the objective of the present work is to integrate such urban-scale models and develop a multi-scale coupling to enable computation of urban wind conditions, and test impact of different turbulence models. The next section describes the multi-scale methodology:

2. Multi-scale methodology description

The multi-scale methodology here consists of unidirectionally coupled HARMONIE-SIMRA-CFD multi scale system (as shown in figure 1). HARMONIE [Seity *et al.*(2011)] model is used for weather forecasting in Norway and SIMRA (Semi IMplicit Reynolds Averaged) model [Utnes(2007)] model is specially designed to model terrain-induced wind and turbulence in complex terrain at high horizontal spatial resolution, and it is capable of resolving important terrain features. Both these programs are based on the mass, momentum and energy conservation principles of fluid mechanics. Earlier a multi-scale methodology was developed for wind farms (details regarding these models can be found in [Rasheed *et al.*(2017)], this multi-scale methodology has been extended to account for buildings by incorporating additional refined-CFD model for building-scale. For sake of completeness, the governing equations are described below:

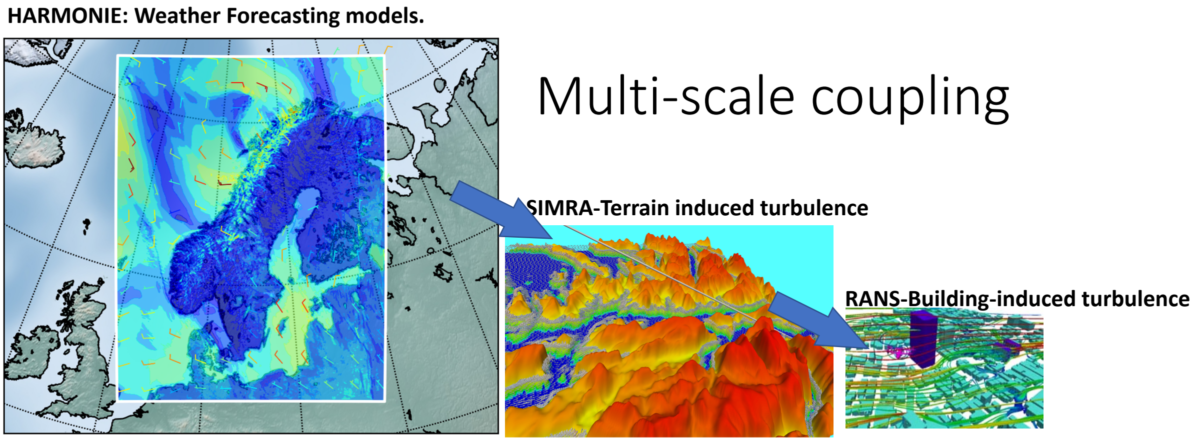


Figure 1. Multi-scale methodology

2.1. Governing Equations

Atmospheric flow at any scale (global, meso or micro) like any other fluid flow is governed by the conservation of mass, momentum, energy and scalars like humidity. The general equations of motion for incompressible flow may be adapted to atmospheric flows by the use of so-called anelastic approximation.

This formulation is often applied in meteorological models, and may be written in the following conservative form :

$$\nabla \cdot (\rho_s \mathbf{u}) = 0 \tag{1}$$

$$\frac{D\mathbf{u}}{Dt} = -\nabla \left(\frac{p_d}{\rho_s} \right) + \mathbf{g}\frac{\theta_d}{\theta_s} + \frac{1}{\rho_s}\nabla \cdot \tau + \mathbf{f} \tag{2}$$

$$\frac{D\theta}{Dt} = \nabla \cdot (\gamma \nabla \theta) + q \tag{3}$$

Here $(\mathbf{u}, p, \theta, \rho)$ represent velocity, pressure, potential temperature and density, respectively. Furthermore, τ is the stress tensor, $\mathbf{f}$ is a source term, $\mathbf{g}$ is the gravitational acceleration, γ is the thermal diffusivity and q is the energy source term. Subscript s indicates hydrostatic values and subscript d the deviation between the actual value and its hydrostatic part, i.e. $p = p_s + p_d$, $\theta = \theta_s + \theta_d$, $\rho = \rho_s + \rho_d$, where the hydrostatic part is given by $\partial p_s/\partial z = -g\rho_s$. The major differences between the three models are treatment of source terms and turbulence models. Regarding source terms, for meso-scale HARMONIE , the source term $\mathbf{f}$ includes rotational effects like the Coriolis forces. These forces are neglected in microscale models SIMRA and CFD. Regarding turbulence, the SIMRA and the micro-scale RANS CFD models utilize a two equation turbulence model where transport equations for turbulent kinetic energy (eqn. 4) and TKE dissipation rate (eqn. 5) are solved.

$$\frac{DK}{Dt} = \nabla \cdot (\nu_T \nabla K) + P_k + G_\theta - \epsilon \tag{4}$$

$$\frac{D\epsilon}{Dt} = \nabla \cdot \left(\frac{\nu_T}{\sigma_e} \nabla \epsilon \right) + (C_1 P_k + C_3 G_\theta)\frac{\epsilon}{k} - C_2 \frac{\epsilon^2}{k} \tag{5}$$

where turbulent viscosity is given by $\nu_T = C_\nu \frac{k^2}{\epsilon}$. The Reynolds stress tensor is given by: $R_{ij} = \nu_T \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) - \frac{2}{3} k \delta_{ij}$ while the eddy diffusivity appearing in the energy equation is $\gamma_T = \nu_T/\sigma_T$, σ_T being the turbulent Prandtl number. The shear production P_k and stratification (buoyancy effect, G_θ) terms in the turbulence model are given by : $P_k = \nu_T \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \frac{\partial u_i}{\partial x_j}$, and $G_\theta = -\frac{g}{\theta} \frac{\nu_T}{\sigma_T} \frac{\partial \theta}{\partial z}$. The conventional constants for the high-Reynolds $(k - \epsilon)$ model are given by $(C_\nu, C_1, C_2, \sigma_e) = (0.09, 1.44, 1.92, 1.3)$

For Large Eddy simulation model at the finest super-microscale resolution, the equations for LES are derived by applying a filtering operator to the Navier-Stokes equations, resulting in the following set of equations:

$$\begin{aligned} \frac{\partial \overline{u}_i}{\partial x} &= 0, & (6) \\ \frac{\partial \overline{u}_i}{\partial t} + \frac{\partial}{\partial x_j}(\overline{u}_i \overline{u}_j) &= -\frac{\partial \overline{p}}{\partial x_i} - \frac{\partial B_{ij}}{\partial x_j} + \nu \frac{\partial 2 \overline{u}_i}{\partial x_j \partial x_j}, & (7) \end{aligned}$$

where $\overline{u}_i$ is the filtered (or resolved) velocity, $\overline{p}$ the filtered pressure, ν the dynamic viscosity and $B_{ij} = \overline{u_i u_j} - \overline{u}_i \overline{u}_j$. The term $\mathbf{B}$ can be modeled as

$$\mathbf{B} = \frac{1}{3} tr(\mathbf{B})\mathbf{I} + \nu_{sgs}(\nabla \mathbf{u} + \nabla^T \mathbf{u}) \tag{8}$$

where $tr(\cdot)$ stands for the trace of a tensor, and $\mathbf{I}$ is the identity matrix. Here, ν_{sgs} is the so called SGS viscosity which is expressed in terms of the subgrid turbulent kinetic energy k_{sgs} as : $\nu_{sgs} = (C_k\Delta)k_{sgs}^{1/2}$ where $C_k = 0.094$. The term k_{sgs} is computed using the following transport equation (as described in [Kajishima and Nomachi(2005)]):

$$\frac{\partial k_{sgs}}{\partial t} + \frac{\partial \overline{u}_i k_{sgs}}{\partial x_i} = 2\nu_{sgs}|\overline{D}_{ij}|^2 - C_e\frac{k_{sgs}^{3/2}}{\Delta} + \frac{\partial}{\partial x_i}\left(\nu_{sgs}\frac{\partial k_{sgs}}{\partial x_i}\right) + \nu\frac{\partial^2 k_{sgs}}{\partial x_i \partial x_i}. \tag{9}$$

While the turbulence in meso-scale HARMONIE model uses a one equation model (similar to the eqn. 4). The turbulent dissipation is estimated from $\epsilon = (C_\mu^{1/2}K)^{3/2}/\ell_t$. Here, the source and sink in turbulent kinetic energy are due to shear (source) and buoyancy (source for unstable and sink for stable conditions) and the turbulent length scale (ℓ_t) is computed based on the stability in atmosphere (based on Richardson number) with additional stability correction for convective conditions. Readers can get more information on meso-scale turbulence formulation from [Bengtsson *et al.*(01 May. 2017)] and [Lenderink and Holtslag(2004)].

2.2. Coupling different codes

The coupling of different codes is shown in figure 1. For Harmonie-SIMRA, basically three velocity components, temperature, turbulent kinetic energy and dissipation are interpolated from the coarser to the finer grid. The wind, temperature, turbulence kinetic energy and dissipation fields computed by the meso-scale model are interpolated onto the SIMRA mesh to initialize the domain. Such a coupled system is being used for forecasting turbulence at many Norwegian airports and wind power production for a wind farm. For coupling SIMRA with micro-scale OpenFOAM solver, a simplified approximation is used with only vertical profiles of variables computed from SIMRA (velocity components, turbulent kinetic energy and dissipation) being used as input for openfoam.

2.3. Application of multi-scale methodology: Case Study of Oslo University Hospital

For studying the impact of multi-scale method, a realistic case study of Oslo University Hospital (OUS) is selected. OUS comprises of four hospitals (Rikshospitalet, Ullevål University Hospital, Radium Hospital and Aker University Hospital) (see figure 2.3). For validating the multi-scale methodology, an experimental measurement campaign involving mast has been conducted. The mast location at a height of 6 m above the building D4 (marked in figure 2.3 and shown in figure 2.3). The simulations are done for a wind case as described in next section.

2.4. Computational Set-up

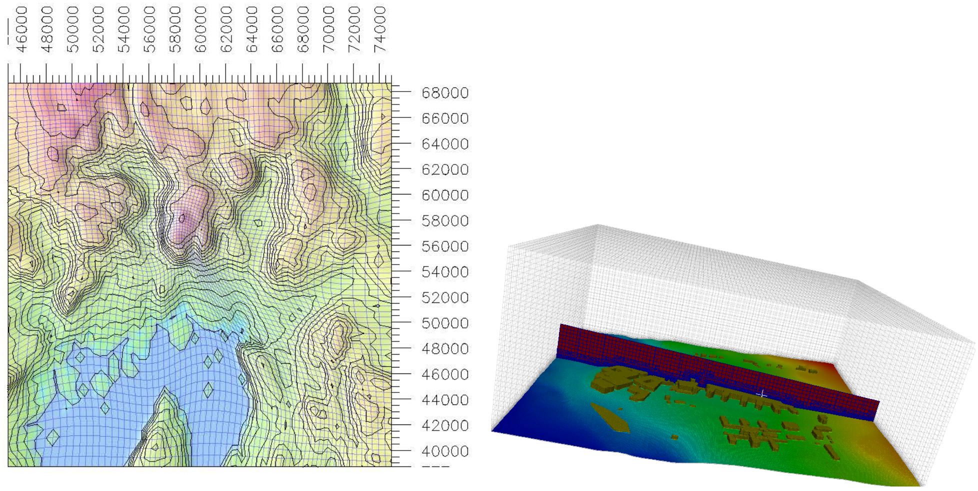
2.4.1. Meshing Details and computational domain The following domain sizes and grid sizes are used for the models: HARMONIE was operated at a horizontal resolution of 2.5 km × 2.5 km shown in Fig. 1 with a model time step of around 75 s. HARMONIE model covers Norway and runs on a computational domain of size $1875km \times 2400km \times 16km$. The model is run on 1840 cores and it takes 87 minutes to complete a 48 hours forecast. SIMRA was operated at a horizontal resolution with finest grid size of about 112 m × 112 m with a domain

(a) Oslo University Hospital with measurement location marked (b) Experimental measurements at 6m above building D4

Figure 2. Case study and experiments

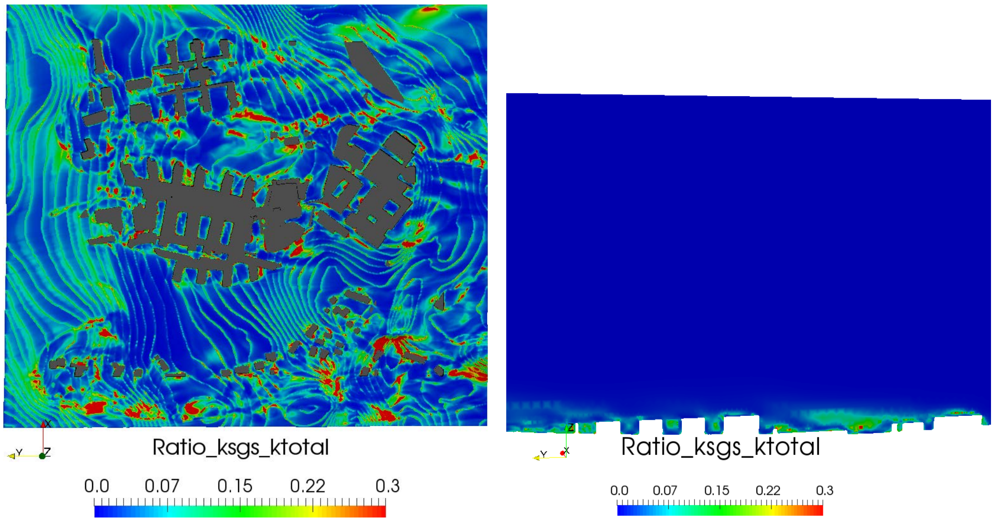
size of 18 Km × 18 Km × 4 Km. The number of cells is about 1.28 million. The SIMRA domain covers the oslo region surrounding the hospitals. Running on 48 cores, SIMRA generally takes 15 minutes to complete steady state simulations for the next 12 hours. For each hour, SIMRA takes the boundary conditions from HARMONIE and runs in a steady state using psuedo-time stepping. The super-micro scale CFD model has a much smaller computational domain size of 760 m × 660 m × 357 m with finest mesh resolution near buildings and terrains being at 0.15 m. A refinement zone is used in the vicinity of terrain and buildings to capture terrain induced flows . Using three different zones of different refinement levels, the mesh grid spacing is slowly increased away from terrain to reach 10 m grid resolution in upper regions of domain where the flow is expected to be uniform and without velocity gradients. The building heights are generally upto around 13m so the building is refined by nearly 80 grid points vertically . Figure 4 shows the mesh used for simulation. The mesh is dominated by hexahedral cells and mesh size is 5.9 Million cells. For the three models employing RANS turbulence model, the grid sizes and domain size have been selected based on previous experience and as per established practise [Bengtsson *et al.*(01 May. 2017), Eidsvik and Utnes(1997), Blocken(2015)], and, hence no-specific grid independence test and domain-size sensitivity was done for this case study. For LES, the more the grid is made fine, the more scales will be resolved so we employed Pope's criteria for checking mesh adequacy. Regarding domain size, the super-micro scale LES model tries to simulate the building-induced turbulence with the building being of sizes of approximately 15m, here the domain inlet boundary is at sea-level and domain extends beyond the recommended distance of 5 times the building height to the top and sides of the computational domain and a distance of 15 times the building height from the outlet boundary downstream of the building [Blocken(2015)]. Hence, the boundary effects will not impact the building-induced flow in any non-physical manner.

In case of LES, the adequacy of mesh for LES Simulations can be judged through the contour of the ratio of sub-grid-scale-kinetic-energy k_{sgs} to total-



(a) SIMRA surface mesh 18kmsx18kms (b) CFD domain mesh

Figure 3. Mesh and domain used in SIMRA and CFD scales



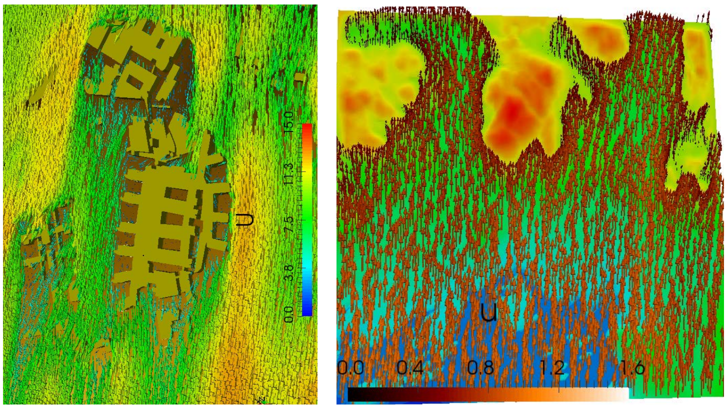
(a) LES-Mesh Adequacy 180 (b) LES-Mesh Adequacy vertical 180

Figure 4. Mesh Adequacy for LES simulation - Ratio of sub-grid to total tke

kinetic-energy k_{total} (as seen in figures 4(a)-4(b)). In LES simulations, the mesh-size determines spatial filtering and establishes cut-off between resolved and unresolved (modeled sub-grid scale) parts of flow. Finer the mesh, more part of flow is resolved and more accurate are the simulation. As per criteria of Pope (2000) [Pope(2020)], for a well-resolved LES, less than 20% of the total kinetic energy should be modeled sub-grid-scale part (i.e. k_{sgs}/k_{total} ratio should be less than 0.2). Figures 4(a)-4(b) shows this criteria being satisfied for most of the regions in the simulation setup.

2.4.2. Boundary conditions and Initial conditions The inlet and outlet boundaries change with wind directions. Outlet boundaries generally assumes fully developed flow with zero gradient for all variables (except pressure). The terrain and buildings have no-slip boundary with fixed velocity of zero with wall functions used. The ground surface roughness is handled using wall functions but since the terrain and building geometry is explicitly modelled, the roughness factor is kept low around 0.01 and care is taken to avoid development of inconsistency between inlet flow and flow at wall by suitable selection of first grid point near wall . For initialization of super-micro scale LES, random perturbations are added to the flow field from RANS SIMRA, and LES is then simulated till the flow develops (about 10 times the flow through the domain) before averaging is started.

2.4.3. Case Study for comparison: The multi-scale approach involving LES is computationally intensive. Hence for comparison, one challenging case is selected. A realistic case has been selected based on the dominant wind direction at site (a south-westerly wind direction of nearly 184 degrees as measured at the nearby MET Blindern observatory, Oslo at 10UTC local time on 9th February 2020). This case involves a challenging high-speed wind profile of gusty dynamic nature. This dynamic nature can be observed by looking at the measured wind speeds at every hour at both the Blindern observatory and at the local experimental mast on the hospital building (see figure 6 - which shows mast measured wind profile at 3 different hours). We compare the computationally predicted mean wind speeds with the mast measured velocity. The next section describes about the experimental set-up. In the computational multi-scale set-up used for this case study, SIMRA captures the terrain-induced flow at the location, while finest-scale CFD model captures the local building-induced flow as shown in figure 5.



(a) CFD (b) SIMRA

Figure 5. Micro-scale CFD Vs SIMRA : building

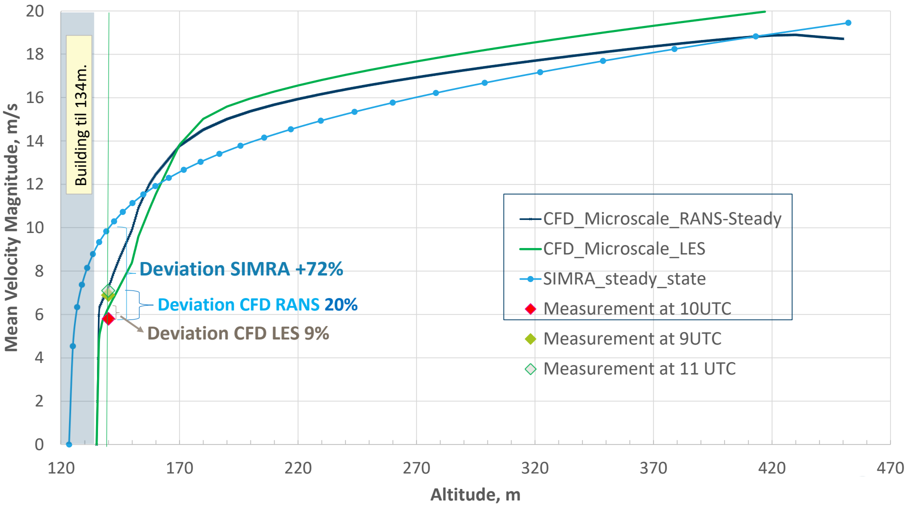
2.5. Experimental measurements using Mast for reference comparison of models

An experimental wind measurement mast was setup at a vertical distance of 6m above the D4 building at the Rikshospitalet to validate the CFD models. For the wind below 4.9 m/s, the measurements are seen to be capturing noise (50Hz noise) due to presence of a fan below the roof that is inducing voltage disturbance affecting the sensor signals. Hence, the measured observation is now used only as reference for a qualitative comparison between SIMRA and local-micro-scale CFD models (LES and RANS), rather than for quantitative validation.

3. Results

The results presented here compares the simulated and experimental measurements:

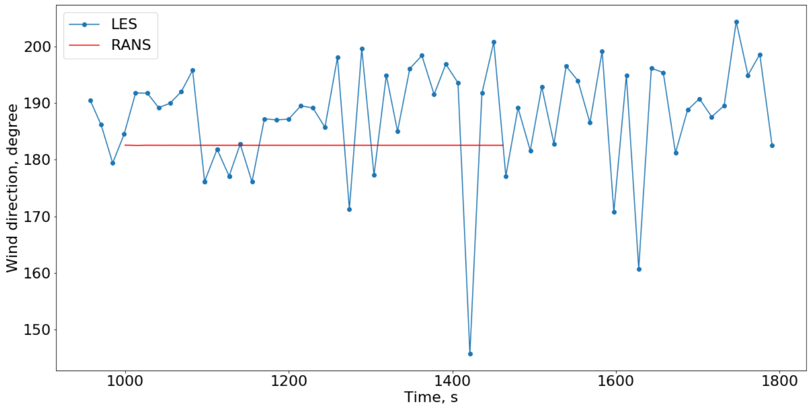
3.1. Comparison between experiments and model predictions



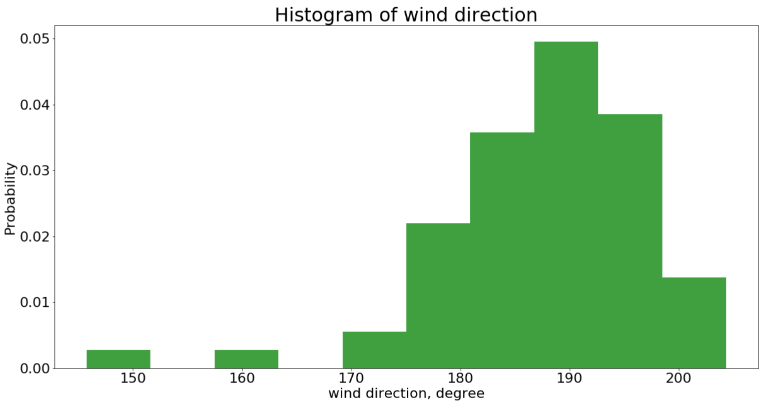
(a) Comparison for case1

Figure 6. Comparison of models with measurement data

Figure 6 shows the vertical profile of mean wind speed at a vertical line passing through the D4 measurement point obtained from the SIMRA and super-microscale CFD simulations. The experimental measurement results from the mast at D4 has been plotted as points on the same graph to enable comparison. Currently, only the mean wind speed are compared . The figures shows that SIMRA (which does not incorporate building impact) has higher deviations that the super-microscale CFD model. Here, the deviations are measured as: $Deviation = \frac{U_{measurement} - U_{CFD}}{U_{measurement}} * 100$. For this case (figure 6), SIMRA deviates highly with around 72% over-prediction while super micro-scale CFD with RANS under-predicts by about 20% and LES performs the best by under-predicting by about 9%. The reasons for ability of LES to predict values nearer to the measured data is due to the fact that it is able to capture the unsteadiness of building-induced flow better than the RANS model as shown in figures7-8. The experimental measurements at nearby hours at 11UTC and 9UTC (as shown in figure 6) reveals that the wind is highly dynamic within the measurement period. The wind-directions predicted by LES (figure 7) as compared to RANS at the mast measurement location (ie at the point 6 m over the building) shows this unsteadiness with wind-direction varying widely from 140 degrees to 210 degrees, while the RANS predicted wind-direction is mostly steady at 180 degree wind. Figure 8 shows the chaotic nature of building-induced turbulence predicted by LES as compared to the RANS model. SIMRA predictions are worse than the finest-scale CFD (LES and RANS) because it is not able to account for the effect of buildings. Both super-micro scale CFD turbulence models (LES and RANS) are able to account for the building-wake effects and hence shows lower wind speeds than SIMRA at regions up-to which the building has influence (as seen in

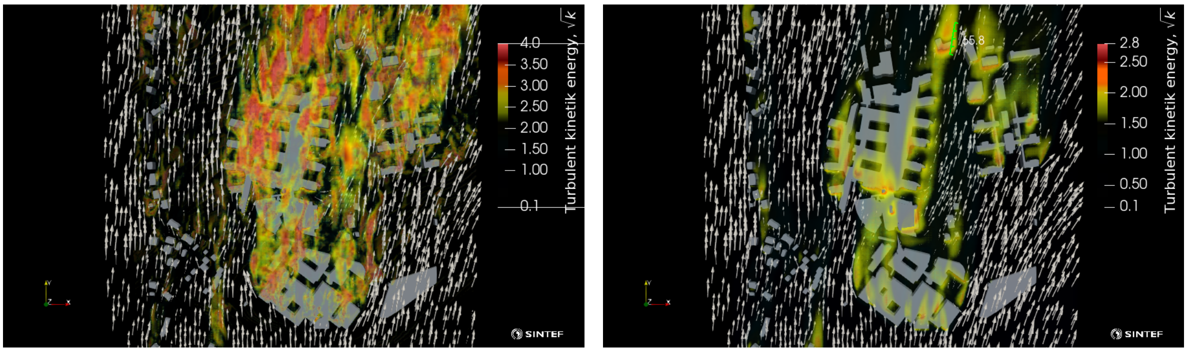


(a) wind rose 180



(b) LES 180

Figure 7. Comparison of wind rose prediction and histogram



(a) LES predicted turbulence 180 (b) RANS predicted turbulence 180

Figure 8. Comparison of turbulence prediction for Southerly 180 wind

figure 5). The results here shows that the micro-scale models with LES will be able to more accurately capture the wind conditions.

4. Conclusion

The work here shows the utility of including an advanced turbulence model (Large eddy simulation) in the finest scale of the multi-scale methodology to enable capturing of flow unsteadiness that exists at micro-scale urban conditions. For our given challenging case study, the inclusion of LES for turbulence modelling at urban-scale simulation has led to both improvements in wind velocity prediction as well as capture of flow unsteadiness as compared to the use of RANS. However, this study has been done only for one case and hence in order to confirm the accuracy of LES , a future work dedicated to planning more validation studies and application of the multi-scale methodology for realistic situations are needed.

5. Acknowledgment

The authors acknowledge the financial support from the Norwegian Research council for the project ”Aerial Transport of biological material (ATB) - Helsevel project call (project number : 282207” under which this work is carried out. We would also like to thank the personnel from FFI (especially Hannibal Fossum) for providing the building data for this study.

6. Reference

[Bengtsson *et al.*(01 May. 2017)] BENGTSSON, L., ANDRAE, U., ASPELIEN, T. and ET AL, Y.B. (01 May. 2017). “The harmonie–arome model configuration in the aladin–hirlam nwp system”. *Monthly Weather Review*, **145(5)**, 1919 – 1935.

[Blocken(2015)] BLOCKEN, B. (2015). “Computational fluid dynamics for urban physics: Importance, scales, possibilities, limitations and ten tips and tricks towards accurate and reliable simulations”. *Building and Environment*, **91**, 219–245.

[Eidsvik and Utnes(1997)] EIDSVIK, K. and UTNES, T. (1997). “Flow separation and hydraulic transitions over hills modelled by the reynolds equations”. *Journal of Wind Engineering and Industrial Aerodynamics*, **67-68**, 403 – 413.

[Kajishima and Nomachi(2005)] KAJISHIMA, T. and NOMACHI, T. (2005). “One-Equation Subgrid Scale Model Using Dynamic Procedure for the Energy Production”. *Journal of Applied Mechanics*, **73(3)**, 368–373.

[Lenderink and Holtslag(2004)] LENDERINK, G. and HOLTSLAG, A.A. (2004). “An updated length-scale formulation for turbulent mixing in clear and cloudy boundary layers”. *Quart. J. Roy. Meteor. Soc.*, **130**, 3405–3427.

[Pope(2020)] POPE, S. (2020). “Turbulent flows.” *Cambridge University Press.*

[Rasheed *et al.*(2017)] RASHEED, A., TABIB, M. and KRISTIANSEN, J. (2017). “Wind farm modeling in a realistic environment using a multiscale approach”. *Ocean Renewable Energy*, **Volume 10**.

[Seity *et al.*(2011)] SEITY, Y., BROUSSEAU, P., MALARDEL, S., HELLO, G., BéNARD, P., BOUTTIER, F., LAC, C. and MASSON, V. (2011). “The arome-france convective-scale operational model”. *Monthly Weather Review*, **139(3)**, 976–991.

[Tabib *et al.*(2017)] TABIB, M.V., RASHEED, A. and UTENG, T. (2017). “Methodology for assessing cycling comfort during a smart city development”. *Energy Procedia*, **122**, 361 – 366.

[Tabib *et al.*(2020)] TABIB, M., MIDTBø, K.H., SKASLIEN, T., RASHEED, A. and KVAMSDAL, T. (2020). “Towards understanding wind impact for drone operations: A comparison of wind models operating on different scales in a nested multiscale set-up.” *Proceedings from the 14th International Conference on CFD in Oil & Gas,Metallurgical and Process Industries*, 155–162.

[Utnes(2007)] UTNES, T. (2007). “Modelling of Stratified Geophysical Flows over Variable Topography”. *Geometric Modelling, Numerical Simulation and Optimization*, ISBN 978–3–540–68782–5,361–390.