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SINTEF, Trondheim, Norway, October 12–14, 2020

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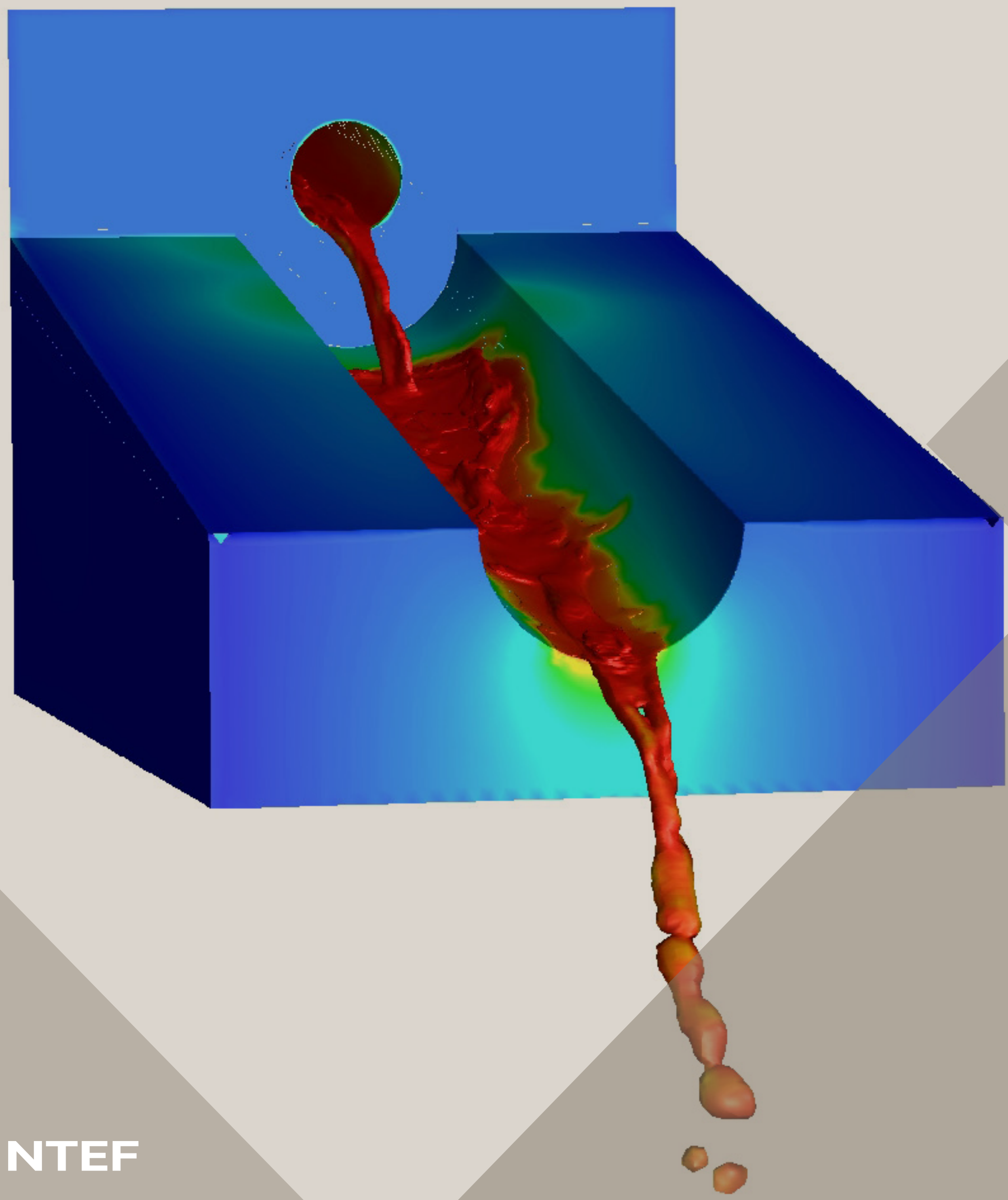

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Editors:
Jan Erik Olsen, Jan Hendrik Cloete and Stein Tore Johansen

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TOWARDS UNDERSTANDING WIND IMPACT FOR DRONE OPERATIONS: A COMPARISON OF WIND MODELS OPERATING ON DIFFERENT SCALES IN A NESTED MULTISCALE SET-UP.

Mandar V TABIB[1 *], Knut Helge MIDTBØ[2], Tor SKASLIEN[2 †], Adil RASHEED[1 3 ‡], Trond KVAMSDAL[1 4]

[1]SINTEF Digital, 7465 Trondheim, NORWAY

[2]Meteorologisk institutte, Oslo

[3]Department of Engineering Cybernetics, NTNU,Trondheim, Norway

[4]Department of Mathematical Sciences, NTNU, Trondheim, Norway

* E-mail: mandar.tabib@sintef.no
† E-mail: torhs@met.no
‡ E-mail: adil.rasheed@ntnu.no

ABSTRACT

The application of Unmanned Aircraft Systems (UAS) in health services is increasing, with a large variety of objectives: delivering medicines and vaccines, transporting blood samples and providing care technology in emergency situations. However, for use in emergency medical purposes, the expectations are a drone should be available at most times. Severe wind conditions are considered to be one of the prime factor that can hamper this expected drone availability. Most of these drone operations are expected to be linked to urban hospitals and understanding urban micro-scale weather patterns are important. The current work tries to develop a 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 code to capture building-induced wind influence. Existence of a large variation in the spatio-temporal scales in an atmospheric flow necessitates such a coupling between different models each of which handles a particular range of scales. In this article, we describe the multi-scale methodology and present a qualitative comparison of the wind velocity predicted by different numerical models with the measured experiment data and then explain the potential of the tool for drone operations.

Keywords: CFD, drones, wind, urban climate.

NOMENCLATURE

Greek Symbols
ρ Mass density, $[^{kg}/_{m^3}]$
μ Dynamic viscosity, $[^{kg}/_{ms}]$
θ Temperature, $[K]$

Latin Symbols
p Pressure, $[Pa]$.
$\mathbf{u}$ Velocity, $[^{m}/_{s}]$.

Sub/superscripts
s hydrostatic part.

INTRODUCTION

Health services are beginning to explore the use of Unmanned Aircraft Systems (UAS) for diverse applications, like for delivering medicines and vaccines, transporting blood samples and providing care technology in emergency situations. 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. For development of this knowledge, tools that can predict urban micro-scale climatology accurately are needed. This has been attempted in different ways, for example, the urban meteorological conditions have been simulated using state-of-the art meso-scale codes with urban parameterizations. These parameterizations are based on the assumption that a city can be represented by regular arrays of cuboids (Kondo *et al.*, 2008). As shown by (Rasheed *et al.*, 2011), this assumption is not valid for European cities. While it is possible to derive statistical information regarding the visibility, temperature and precipitation using these models in combination with measurement data, the coarseness of the model's horizontal resolution (finest being 500m) makes it impossible to model flow induced by buildings or other structures which may have a profound impact on the operating of UAVs.Recently, micro-scale modelling using conventional CFD code has come up with an alternative and researchers have been able to simulate full cities (Ashie and Kono, 2011; Tabib *et al.*, 2017) 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 develop a multi-scale coupling to enable computation of urban wind conditions. The next section describes the multi-scale methodology:

MULTI-SCALE METHODOLOGY DESCRIPTION

The multi-scale methodology here consists of unidirectionally coupled HARMONIE-SIMRA-CFD multiscale system (as shown in figure 1). There have been other multi-scale approaches ((Kunz *et al.*, 2000; **?**) but they have been mostly devoted to wind energy requirements. The current work involves a multi-scale approach with the level at finest scale being able to resolve the impact of buildings on wind. HARMONIE (Seity *et al.*, 2011) is a meteorologicial program used for weather forecasting in Norway and SIMRA is a program specially designed to model terrain-induced wind and turbulence in complex terrain at high horizontal spatial resolution, and 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 models are described below as well:

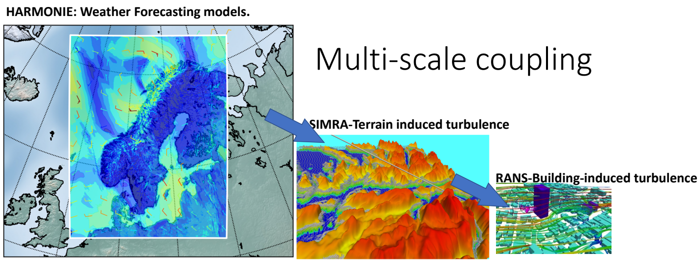

Figure 1: Multi-scale methodology

HARMONIE - a meso- scale numerical weather model

The atmospheric modelling component in the coupled system is a meso-scale model named HARMONIE that can simulate weather phenomena that spans over 100s of kilometers of distance and lasts until days (hence called meso-scale in metereology). based basically on the equations presented below albeit in a slightly modified form to suit meteorology. The model is a non-hydrostatic model, in which the dynamical core is based on a two-time level semi-implicit semi-Lagrangian discretization of the fully elastic equations, using a hybrid coordinate system in the vertical direction ([2]). The surface model Surface Externalise (SURFEX) is used for the calculations of fluxes in the surface layer. One-hourly boundary and initial data comes from the global model called ECMWF (http://www.ecmwf.int/). Although the model captures large scale phenomena (as will be shown later), it does not account for micro-scale flow phenomena driven by terrain complexities. The model has a variety of parameterization schemes for sub-grid scale physical processes. At the upper boundary a condition of zero vertical velocity is imposed.

SIMRA- A micro-scale terrain induced turbulence

SIMRA (Semi IMplicit Reynolds Averaged) model (Utnes, 2007a,b), which is based upon the RANS equations with a standard $k - \epsilon$ turbulence closure (Rodi, 1997; Mohammadi and Pironneau, 1994), is a fully three-dimensional model for anelastic flow. From metereological perspective, it has the capability of predicting micro-scale flows with separation, attachment, hydraulic transition, internal wave breaking and mountain waves, and phenomena occurring from minutes up to an hour and cover small distances such as less than 10 kilometers (hence, it is called micro-scale model). It has finer resolution and near wall boundary conditions that ensures that it is able to resolve the impact of terrain and ocean surfaces. It makes use of the Boussinesque approximation. The governing equations of mass, momentum, energy, turbulent kinetic energy and dissipation are discretized using a finite element method and solved by a projection method. Thus, the model solves prognostic equations for all velocity components, potential temperature and pressure (Eqn. 1 and 2). Turbulence is modeled using two equations: one for turbulent kinetic energy (Eqn. 4) and another for turbulent dissipation (Eqn. 5). A projection method is used for the solution of the Reynolds equations, and a mixed finite element formulation is used for space discretization. Since the effects of Coriolis force at this scale is negligible this is ignored in the model. A Taylor-Galerkin method is used for time discretization. A special feature of this model is the use of logarithmic element interpolation at the near-ground location in order to satisfy logarithmic boundary conditions accurately. This model has been tested against various data, from two-dimensional flow over a single hill in neutral and stratified flow to three-dimensional flow over different hill shapes (Eidsvik, 2005; Eidsvik and Utnes, 1997; Eidsvik *et al.*, 2004). The code has been parallelized using Message Passing Interface (MPI). The code computes wind, temperature and turbulent kinetic energy and dissipation. More details, description and validation results can be found in (Utnes, 2007a,b). SIMRA is designed to be used at the micro-scale level (this scale in metereological parlance covers terrain induced turbulence) with an efficiency of real-time simulation. Hence, simra employs orthogonal structured mesh to resolve the terrain at that scale and the solvers suited to such mesh are efficient and enable real-time analysis. SIMRA is well validated at this scale. However, SIMRA will not work at super-micro scale level as in order to resolve the terrain and buildings at such finer mesh, the resultant volumetric mesh needs to consider non-orthogonal unstructured cells. This helps to avoid Jacobian from being non-negative during the mesh generation process, and such unstructured non-orthogonal meshes need different kind of solvers that have ability to deal with sparse non-diagonally dominant matrices. Hence, we use OpenFOAM to develop the super-micro scale model as it has in-built solvers to work with the finer unstructured non-orthogonal mesh (with non-orthogonal corrections employed). The OpenFOAM can be employed both at micro and super-micro scale, but on the micro-scale level, Simra is expected to be more computationally efficient due to its solvers and physics. Hence, the choice of models at different levels in the multi-scale set-up has been done keeping in view their ability and balance between accuracy and efficiency. The definition and segregation of scales (meso,micro,super micro) is as per the norms used in Metereology.

CFD for urban simulation: A super-microscale phenomena.

The solver is created in OpenFOAM-2.3.0 (OF) (http://www.openfoam.com/) using the finite volume discretization of the equations presented below. To ensure continuity, OF uses an elliptic equation for the modified pressure which involves combining the continuity equation with divergence of momentum equation. This elliptic equation along with the momentum equation, energy equation and turbulence equation are solved in a segregated manner using the SIMPLE algorithm for steady state or using PISO-SIMPLE algorithm (PIMPLE algorithm) for unsteady state. The solver can be run using both steady state and unsteady state manner. For this work, a steady state solver is used with turbulence modelled using realizable k-epsilon model. As compared to standard k-epsilon model, the realizable k-epsilon turbulence model is known to provide better predictions for turbulent flows in

regions pertaining to flows involving boundary layers separations, re-circulation and boundary layers with strong adverse pressure gradient that are expected in hilly regions. This is owing to use of a variable turbulent viscosity (C) in realizable k-epsilon as compared to a constant viscosity value that standard k-epsilon uses and use of a new transport equation for the dissipation rate, , that is derived from an exact equation for the transport of the mean-square vorticity fluctuation. The realizable k-epsilon model ends up satisfying certain mathematical constraints on the Reynolds stresses, consistent with the physics of turbulent flows. Authors are aware that there are better performing turbulence models like Shear Stress Transport (SST), but the choice of realizable k-epsilon model had also to do with its ability to be computationally efficient while predicting the statistical mean properties of turbulent flows.
All the equations (except k and turbulence equations) use second order linear discretization scheme, while the turbulent equations use liner-upwind convection schemes. Similarly, the diffusion term involving Laplacian operator (the divergence of the gradient) is simplified to compute the gradient of variables at the faces. The gradient term can be split into contributions from the orthogonal part and the non-orthogonal part, and both these contributions have been accounted for.
The next section describes the governing equations:

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 that may include rotational effects, $\mathbf{g}$ 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 $\partial p_s/\partial z = -g\rho_s$. In addition, the following expression for hydrostatic density may be derived from the state equation and the definition of potential temperature:

$$\rho_s = \frac{p_s}{R\theta_s}\left(\frac{p_o}{p_s}\right)^{R/C_p} \tag{4}$$

where R is the gas constant and C_p is the specific heat at constant pressure. Hence, once the hydrostatic (potential) temperature profile is given, the hydrostatic pressure and density may be calculated, and then substituted into Equations 1 and 2.
It may be noted that the Boussinesq approximation is obtained from the system of Equations 1 and 2 by assuming constant values (ρ_o, θ_o) instead of the hydrostatic values, and that formulation may well be used for incompressible flow and ordinary temperature.
In a mesoscale context like HARMONIE , the external force $(\mathbf{f})$ in momentum equations include the Coriolis forces. These forces are neglected in microscale models SIMRA and CFD. Further, the thermal diffusivity (γ) can be used to model the radiative heating of the atmosphere.
The aim of the present study is to solve these equations for high Reynolds-number flows. For this purpose we apply an Reynolds-averaged modelling of the equation system, together with a turbulence model. Presently a standard high-Reynolds $(k-\epsilon)$ turbulence model is used for this purpose in the micro-scale models. The equations are shown below :

$$\frac{DK}{Dt} = \nabla\cdot(\nu_T\nabla K) + P_k + G_\theta - \epsilon \tag{5}$$

$$\frac{D\epsilon}{Dt} = \nabla\cdot\left(\frac{\nu_T}{\sigma_e}\nabla\epsilon\right) + (C_1P_k + C_3G_\theta)\frac{\epsilon}{k} - C_2\frac{\epsilon^2}{k} \tag{6}$$

where turbulent viscosity is given by $\nu_T = C_\nu\frac{k^2}{\epsilon}$. The Reynolds stress tensor is given by

$$R_{ij} = \nu_T\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) - \frac{2}{3}k\delta_{ij} \tag{7}$$

while the eddy diffusivity appearing in the energy equation is $\gamma_T = \nu_T/\sigma_T$, σ_T being the turbulent Prandtl number. The production and stratification terms in the turbulence model are given by

$$P_k = \nu_T\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\frac{\partial u_i}{\partial x_j}, \quad G_\theta = -\frac{g}{\theta}\frac{\nu_T}{\sigma_T}\frac{\partial\theta}{\partial z} \tag{8}$$

Conventional constants for the high-Reynolds $(k-\epsilon)$ model are given by

$$(C_\nu, C_1, C_2, \sigma_e) = (0.09, 1.44, 1.92, 1.3) \tag{9}$$

The value for C_3 is more uncertain. In the present study we assume $C_3G_\theta = \max(G_\theta, 0)$, i.e. $C_3 = 0$ in stably stratified flows, else $C_3 = 1$
While the microscale and supermicroscale models utilize a two equation turbulence model (one for turbulent kinetic energy given by Eqn. 5 and another for dissipation given by Eqn. 6), the mesoscale model uses a one equation model consisting of the Eqn. 5. The turbulent dissipation is estimated from $\epsilon = (C_\mu^{1/2}K)^{3/2}/\ell_t$. ℓ_t is computed using the relationship

$$\ell_t \approx \frac{\min(\kappa z, 200m)}{1 + 5Ri} \tag{10}$$

where

$$Ri = \frac{(g/\theta)\partial\theta/\partial z}{(\partial u/\partial z)^2} \approx -\frac{G}{P} \tag{11}$$

In convective conditions the stability correction $(1 + 5Ri)$ is replaced by $(1-40Ri)^{-1/3}$. The gradient Richardson number Ri is supposed to be smaller than $1/4$. The coefficients are $(C_\mu, C_1, C_2, C_3) = (0.09, 1.92, 1.43, 1)$ and the coefficients $\kappa, \sigma_K, \sigma_\epsilon$ are $0.4, 1, 1.3$, respectively.

Coupling different codes

The coupling of different codes is shown in 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. A more comprehensive mapping of variables from SIMRA to OpenFoam is being developed.

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) that plans to research an implementation of Unmanned Aircraft Systems for a fast, secure and predictable transport of biological material and blood products between these hospitals. The location of terrain and buildings from where the drones are expected to operate have been shown in figure 2. The drone operations are expected to be impacted by local turbulence and wind shear and hence understand wind conditions is essential to establish safe drone flight trajectories. 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 and shown in figure 3). The simulations are done for two wind cases as described in next section.

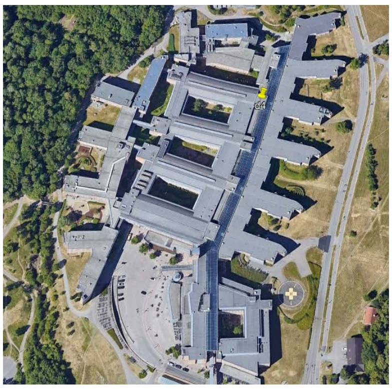

Figure 2: Oslo University Hospital with measurement location marked

COMPUTATIONAL SET-UP

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. HARMONIE model covers Norway and runs on a computational domain of size 1875km × 2400km × 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 size of 18 Km × 18 Km × 4 Km.the number of cells is about 1.28 milion. 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. The super-micro

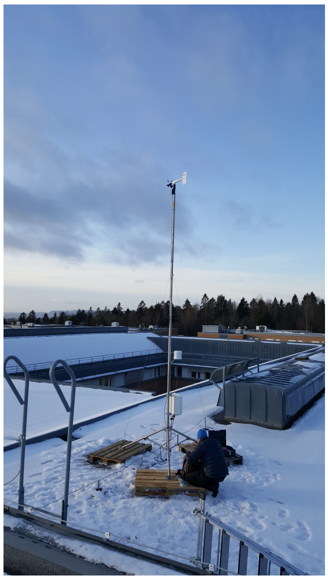

Figure 3: Experimental measurements at 6m above building D4

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.

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.

Choice of wind direction and Case Studies

Two realistic cases are selected to be simulated for comparison with experimental measurements : (a.) Case 1: Simulating the scenario of 9th February,2020 at 1000 UTC time with wind direction of 180 degrees and (b) Simulating the scenario of 13th February, 2020 at 15 UTC with wind direction of 344 degrees (i.e north westerly flow). The choices are made based upon considerations of dominant wind from the wind rose (like 184 degrees wind direction - South westerly flow, see figure 5) and wind profile considered challenging to drone operations due to gusty nature (wind direction 344).

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 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 qualita-

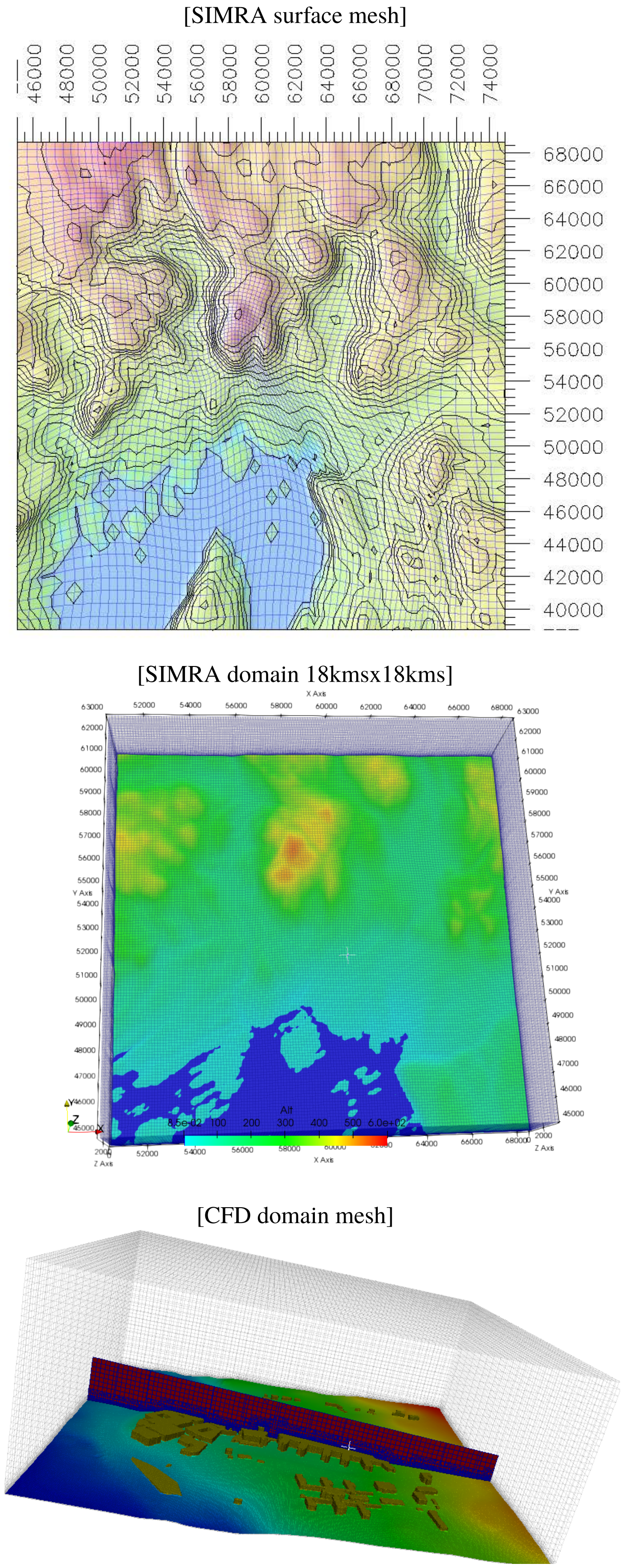

Figure 4: Mesh and domain used in SIMRA and CFD scales

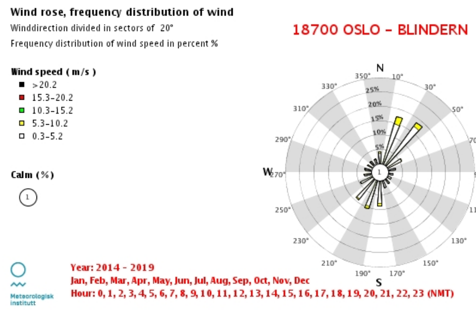

Figure 5: Wind rose to determine wind direction for study

tive comparison between SIMRA and local-micro-scale CFD model, rather than for quantitative validation.

RESULTS

The results presented here compares the simulated and experimental measurements:

Comparison between experiments and model predictions

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 while the observed gusts (max mean wind speed) are not compared as a steady state simulation is done with steady inlet profile. 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: $Deviation = \frac{U_{measurement} - U_{CFD}}{U_{measurement}} * 10.$

For the case 1 of 13April2020 (figure 6), SIMRA deviates with around 32% over-prediction while micro-scale CFD underpredicts by about 24% . For the case 2 of 9thFebruary2020 (figure 6), SIMRA deviates highly with around 72% over-prediction while super micro-scale CFD underpredicts by about 20%. The reasons for CFD to predict closer to measured data is due to the fact that it is accounting for impact of buildings - which is influencing the measurements (as shown in figure 9 and discussed in later section) It is important to note that these comparisons (validations) are being attempted in realistic conditions over which we have little control (as is possible in the case of wind tunnel where we can control inlet wind conditions and thus enable proper validation). The observed deviations reported below are attributed to factors related to both experimental and computational things, 1. The incorporation of unavoidable external noise in the signal collected by the mast has introduced measurement errors in wind below 5 m/s. 2. The measurements at nearby hours at 11UTC and 9UTC (as shown in figure 6) Case 2 reveals that the wind is highly dynamic within the measurement period. While the steady state solver in this work uses a steady inlet profile for the given hour (i.e at 10UTC - the hourly period of comparison) as we do not have information on change in wind conditions within the hour (10UTC). 3. Currently, a simple RANS turbulence model has been used. 4. The approximation considers only vertical variation for inlet profile and a full mapping may help to improve the model further.

So, the comparison with experiments and deviation could be used only for qualitative purposes and shows results along expected lines and known lines - that is the super-microscale CFD is able to account for building wake effects and hence shows lower wind speeds than SIMRA at regions up-to which the building has influence. So, such micro-scale models will be able to more accurately capture the wind conditions experienced by the drones.
Next, we qualitatively define the influence of different models:

Qualitative capabilities of models in the multi-scale framework

Figures 7-9 below shows qualitative capabilities of different models for the case 2 study. HARMONIE (figure 7) is able to capture the large scale meso-scale effects happening at an altitude of thousands of meters . It captures a major wind shift when crossing the frontal surface above Oslo and the associated jet stream in troposphere height is from the Northwest. The figure shows wind tangent to the cross-section for both the W-E and S-N together with potential temperature. Here, the frontal zone is seen aloft (a few thousand meters) and it is associated with a potential temperature gradient and a wind shear. This meso-scale model can be used to provide boundary profiles for the micro-scale models - which then can capture the local wind conditions around the urban hospital. The wind conditions in an urban location are impacted by buildings and urban landscape, and a meso-scale model such as HARMONIE that is operating at a resolution in scale of kilo-meters can not capture this. The impact of terrain and buildings are shown in figures below (figure 8-9) from the results of micro-scale models (SIMRA and CFD). As compared to the meso-scale Harmonie predictions, the

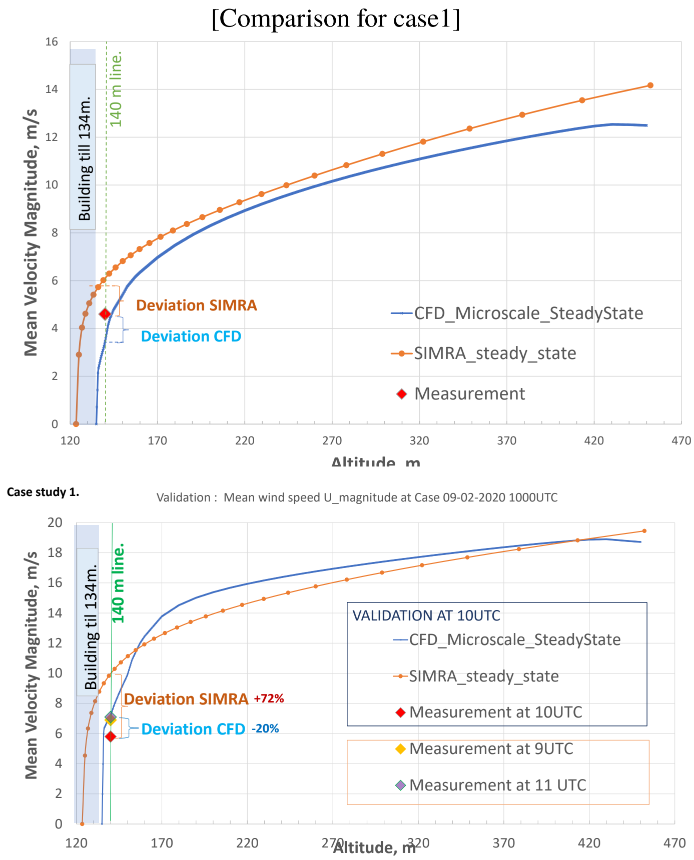

Figure 6: Comparison of models with measurement data

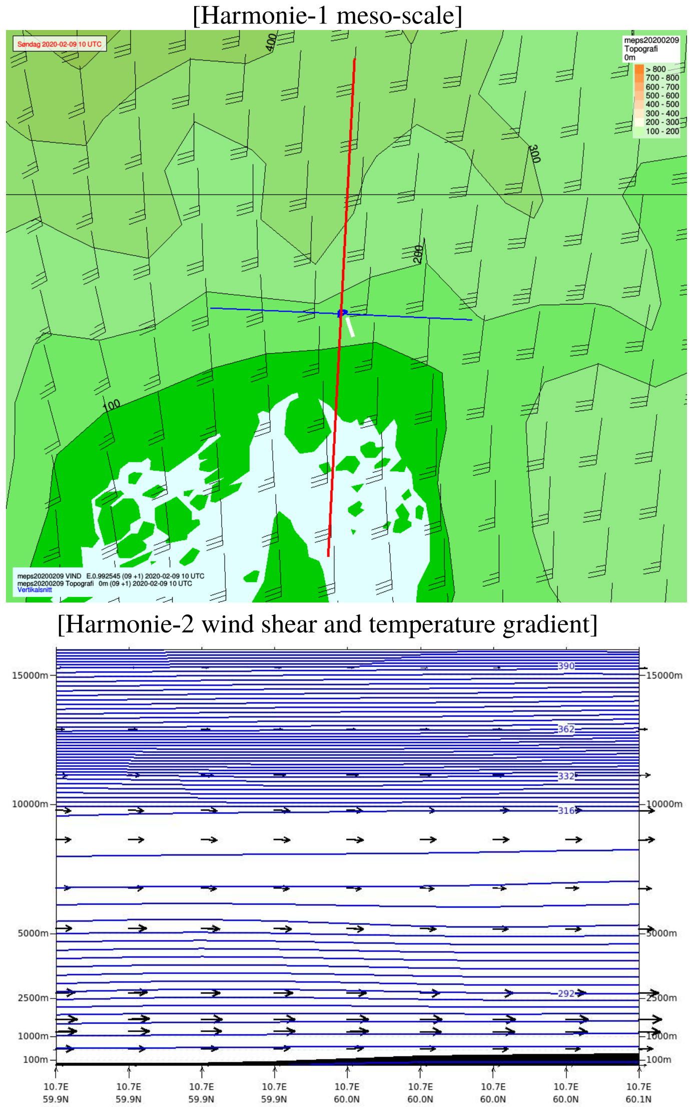

Figure 7: Harmonie meso-scale predictions

micro-scale SIMRA model shows that it is able to capture the impact of terrain (figure 8). This result is along expected lines. The terrain in north of Rikshospital, Oslo is hilly with elevation up-to 500m high. This can have an impact on the wind experienced at the hospital. HARMONIE owing to its coarse resolution (in kms) won't be able to capture this terrain impact. The figures shows that the wind vectors at different heights (300m, 140m) are impacted by terrain, and the turbulence emanating from the hilly terrain (terrain-induced turbulence) for the case 2 scenario (i.e. the south-westerly wind) can also been seem in the figure. At height D4 (140 m above sea-level, i.e. about the same height as the location of mast), the figure shows that SIMRA is not able to capture the impact of buildings as this needs grid resolutions to be below atleast a tenth-of a meter so as to explicitly resolve the buildings, while SIMRA operates at a resolution that is about two orders of magnitude higher (112 m resolution). For the cases of wind blowing from other directions (like northerly, north-easterly (NE) and north-westerly (NW)), the terrain-induced turbulence and wakes should impact the local-wind conditions on downstream of hill around the hospital.

As compared to the meso-scale Harmonie and to the micro-scale SIMRA, the super-refined micro-scale CFD model shows that it is able to capture the impact of buildings (figure 9). The figures shows the wind velocity vectors at 10m above ground level and at a vertical plane across the D4 measurement point (D4 represented by a white cross in the figures). The figures show that the D4 measurement location is influenced by the building. Super-micro scale CFD shows that the D4 mast location lies in the building-induced wake region thus experiencing higher turbulence and lower velocity, and hence, the super micro-scale CFD predictions are closer to the mast observations with lower velocity than those predicted by SIMRA (as seen in figure 6).

Thus, the current work qualitatively shows the utility of using a multi-scale approach to obtain wind conditions around an hospital in urban landscape. The quantitative accuracy of this multi-scale approach could not be checked as the experimental data from MET masts has significant noise from external source, and hence the measurement data has been used only for verification purposes.

CONCLUSION

The work shows the utility of the multi-scale tool for generating urban-scale wind conditions. The multi-scale tool in the form presented in this paper is capable of creating a micro scale wind atlas taking into account different combinations of meteorological parameters (like wind directions, building designs etc). However, we do admit that there is scope for a more detailed study and better validation studies (by obtaining better experimental data). In the near future, we intend to develop a more comprehensive coupling between the micro-scales codes and investigate influence of micro-scale turbulence on the drones under unsteady conditions.

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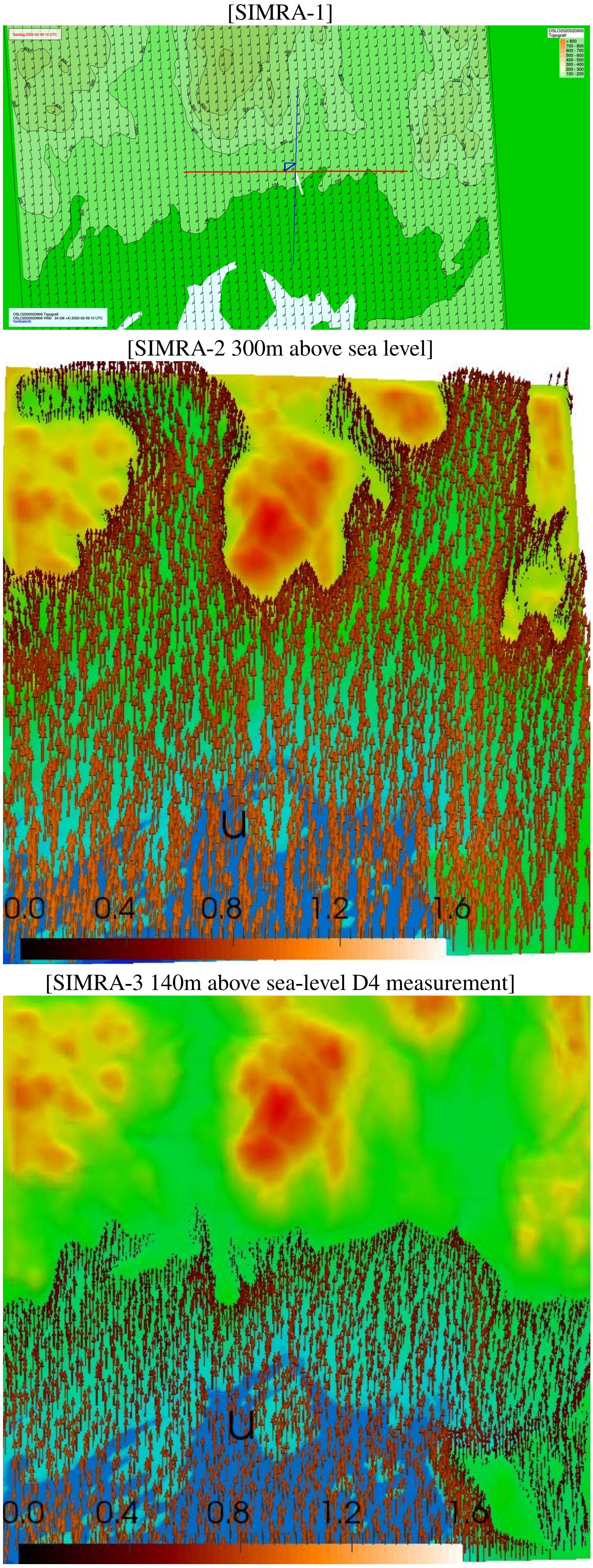
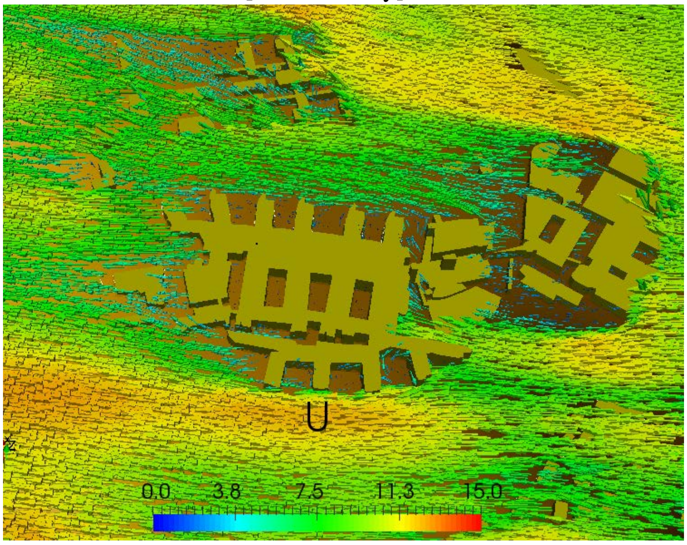
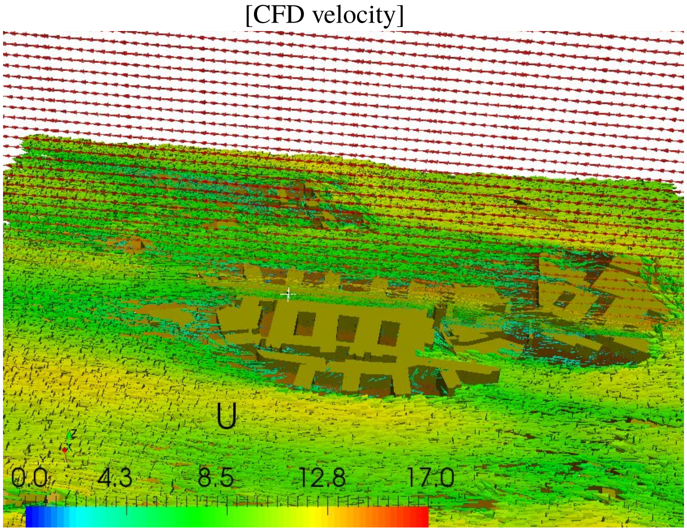


Figure 8: SIMRA wind vectors 10 UTC and terrain induced effects

[CFD velocity]



[CFD velocity]



[CFD turbulence]

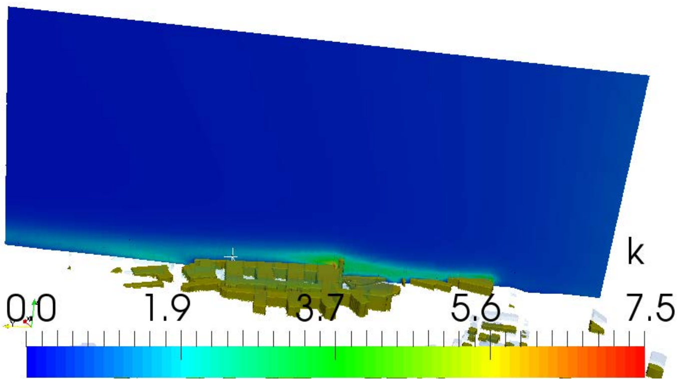


Figure 9: super micro-scale CFD for building-induced effects

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