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IEA-Task 31 WAKEBENCH: Towards a protocol for wind farm flow model evaluation. Part 1: Flow-over-terrain models

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IEA-Task 31 WAKEBENCH: Towards a protocol for wind farm flow model evaluation. Part 1: Flow-over-terrain models

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Abstract

The IEA Task 31 Wakebench is setting up a framework for the evaluation of wind farm flow models operating at microscale level. The framework consists on a model evaluation protocol integrated on a web-based portal for model benchmarking (www.windbench.net). This paper provides an overview of the building-block validation approach applied to flow-over-terrain models, including best practices for the benchmarking and data processing procedures for the analysis and qualification of validation datasets from wind resource assessment campaigns.

A hierarchy of test cases has been proposed for flow-over-terrain model evaluation, from Monin-Obukhov similarity theory for verification of surface-layer properties, to the Leipzig profile for the near-neutral atmospheric boundary layer, to flow over isolated hills (Askervein and Bolund) to flow over mountaneous complex terrain (Alaiz). A summary of results from the first benchmarks are used to illustrate the model evaluation protocol applied to flow-over-terrain modeling in neutral conditions.

Introduction

The IEA Task 31 Wakebench was initiated in 2011 to establish an international forum for networking and research collaboration in the field of wind farm flow modeling. The objective of the project is to establish a framework for verification, validation and uncertainty quantification that will first be used to produce best-practice guidelines for flow-over-terrain and wind farm wake models. The scientific scope of the project is mainly addressing microscale atmospheric boundary layer (ABL) and wind farm wake (far-wake) models suitable for wind resource assessment and wind farm design applications. The framework consists on a model evaluation protocol integrated on a web-based portal for model benchmarking (www.windbench.net) [1], that contains a repository of test cases, an inventory of models and a set of online tools for peer reviewing, discussion and reporting. In the future the scientific scope will be extended to neighboring research communities, notably mesoscale and near-wake models, and will define a basis for uncertainty quantification of the wind conditions model-chain.

The building-block validation approach analyzes a complex system, consisting in this case of a wind turbine and its siting and environmental conditions, by subdividing it in subsystems and unit problems to form a hierarchy of benchmarks with a systematic increase of complexity [2][3][4]. This allows isolating individual or combined elements of the model-chain and evaluate the potential impact on the full system performance. The process typically imply analyzing idealized conditions using theoretical approaches, parametric testing in control environment with scaled-down models in wind tunnels and field testing of scaled or full-scale prototypes in research conditions as well as operational units in industrial conditions. This increasing physical complexity is typically associated with decreasing levels of data quality and resolution because of practical as well as economical limitations. An essential aspect of the evaluation process is the definition of fit-to-purpose metrics to assess the performance of models on variables of interest for the target application [5].



For flow-over-terrain modeling, the range of complexity is presented here consisting on: Monin Obukhov similarity theory for the atmospheric surface-layer, the Leipzig wind profile for the near-neutral ABL, the Askervein isolated hill, the Bolund isolated hill with escarpment and the Alaiz test site in more realistic (wind farm) complex terrain conditions.

An overview of the model evaluation protocol is presented considering results from the Wakebench activities related to flow-over-terrain benchmarks. A separate paper summarizes the results for the wake modeling benchmarks [6].

Flow-Over-Terrain Models

In the present case we shall focus on microscale wind farm models producing mean flow characteristics, i.e. steady-state solutions, since this approximation has proven effective for wind resource assessment purposes. The initial benchmarks are adapted to these type of models and therefore will not focus on the dynamics of the flow.

Outside of the benchmark group, model and users names are made anonymous. During this initial stage, it is more important to focus on identifying consistency among groups of models than evaluating individual issues related to individual models. This task is left to the user, who benefits from the benchmarking activities by having access to detailed information about the other simulations of the group.

The models typically operate in neutral atmospheric conditions. This is also the case for the first benchmarks presented next with results for two RANS models. Preliminary results are provided for these two models to illustrate the model evaluation procedure implemented in the IEA Task 31.

Model Evaluation Procedure

The credibility of a model is built upon two essential principles: verification and validation, defined by the AIAA (1998) guide as [2]:

- **Verification** is the process of determining that the model implementation accurately represents the developer's conceptual description of the model and the solution of the model.
- **Validation** is the process of determining the degree to which the model is an accurate representation of the real world from the perspective of the intended uses of the model.

Accuracy is evaluated differently in verification and validation:

- In verification activities accuracy is measured with respect to benchmark solutions of simplified model problems
- In validation activities accuracy is measured with respect to experimental data

In both cases, accuracy is measured on a selected set of variables within a range of application, relevant for the intended use of the model. Typically, in wind assessment studies, the main focus shall be on mean velocity (U) and turbulent kinetic energy (tk_e) as they are directly related to the annual energy production (AEP) and turbulence intensity (I), target parameters for wind turbine siting. Concerning flow over isolated hills, like Askervein or Bolund, a well established non-dimensional parameter for the wind speed is the fractional speed-up ratio FSR :

$$FSR = \frac{U - U_0}{U_0} \quad (1)$$

where U_0 is the upstream flat-terrain velocity at the same height as U . In resource assessment campaigns it is more appropriate to consider U_0 at the top-level of a reference met mast, typically the one with a longer measurement period. In this case a velocity ratio

$$\hat{U} = \frac{U}{U_0} \quad (2)$$

is defined (also called site calibration factor or simply speed-up factor).

Similarly, tk_e can be made dimensionless by dividing by a reference tk_{e_0} derived from a reference mast.

$$\widehat{tke} = \frac{tke}{tke_0} \quad (3)$$

Alternatively, the turbulence intensity is defined by

$$I = \frac{\sigma_u}{U} \quad (4)$$

where σ_u and U are respectively the standard deviation and mean value of the horizontal velocity. Other variables of interest for wind turbine siting are the vertical wind shear, typically characterized by the power-law exponent α , the wind direction vertical shear (wind veer) and the vertical flow angle (or W/U in terms of a velocity ratio between the vertical and horizontal components).

Comparison between simulated (*sim*) and observed (*obs*) data is visualized with conventional 2D profile plots and quantified with statistical metrics. The selection of good metrics is essential to compare results from different benchmarks. Among the wide variety of statistical tools (see for instance [4]) we shall use the normalized mean absolute error *NMAE* as a first common reference for its simple use and interpretation:

$$NMAE(\hat{\delta}_{ijk}) = \frac{1}{\hat{\delta}_{ijk}^{obs} \cdot N_s} \sum_{s=1}^{N_s} |\hat{\delta}_{ijk,s}^{obs} - \hat{\delta}_{ijk,s}^{sim}|, \quad \hat{\delta}_{ijk} = \frac{\delta_{ijk}}{\delta_0} \quad (5)$$

where $\hat{\delta}_{ijk}$ is any variable of interest made dimensionless by dividing by a reference value δ_0 .

The *ijk* subscript refers to a certain class of wind conditions (flow case) which is typically defined from observations in terms of ensemble or bin averages for a range of velocity (*i*), wind direction (*j*) and stability (*k*). The summation is done for N_s sensor locations typically related to a profile of measurements.

Generating validation data from field campaigns is conducted by filtering the wind conditions based on the reference mast velocity, wind direction and stability. Bin-averaged statistics depend on the distribution of these relevant quantities during the evaluation period. When the data is subdivided into stability classes, the statistical significance of the measurement period may be compromised by the short duration of the campaign. Hence it is important to assess the long-term representativeness of the bin-averaged variables of interest before using them for model validation. A methodology for the assessment of long-term representativeness is defined in [7]. It is suitable for typical situations where a long-term reference mast is complemented with other short-term additional masts from which we obtain local speed-up factors for validation.

Benchmarks

Monin-Obukhov: verification of similarity theory in the surface-layer

Monin Obukhov (M-O) similarity theory [9] sets the point of departure of modern micrometeorology [10]. It is valid in the surface layer, i.e. approximately in the first 10% of the ABL, where Coriolis effects are negligible compared to friction, and under stationary and horizontally homogeneous conditions with no radiation. In these ideal conditions the vertical variations of wind direction, shear stress, heat and moisture fluxes are constant. M-O theory states that any dimensionless turbulence characteristic will only depend on a reduced set of scales. In neutral conditions these are the friction velocity (u^*), for the velocity scale, and the height above the ground (z) for the length scale. Hence, the non-dimensional velocity gradient ϕ_m is defined as:

$$\phi_m = \frac{\kappa z}{u_*} \frac{\partial U}{\partial z} \quad (6)$$

where $\kappa=0.41$ is the von Karman constant. In neutral conditions $\phi_m = 1$ and, after integration of (6) from the roughness length z_0 to a certain height z , the well-known logarithmic profile:

$$\frac{U}{u_*} = \frac{1}{\kappa} \ln\left(\frac{z}{z_0}\right) \quad (7)$$

is obtained. In the surface layer the turbulent kinetic energy is constant with height:

$$\frac{tke}{u_*^2} = \frac{1}{C_\mu^{1/2}} \quad (8)$$

where C_μ is a constant that typically takes values like 0.09 or 0.033 [11].

M-O theory is used to design wind engineering surface layer models. When an empty domain is simulated, in steady-state with homogeneous surface conditions, the flow should produce the fully-developed log-profile predicted by the theory. For instance, Richards and Hoxey [12] calibrated the RANS $k-\epsilon$ turbulence model by enforcing consistency with M-O theory in the surface layer in neutral conditions. Alinot and Masson [13] followed the same approach to derive consistency conditions for a $k-\epsilon$ model in stratified conditions.

Hence, the objective of the M-O benchmark is to demonstrate that the flow model, when run in steady and horizontally homogeneous conditions, is able to reproduce the analytical expressions of the profiles predicted by the theory for neutral conditions. An empty domain of 3 x 0.5 x 0.5 km (x,y,z) dimensions is simulated for a range of surface roughness conditions ($z_0 = [0.002, 0.03, 0.4]$ m). If the model is consistent with the theory, the analytical profiles (7) and (8) used at the inlet should be equal to the profiles obtained at the outlet of the domain. This benchmark also allows to check the equilibrium of the wall functions with the turbulent flow model [14]. Hence, in a building-block approach, this benchmark shall be used for verification purposes before conducting validation on any other test case where surface layer modeling is adopted.

Figure 1 shows the outlet profiles for the case of a roughness length of 0.0002 m, typical of offshore conditions, for three RANS and one LES simulations. Similar results (not shown) are obtained for the other roughness cases. The four models are able to produce a logarithmic velocity profile in the relevant range for wind turbines. Next to the wall some deviations occur in one $k-\epsilon$ model due to a very large first-cell height. The LES model is not designed to run under surface layer conditions and show the typical decreasing tke with height of ABL models. The RANS models are able to produce a reasonably constant tke and ϕ_m profiles in the relevant height range.

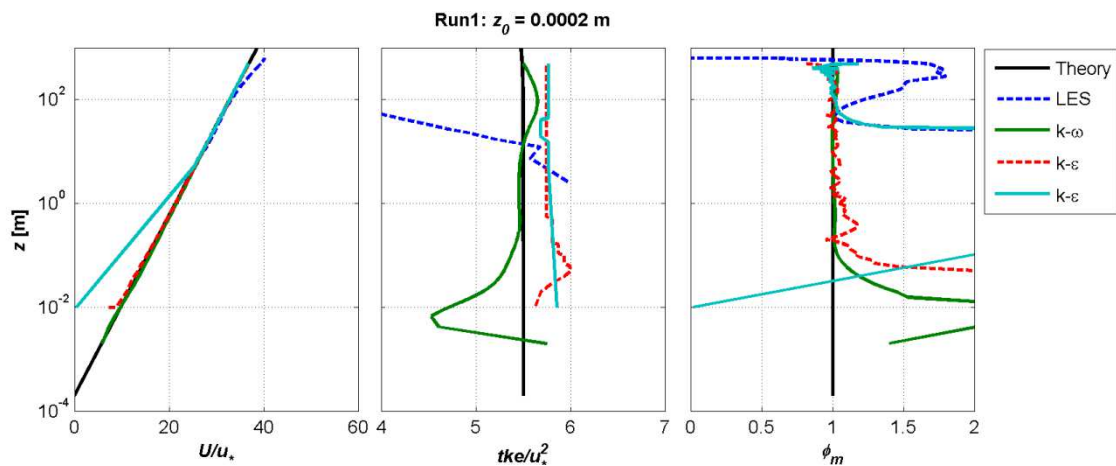


Figure 1: Non-dimensional profiles of velocity, tke and wind shear for three RANS models and one LES model. Roughness length typical of offshore conditions $z_0 = 0.0002$ m

Considering the results for verification purposes we could conclude that the RANS models are well designed since they produce consistent results with M-O theory. The LES simulation is not able to produce a constant flux layer so it shall not be used in connection with surface-layer modeling.

Leipzig: verification of ABL neutral profile

The Leipzig wind profile measurements were done on a grass-covered airfield with flat surroundings. Upstream, the air passes over the city of Leipzig. The profile results from a set of 28 pitot-balloon observations with two theodolites, between 9:15 and 16:15 on October 20, 1931, during stable weather [15]. During the experiment, the surface isobars were rectilinear indicating that the geostrophic conditions were steady and the horizontal gradients were negligible.

Lettau [16], performed a reanalysis of the measurements which resulted in a smooth profile, a "representative average" of the original, more scattered data. This classical profile has been discussed extensively in the literature. The boundary layer meteorology folklore considers this profile as a reference for an idealized neutral, barotropic (geostrophic wind constant with height), horizontally homogenous steady-state atmospheric boundary layer (ABL). However, it has been also argued that the profile was obtained in slightly stable conditions with an Obukhov length in the order of 500 m [20] obtained by profile fitting in the lower 150 m. In fact, Lettau [16] reports a lapse rate of potential temperature of 0.35 K / 100 m.

Even though it is relatively old, the Leipzig data is useful because of the steady barotropic conditions of the experiment. Being a well-established reference, it is suitable for model intercomparison studies. However, since the dataset is very limited regarding thermal stratification properties, it cannot be used as a complete model validation dataset. Instead, it shall be used for verification purposes by comparing the results among other models and checking the consistency of the results at reproducing a realistic near-neutral ABL wind profile.

The boundary layer is forced with a geostrophic wind of $G = 17.5 \text{ m s}^{-1}$ over uniform terrain with a roughness length of $z_0 = 0.3 \text{ m}$. The Coriolis parameter is equal to $f_c = 1.13 \cdot 10^{-4} \text{ s}^{-1}$ and the resulting friction velocity is $u_{\tau_0} = 0.65 \text{ m s}^{-1}$.

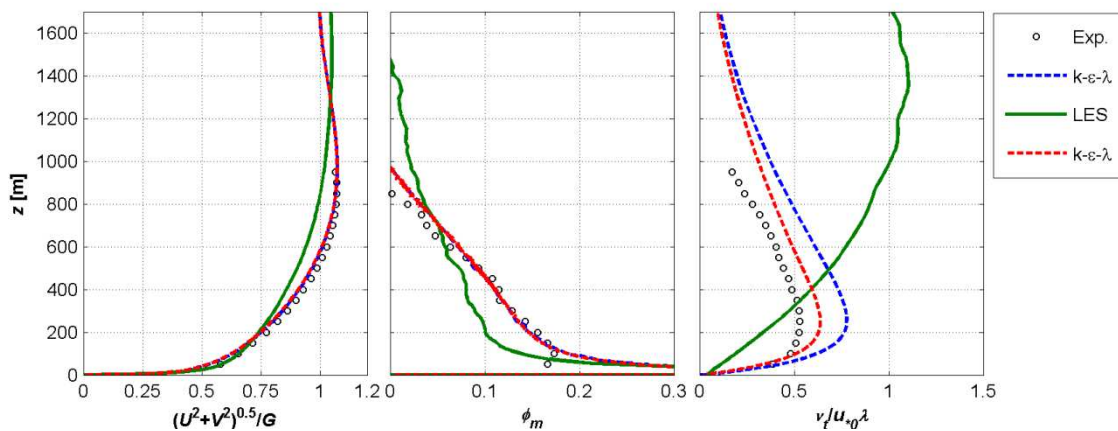


Figure 2: Non-dimensional profiles of velocity, wind shear and eddy viscosity for the Leipzig ABL

Figure 2 shows the results of two RANS and one LES model simulations. Both RANS models follow the approach of Detering and Etling [17] or Apsley and Castro [18] of introducing an asymptotic length through the ϵ equation that limits the mixing length that would otherwise grow linearly as predicted by surface layer theory ($l = \kappa z$). This mixing-length limiter λ was parameterized by Blackadar [19] as a function of the geostrophic wind and the Coriolis parameter:

$$\lambda = 0.00027 \frac{G}{|f_c|} \approx 0.063 \frac{u_*}{|f_c|} \quad (9)$$

equal to 42 m or 36 m if the G or u_* is respectively used at the Leipzig wind profile. Both RANS simulations differ on the value of λ but produce very similar results consistent with the observations at Leipzig. However, the LES model predicts too much mixing in the upper part of the boundary layer resulting in too high boundary layer height.

Askervein hill: isolated hill of gentle slopes

The Askervein hill experiment [9] can be considered the cornerstone of boundary layer flow over hills. It is based on two field campaigns conducted in 1982 and 1983 on and around the Askervein hill, a 116 m high (126 m above sea level) hill on the west coast of the island of South Uist in the Outer Hebrides, Scotland. The hill is isolated in all wind directions but the NE-E sector. To the SW there is a flat uniform fetch of 3-4 km to the coastline where there are sand dunes and low cliffs. A uniform roughness of 0.03 m is assumed all over the hill.

Over 50 towers were deployed and instrumented for wind speed and turbulence measurements, 35 of them consisting on 10-m masts equipped with a cup anemometer to measure the mean flow along three lines A, AA and B (Figure 3). Vertical profiles are measured with taller masts at a reference upstream position RS, at the hill top HT and at the centre point CP.

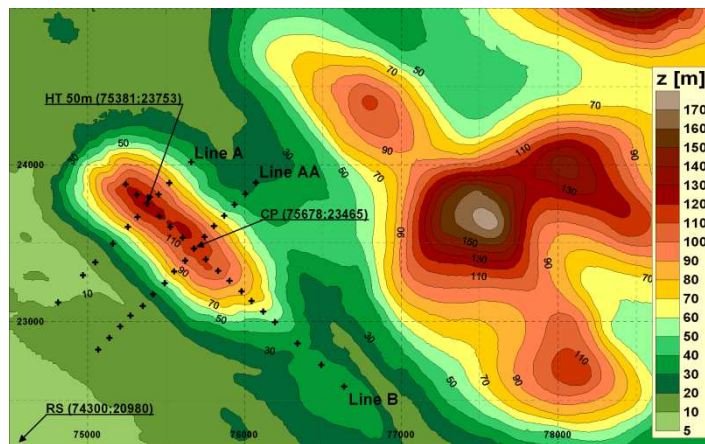


Figure 3: Mast layout on the Askervein hill experiment

The smooth slopes of the hill, generally less than 20% with some small areas reaching 30%, ensures fully attached flow most of the time, being a rather friendly site for flow models. Many CFD simulations of the Askervein hill test case have been published for the 210° flow case, for example Castro et al. [22] based on RANS modelling and Silva et al. [23] based on LES.

Figure 4 shows the vertical profiles at the reference (RS) and hilltop (HT) positions for two RANS models that were previously verified on the M-O benchmark. Note that tke/tke_0 is used instead of tke/S_0^2 in order to compare two models with different C_μ constant.

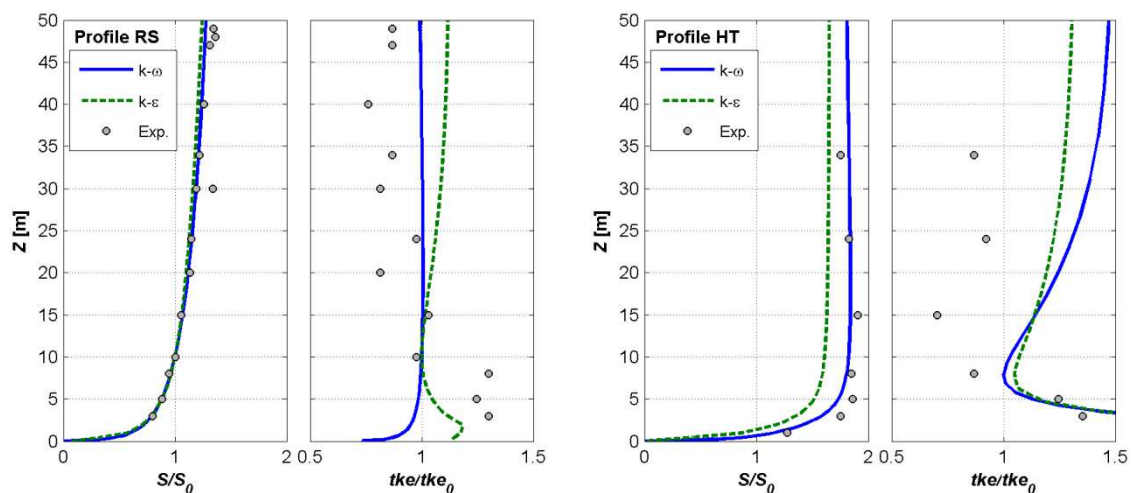


Figure 4: Vertical profiles of non-dimensional horizontal velocity S and tke at the reference (RS) and hilltop (HT)

They both show quite similar performance although the $k-\omega$ is a bit superior at predicting the speed-up at the hilltop. Both models overpredict tke at the hilltop.

Figure 5 shows the results of the 210° wind direction run along the lines A (left) and AA (right) for the 10-m mean wind speed and tke . While the mean flow field is reasonably well

reproduced, especially by the $k-\omega$ model, the tke is underestimated at the lee side of the hill. This deficiency is attributed to the limited applicability of isotropic turbulence models in wake flows as much better agreement is found with LES models [23]. Results for profile B (not shown) show similar performance on the mean flow, with better performance from the CP position to the east where the slopes are gentle.

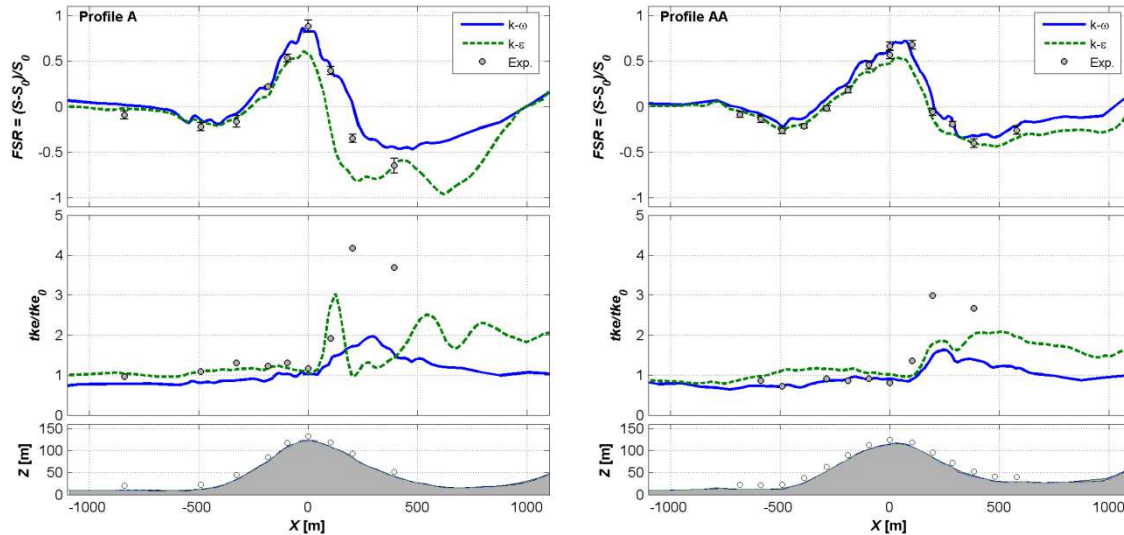


Figure 5: Horizontal profiles of non-dimensional velocity and tke along the A and AA lines

Table 1 show a quantitative evaluation of the performance of the two models under evaluation using the $NMAE$ metric defined in (5). Both models are consistent at showing a similar level of performance while the $k-\omega$ model, in this case, is better.

Table 1: $NMAE$ [%] for FSR and tke/tke_0 at the horizontal profiles (A, AA, B) and vertical profiles (RS, HT, CP)

FSR	A	AA	B	RS	HT	CP
$k-\omega$	12.12	6.80	4.53	1.75	8.77	7.53
$k-\epsilon$	19.23	7.36	13.22	3.32	27.98	20.39
tke/tke_0	A	AA	B	RS	HT	CP
$k-\omega$	40.75	29.78		16.87	37.74	37.99
$k-\epsilon$	40.62	29.96		20.09	36.09	53.20

Bolund hill: isolated hill with a escarpment

Bolund is a 12 m high, 130 m long and 75 m wide isolated hill situated to the North of DTU Risø campus in the Roskilde Fjord, Denmark. It is surrounded by water in all directions except to the E, where a narrow isthmus leads to the mainland. The hill is characterized by an estimated uniform roughness of 0.015 m and surrounded by water with a estimated roughness length of 0.0003 m. An almost vertical escarpment in the prevailing W-SW sector ensures flow separation in the windward edge resulting in a complex flow field, quite challenging for flow models.

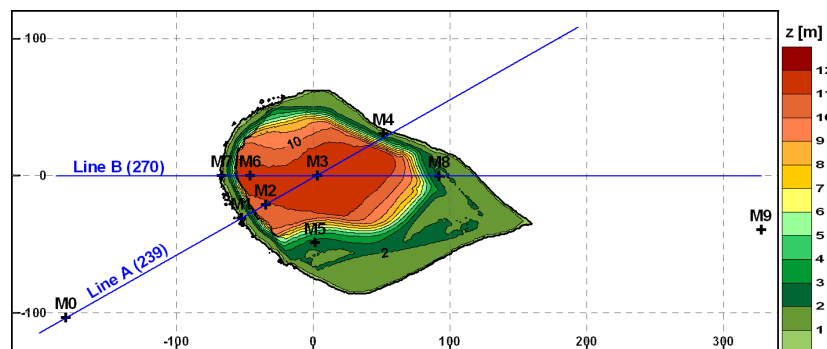


Figure 6: Mast layout on the Bolund hill experiment

The masts are positioned along two lines: A and B (Figure 6). Two additional masts (M0 and M9) were installed to measure the incoming undisturbed flow for westerly and easterly winds respectively. Mast M9 is placed in the coastline, where the roughness length is again 0.015 m. The masts are equipped with 23 sonic (Metek USA 1-Basic) and 12 cup anemometers (Risø Wind Sensor P2546) at heights between 2 and 15 m. The Bolund experiment comprises a measurement campaign of three months between 2007 and 2008 [24][26].

A blind test experiment was conducted in 2009 consisting on the simulation of four wind direction cases (270°, 255°, 239° and 90°) with prescribed boundary conditions of neutral flow [25]. In total 49 different simulations were submitted, composed of 3 physical models, 9 linearized numerical models and 37 CFD models (5 LES, 7 RANS 1-equation and 25 RANS 2-equation). The physical models predicted reasonably well the mean velocity profiles but under-predicted the turbulent kinetic energy. Linear models produced the worse results as they were not capable of reproducing the flow around the steep escarpment. RANS models provided the best results although the spread of the simulations was quite big, indicating user dependencies especially regarding mesh generation. LES-based models had problems but presented promising results with regard to turbulence modeling in the flow separation area just after the escarpment.

The same flow cases of the 2009 blind test have been revisited in Wakebench. Figure 7 shows the horizontal profiles of non-dimensional velocity and *tke*, considering the 5-m level sonic anemometer at M0 as reference for the inflow velocity and *tke*. Results from two RANS models are presented.

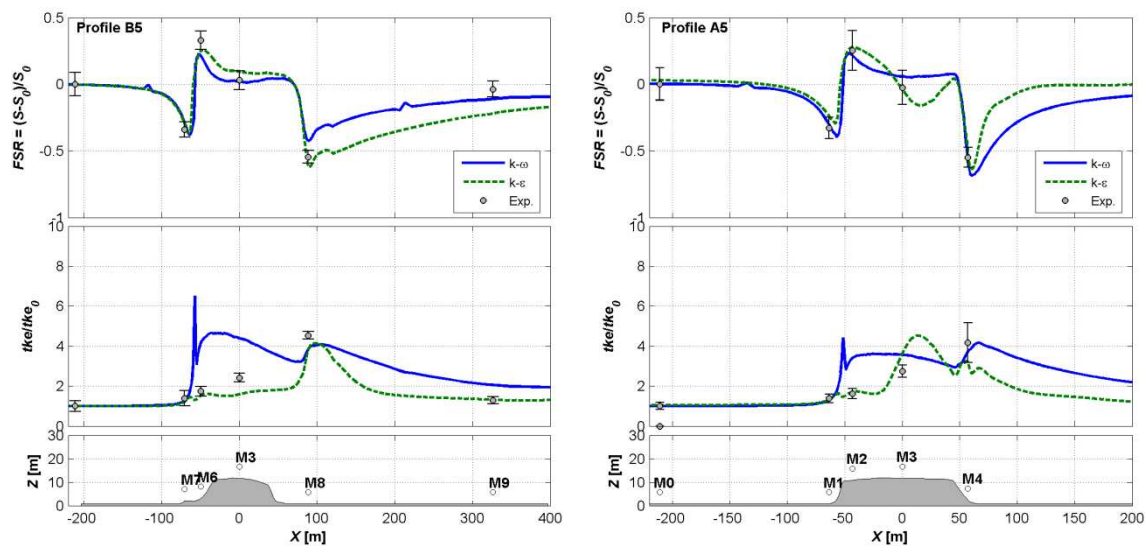


Figure 7: Horizontal profiles of non-dimensional velocity and *tke* along the B (run 1, WD = 270°) and A (run 3, WD = 239°) lines at 5 m above ground level

Table 2: *NMAE* [%] for *FSR* and *tke/tke0* at the horizontal profiles A and B at 2 and 5 m

<i>FSR</i>	Run 1: <i>WD</i> = 270°		Run 3: <i>WD</i> = 239°		Run 4: <i>WD</i> = 90°	
	B2	B5	A2	A5	B2	B5
k- ω	10.18	6.19	14.10	2.95	22.89	24.31
k- ϵ	16.44	7.29	19.64	3.48	7.04	8.32
<i>tke/tke0</i>	B2	B5	A2	A5	B2	B5
k- ω	37.80	47.83	42.43	37.47	61.04	53.38
k- ϵ	56.57	16.01	61.79	28.83	35.29	38.13

Table 2 summarizes the performance of the two models at predicting the *FSR* and *tke/tke0* along horizontal profiles for different wind directions and two heights, 2 and 5 m. The results are consistent with the blind test of 2009 with much better performance at 5 m than at 2 m. Contrary to Askervein, this time the k- ϵ model shows superior performance probably due to a much finer grid that can better resolve the flow around the escarpment areas of Bolund. Considering the

results at 5-m level we can see similar performance as Askervein in the *FSR* but worse results in the *tkc* due to a more complex flow.

Alaiz test site: complex mountainous terrain

The Alaiz mountain range is located in the region of Navarre (Spain), around 15 km SSE from Pamplona. The prevailing wind directions are from the North and from the South. To the North a large valley is found at around 700 m lower altitude. To the South, complex terrain is found with the presence of some wind farms, the closest one operated by Acciona situated 2 km behind the row of six wind turbine stands of the test site. Five reference met masts (MP0, MP1, MP3, MP5 and MP6), 118 m tall, are located in front of the turbine positions (A1-6) at a distance of around 250 m.

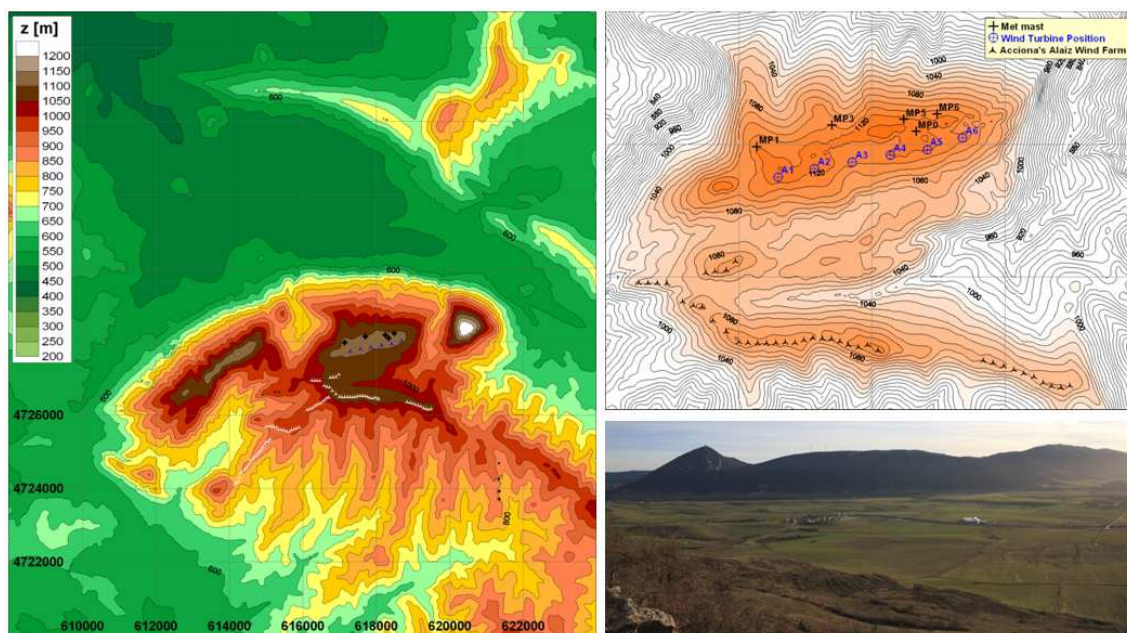


Figure 8: Alaiz elevation map, close-up of the test site and view from the upstream ridge

The site is characterized by two roughness levels. The western part of the test site, limiting with the MP3, position is covered with a dense canopy composed of bushes and beech trees 10-15 m high. The eastern part is covered by low bushes not higher than 0.5 m.

The test site has been operational since end of 2009 with the first wind turbines installed in the summer of 2011. The standard configuration of each mast is designed for multi-megawatt wind turbine testing and includes cup anemometers and wind vanes at [78,90,102,118] m and temperature/humidity measurements at [81,97,113] m.

The site calibration campaign is of special interest for the validation of microscale flow models since it provides local speed-up factors between the reference met masts and the turbine positions. The site calibration consists on two phases corresponding to the eastern site calibration (SC1: A4-A5-A6 vs MP0-MP5-MP6) and the western site calibration (SC2: A1-A2-A3 vs MP1-MP3-MP5). The wind conditions at Alaiz are modulated by atmospheric stability with neutral conditions rarely happening [27]. The generation of validation datasets from the site calibration campaign is described in [7]. The method allows extracting the velocity bin with the best mast coverage considering the long-term statistical representativeness, which is determined by comparing the statistics from the short-term site calibration campaign to the long-term measurements at a reference station, in this case the MP5 position.

The Alaiz test case consist on a first benchmark to run sensitivity analysis on modeling criteria that is typically adopted when approaching the simulation of a realistic site for wind farms in complex terrain: selection of the domain dimensions, mesh type and resolution, roughness definition, and wind direction binning. A follow-up benchmark is proposed to compare simulations from the sensitivity analysis with observational data in blind conditions, i.e. benchmark participants do not have the validation data a priori so it is not possible for them to tune the models.

Results of the blind test will be readily available in May 2014.

Conclusions and Outlook

In the frame of the IEA Task 31 a model evaluation protocol for flow-over-terrain and wind farm wake microscale models is under development. This paper summarizes the most important elements of the verification and validation process applied to flow-over-terrain model intercomparison benchmarks. Preliminary results are provided on a hierarchy of test cases of increasing complexity as practical implementation of the protocol.

A few more cases will complete the work plan of Task 31 concerning flow-over-terrain modeling. The San Gregorio wind farm in extreme complex terrain will be studied to assess the whole range of flow modeling complexities considering both the resource assessment phase (flow-over-terrain validation) and the operational phase (wakes from turbines and from a neighboring wind farm) [28].

Atmospheric stability has been recently approached using the GABLS idealized test cases as baseline for atmospheric boundary layer models: GABLS I, a moderately stable boundary layer at a constant cooling rate during 9 hours [29][30]; GABLS II, a diurnal cycle under constant geostrophic forcing [31][32]. Inclusion of stability is the next challenge of flow-over-terrain models for wind resource assessment applications. It also allows to build the bridge between microscale and mesoscale models. A follow-up Task is under preparation to continue the benchmarking activities of Task 31. The scope will be extended to mesoscale and near-wake models to complete the atmospheric model evaluation framework and set up methodologies for uncertainty quantification for resource assessment.

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