Impact of Complex Orography on Wake Development: Simulation Results for the Planned WindForS Test Site

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Abstract. In Southern Germany a test site will be erected in complex terrain. The purpose is to enable detailed scientific studies of terrain impact on the characteristics of two research wind turbines and to demonstrate new technologies. Within preparatory studies an appropriate site was identified and examined by field tests and numerical studies in more detail. The present paper summarizes CFD analyses on the impact of the local test site orography on the wake development of a virtual wind turbine. The effects of the orography are identified by comparative simulations for the same turbine using comparative wind situation in flat terrain.

1. Introduction

To further increase the share of onshore wind energy, the erection of wind farms in complex terrain and at exposed locations will be necessary. Due to the impact of orography and vegetation the inflow experienced by the turbines can feature noticeable inclination angles, differing turbulence and strong deviations in the shear profile compared to flat terrain. This has an impact on turbine loads and load variations compared to operation in flat terrain citeschulz2014, [1], [2]. The changed load characteristics along with the altered local flow field in complex sites are expected to impact the development of the turbine wake [3], although detailed studies are still lacking.

Scientific studies on the use of wind energy in complex terrain are one focus of WindForS, the Southern German Wind Energy Research Cluster [4]. WindForS is comprised of 24 institutes from 7 institutions of higher education and research institutes of the German states Baden-Württemberg and Bavaria. One goal pursued since long is the erection and scientific utilization of a wind energy test site in complex terrain including research wind turbines and extensive measurement instrumentation [5]. The objective is to conduct combined field tests and numerical studies on the impact of complex orography on aerodynamics, loads, aeroelastic behaviour and aeroacoustics of wind turbines. Further, the research turbines shall enable development and prototype testing of new technologies and control strategies. A demand for such a test site is seen because all existing test sites, except one (Aláiz, Spain), are on flat terrain as they are used for certification measurements [1].
Studies to characterise the wind conditions in complex terrain, definition of requirements for the research turbines and the measuring techniques as well as the selection of an appropriate test site location was advanced in the two WindForS collaborative projects LiDAR Complex and KonTest, both funded by the German Federal Ministry for Economic Affairs and Energy (BMWi). While LiDAR Complex was aiming on enhancing and qualifying different field measuring techniques and numerical methods for application to complex terrain studies, preparatory plannings of the test site and preparation of the numerical tools were conducted in KonTest. Meanwhile, the funding of two research wind turbines of the 800kW class, four meteorological masts, remote sensing devices and other measurement technique was approved by the BMWi. The funding also includes accompanying research activities and establishing detailed numerical models of the research turbines. The activities are pooled in the WINSENT collaborative project. Supplementary funding by the state of Baden-Württemberg will support the realization of the test site.

In the present paper, scale-resolving DES simulations (Detached Eddy Simulation) on the impact of the test site orography on the wake development of a virtual wind turbine are discussed. The results are contrasted with simulations of the same turbine in flat terrain to identify the impact of the orography. In the subsequent section, information on the test site, the research turbines and the intended techniques for flow field measurements are presented. Sec. 3 gives an overview of the flow solver, the numerical setup and the wake evaluation techniques applied in the present study. In Sec. 4 the impact of the complex orography on the unsteady wake development will be discussed for a virtual wind turbine.

2. Planned Test Site in Complex Terrain

The above mentioned KonTest project served for the preparation and planning of the test site in complex terrain. Firstly, the scientific requirements with respect to the topology of the site, the specification of the requirements for the research turbines, the instrumentation and supplementary field measuring techniques were defined. It was searched for an escarpment with an un–forested plateau as site for the turbines but with orography–caused disturbances of the inflow. In a second step, these criteria formed the basis for an evaluation of potential locations in Southern Germany. Among the candidate sites an area close to the village of Stötten in Baden-Württemberg was selected for further detailed local studies. The investigated location has a mean wind speed of 6 m/s at a height of 75 m above ground. Meteorological data, such as wind speed, turbulence and wind profile were collected by means of met mast, RASS and LiDAR measurements as well as by UAV-borne flow fields surveys [3], [6], [7]. The measurements showed that the wind speed is accelerated close to escarpment by up 60%. It could be seen, that there is a wide range of different flow characteristics for different wind directions. The in-field measurements were supplemented by numerical simulations to further characterise the local flow field [3], [8], [9], [10].

The field tests and the numerical studies confirmed the suitability of the location and were used for specification of the position of the research turbines and met masts to be erected. The choice of the positions, however, was constrained by infrastructural aspects and building conditions. According to current planning two turbines equipped with dedicated measuring technique will be installed by the end of 2018. Each of the turbines will generate around 750 kW nominal output and feature a hub height of 75 m and 50 m rotor diameter [3], [5]. Consciously, a smaller size compared to current state-of-the-art commercial turbines was chosen to enable future turbine modifications at affordable costs. But this turbine size still allows transferring knowledge of parameters such as loads, controller settings and turbine behaviour to larger wind turbines because different detailed simulation models exist. The turbines will be erected side by side to have the possibility to directly compare the behaviour of one modified turbine to the baseline turbine. One important requirement was that the involved researchers have full access
to all turbine and controller data.

It is planned to position one meteorological mast in front of and one behind each turbine whose maximum height should compare to the height of the highest blade tip position of the turbines. The topview of the orography of the selected test site is shown in Fig. 1 along with the planned locations of the research turbines and the met masts. Further, the simulation domain (compare Sec. 3) of the present CFD studies is illustrated. The plan is to equip the met masts with various meteorological sensors including ultrasonic anemometers in addition to the ground- and nacelle-based Lidars that will be installed. Like during the preparatory studies, UAVs will characterise the local flow field from the valley to the vicinity of the turbines including the wake behind the turbines. Lidar, met mast, eddy covariance and ceilometer measurements will serve to examine the wake of the turbines in detail, too.

![Figure 1: Topview of the orography of the planned test site area](source: USTUTT-IAG, USTUTT-SWE, GoogleEarth).

3. Numerical Model and Evaluation

3.1. Flow Solver

In the present study scale-resolving Detached-Eddy-Simulations (DES) were performed to examine the impact of complex orography and inflow turbulence on the development of the unsteady wake characteristics. The simulations were performed using the flow solver FLOWer that was mainly developed by the German Aerospace Center (DLR) within the past MEGAFLOW project [11]. FLOWer is a compressible finite–volume flow solver that uses block-structured grids and features a wide range of turbulence models [11]. In addition, it can handle rotating structures and the user can apply the (Chimera) overset grid technique [12] to embed separately meshed components into one computational grid. During the last years the code was systematically extended for wind turbine and helicopter application at the institute of the present authors. Amongst other features, this involves time-accurate structural coupling for aeroelastic analyses of wind turbines, inclusion of a generalized grid deformation algorithm, implementation of a higher-order numerical scheme, of actuator line approaches as well as options for imposing inflow turbulence and shear.

To enable the consideration of turbulent, atmospheric inflow conditions during the simulation two options were implemented. A Dirichlet boundary condition allows to feed in a stationary or unsteady velocity field at the inflow boundary of the computational domain [13]. The velocity field can be obtained from precursor LES simulations or from generic shear profiles, optionally superimposed by synthetically generated turbulence. To reduce the impact of disturbances from the inflow boundary on the injected turbulence, the turbulence field can also be imposed by means of volume forces in a plane further downstream as proposed by Troldborg [14]. In the present study this approach was used to impose synthetic turbulence generated by means of the Mann model [15]. More information about these options can be found in Refs. [13], [16], [17]. In the past this flow solver was already applied and qualified for detailed wake studies, e.g. on the
Mexico rotor including yaw effects [18], [19], [20] or the AVATAR rotor in ambient turbulence [16].

3.2. Wind Turbine and Meshes
At the beginning of the present study the size and the type of the research turbines to be installed was not yet decided. Therefore, available data of a 2.4 MW low wind speed onshore wind turbine were used for this wake study. The turbine features a hub height of 95 m and a rotor diameter of 109 m. The actual tilt and cone angles were considered in the present setup. Making use of the Chimera overset grid approach dedicated meshes were generated for the different components of the turbine, overlapped and embedded into a background mesh that covers the complete flow domain. The rotor blades were meshed by using the automesh script developed at the institute of the present authors. This script enables automated generation of high-quality structured meshes around single rotor blades in combination with the commercial grid generator Pointwise. It offers several parameters to control the composition and the resolution of the grid. The present blade grid is of C-topology and features 141 grid cells in radial, 101 in wall normal and 221 in circumferential direction. Together with additional grid blocks in the blade wake and outwards of the blade tip this sums up to about 7 Mio. grid cells per blade. In wall normal direction the blade boundary layer is resolved by about 30 ∼ 40 grid layers and the thickness of the first layer relates to a normalized wall distance of $y^+ \approx 1$. The grid is adapted in radial direction to ensure these characteristics along the complete blade span.

A single mesh consisting of 4.3 Mio. grid cells was introduced for nacelle and tower to minimise the interpolation effort needed for the grid overlap. For the hub a rotating separate grid (2.2 Mio. cells) was introduced that overlaps with the fixed nacelle and tower mesh during the simulation. The hub mesh is further connected with a joint mesh that was introduced to build a connection between blades and hub and features $3 \times 0.3$ Mio. grid cells [9]. This approach was chosen since a better mesh quality and a lower total amount of cells could be realised than meshing the joint together with the hub.

The objective of the present study was to examine the impact of complex orography on the development of the turbine wake. To have a reference, a background grid for a flat terrain scenario was created first. The background grid extends about 1900 m × 1200 m × 1000 m in streamwise, lateral and vertical direction, respectively. The value for the vertical direction has to be interpreted as mean value as, for obvious reasons, it is dependent on the position inside the terrain. Hanging grid node technique was utilised in the Cartesian domain to enable a refinement in the areas of interest while keeping the total number of grid cells within an acceptable limit. The refined mesh is cube-shaped and shows an extent of 300 m by 300 m in vertical and lateral direction [3], [17]. The resolution of the refined domain is 1 m in each direction of space and it ranges from the inlet towards the outlet to enable a resonable high resolution of the inflow turbulence and the wake region (compare Fig. 2). Outside of the refined domain the background mesh is successively coarsened, still capturing the general flow features but not the turbulence statistics. For the background mesh a total number of about 150 million cells were introduced.

A second background grid was generated that features the real orography of the site described in Sec. 2 at the lower boundary of the computational domain. The orography data were taken from a digital terrain model provided by the LGL (State Agency for Spatial Information & Rural Development Baden-Württemberg). A script was applied that maps the flat terrain mesh onto the surface of the complex terrain by means of mesh deformation. Further away from the surface, the deformation fades out and cubic cells are created. The resulting complex terrain background mesh, therefore, features the same mesh topology and number of grid cells as the baseline mesh for flat terrain [3], [17]. Figure 2 shows a sketch of the complex terrain background grid along with the embedded meshes around the turbine components.
3.3. Numerical Setup and Procedure of the Simulations
All simulations of the present study were conducted as zonal DES simulations utilising the Spalart–Allmaras turbulence model with Edwards modification [21]. For each simulation, a number of 40 inner iterations per physical time step was chosen with a dual–time stepping method for temporal discretisation according to Jameson [22]. A fifth order WENO (Weighted Essentially Non–Oscillatory) scheme [23], [24] was used to determine the convective fluxes in all regions of interest and a second order Jameson–Schmidt–Turkel method was utilised in regions of minor interest [25]. The boundary layers around the components of the wind turbine were calculated fully turbulent. Aeroelastic effects on rotor and tower were completely neglected in the present study.

In this paper results of four simulations will be discussed. Two simulations without wind turbine, one for flat terrain and one for complex terrain situation. Thereafter, two further simulations on the same background grids but with embedded wind turbine were performed. All simulations were started with a coarse time step of 0.26 s (corresponding to 20° rotor rotation) and were conducted over 36 rotor revolutions. This served to initialise the flow field and to propagate the inflow turbulence throughout the whole computational domain. Thereafter, another 36 revolutions were simulated with a refined time step of 0.026 s (2° azimuth) to develop smaller scale turbulence. Finally, the simulations were continued with the same time step for further 12 revolutions and flow field data were stored for the subsequent evaluation and wake analysis.

3.4. Wake Evaluation Techniques
To enable flow physics studies of the wake development the time-averaged velocity profiles and the spectra of the velocity fluctuations were evaluated. Further, the trajectory of the wake centerline and its spatial motion were analyzed. The centerline was determined by means of mass centers on cross axes of the wake. These cross axes are arranged parallel to the rotor plane, compare Fig. 3. The mass centers are calculated in analogy to the following equation:
\[
    y_{\text{centerpoint}} = \frac{\int y (u - u_\infty) dy}{\int (u - u_\infty) dy}
\]

Here, \(u\) is the local velocity and \(u_\infty\) represents the anticipated mean velocity of 11 m/s at hub height (compare Sec. 4.1). This evaluation provides the mass center for each cross axis. The cross axes are placed one after the other at a certain distance downstream of the rotor plane, see Fig. 3. This figure visualizes the flow field in a horizontal plane extracted at hub height. The centerline can then be determined by connecting the resulting positions obtained by Eq. (1) for each cross axis. Care must be taken to ensure that the cross axes completely include the wake in y-direction (see Figure 3). However, the cross axes should not project too far into the ambient flow domain in order to avoid sources of error.

This method can also be used to display a whole array of centerlines for a sequence of time steps to examine the temporal variation of the wake geometry and the meandering process. The amplitudes and the standard deviation of the centerline can then be evaluated over an arbitrary period of time. In addition, the temporal mean value of the centerline is determined. This approach allows to characterise the unsteadiness of the wake development and to visualise the meandering.

4. Results
The objective of the present study was to examine the impact of complex orography on the development of the wake of a wind turbine. For this purpose, scale-resolving DES simulations with the numerical setup as described in Sec. 3.3 were conducted. One baseline simulation for the 2.4 MW turbine presented in Sec. 3.2 in flat terrain and one simulation considering the real orography of the planned test site near Stötten (compare Sec. 2) were performed. It was intended to mimic the real atmospheric inflow conditions (shear profile, turbulence) of the terrain at the prevailing wind direction based on in-field measurements. Two challenges are associated with this objective. Firstly, to define realistic unsteady time series of the inflow velocity vector for the complete inflow plane of the simulations and, secondly, to ensure consistent wind speed at the turbine location for the flat and the complex terrain simulations.

4.1. Inflow Conditions
The inflow plane of the complex terrain simulation is located in the flat valley upstream of the escarpment at a distance of 1200 m (about 11 rotor diameter) upstream of the virtual turbine. Near this location neither a met mast was installed, nor were LiDAR or UAV-borne measurements available. Therefore, data of a met mast that is located about 1 km downstream of
the escarpment were utilised. As the test site and this met mast are located on a flat plateau it was assumed that the disturbances caused by the escarpment are largely abated at the position of the met mast and therefore represent a realistic basis for the definition of the inflow conditions in the present simulations. This mast has a height of 100 m and is equipped with four cup anemometers, three 3d sonic anemometers, vanes as well as pressure and temperature sensors. All data were recorded with a sampling rate of 20 Hz which enables to derive information about the turbulence level. Further information can be found in Ref. [3].

Met mast data with the above measuring technique have been taken since February 2015. To derive the inflow properties for the present simulations one bin of measurement data containing data of one year was filtered for neutral conditions and evaluated for the prevailing wind direction of 295° featuring a wind speed of 11 m/s at 95 m height, which represents the hub height of the virtual turbine [7]. With the chosen wind direction the flow in the mid-plane of the simulation is almost orthogonal to the shape of the escarpment. As the current version of flow solver FLOWer does not consider stratification effects, a neutral atmospheric boundary layer with an exponent of \( \alpha = 0.14 \) was used to define the inflow condition for the simulations. This velocity profile was prescribed at the inflow plane of the computational domain by means of a Dirichlet boundary condition (compare Sec. 3.1).

Preparatory simulations with the setup described above but without wind turbine were conducted to ensure comparative conditions for the flat and complex terrain simulations at the location of the virtual turbine. Following the met mast data for the selected wind situation a wind speed of 11 m/s at hub height was anticipated for both terrains. This velocity was realised in the definition of the power-law profile prescribed at the inflow plane of the flat terrain simulation. For the complex terrain the flow is accelerated by the displacement of the escarpment. Thus, a smaller velocity has to be defined at the inflow plane which is located in the flat valley, compare Fig. 2. Pre-simulations showed that an inflow speed of 8 m/s provides the intended hub height velocity of 11 m/s at the position of the virtual turbine [9, 17].

Based on the anemometer data different modelling parameters of the Mann model [15] for synthetic generation of the inflow turbulence were derived. As input parameters the length scale \( L \), the stretching factor \( \Gamma \) and the dissipation \( \alpha \varepsilon^{2/3} \) are needed. The distribution of the energy in the spectrum was derived from \( L \) and \( \alpha \varepsilon^{2/3} \), whereas \( \Gamma \) controls the shear. For the present simulations \( L \) was set to 40 m, \( \alpha \varepsilon^{2/3} = 0.035 \) and \( \Gamma = 3.9 \). A turbulence intensity of \( TI = 10\% \) (related to the respective mean inflow velocity of the two terrain simulations) was specified based on the anemometer data. The turbulence generated by the Mann–box is fed into the flow domain via source terms as described in Sec. 3.1.

4.2. Pure Terrain Simulations
First, simulations without consideration of the wind turbine were conducted to characterise the local flow field, to confirm that the intended mean velocity at hub height was achieved and to support the interpretation of the wake development. The resulting time-averaged boundary layer profiles of the pure terrain simulations are depicted in Fig. 4 for different streamwise positions. While the blue profiles represent the results of the flat terrain the red curves give the results for the complex terrain simulation. The dashed lines display the velocity profiles prescribed at the inflow plane. Comparisons between measurements and simulations have been published by [3] and [17] and will not be discussed here.

At 700 m, which is at the beginning of the slope, the predicted profile for the complex terrain already shows some flow acceleration at medium height (50 ~ 150 m) above ground. At 950 m the complex terrain simulation provides a significant acceleration particularly near ground, i.e. the boundary layer profile is enriched. The effect is even stronger at 1200 m which is the location of the virtual turbine. Note, that the hub and the rotor diameter are sketched in the graph. It is obvious that the average velocities at hub height (95 m) coincide for both terrain
simulations. However, below hub height the complex terrain simulation shows significantly higher wind speed while above hub height the velocity is lower compared to the flat terrain result. Near tip height even negative shear can be observed. Across the rotor plane the velocity appears to be much more uniform compared to the flat terrain. In consequence, the azimuthal load variations caused by shear are reduced for the present complex terrain simulation. On the other side, the inflow shows some inclination at the position of the turbine which increases the load variations, compare Ref. [9]. It should be noted, however, that this result in first instance holds for the present orography (turbine located on a flat plateau downstream of an escarpment, no impacting vegetation) and wind condition (wind direction perpendicular to the ridge, neutral stratification) considered. The results, therefore, cannot be generalized for other complex terrain or wind conditions.

Figure 4: Boundary layer profiles at different positions [17].

4.3. Simulations Including a Virtual Wind Turbine

In a next step the meshes of the virtual turbine were embedded into the terrain background meshes to examine the impact of the complex terrain on the wake development. The same setup as for the pure terrain simulations was used. Fig. 5 visualises snap shots of the wake development for flat terrain (upper picture) and complex terrain (lower picture). The figures show the axial velocity in a vertical plane parallel to the inflow direction with $\Delta z$ being the height above the local ground level.

On first glance, the higher speed close to the ground downstream of the tower in complex terrain is prompting. As a result of the terrain-caused flow enrichment near ground (compare Sec. 4.2), the tower wake deficit is fed with more energy from the surroundings than in the flat terrain case. In general the wake in complex terrain looks less disordered and its propagation seems much more straight than in flat terrain. Close to the turbine an upward deflection of the wake can be observed. This is the result of an upward flow inclination caused by the displacement effect of the upstream escarpment. The time-averaged deflection appears to be stronger than the average inclination angle across the rotor plane, i.e. comparable skew effects for turbines under yaw condition can be observed. Further downstream the inclination quickly decays and the upwards deflection of the wake is reduced accordingly [17]. Around $l/R = 6$ the wake seems to break up loosing its structure for both terrains. The mixing in the complex terrain, however, appears to be weaker than in flat terrain. This is attributed to a reduced turbulence level (related to the local mean velocity) caused by the flow acceleration near the ridge [9], [17].

Looking at some cuts parallel to the rotor plane the radial extent of the wake can be investigated in more detail. Figs. 6 and 7 show the mean velocity fields for both cases at
various downstream locations. In flat terrain (Fig. 6) the footprint of the rotor is nicely visible in a circular area of reduced velocity at a relative distance \( \frac{l}{R} = 1 \) downstream of the turbine position. The footprint of the tower diminishes in the low speed region close to the ground. Moving downstream the velocity deficit smears as fluid of higher energy is transported into the wake domain. As a result of the mixing process, the deficit gets more bell–shaped with increasing downstream distance and the wake edge begins to fade. In complex terrain (Fig. 7) the incoming velocity field is more homogeneous with less wind shear, compare Sec. 4.2. In consequence, the surrounding of the rotor and nacelle footprint features a more homogeneous field than in flat terrain. As the ambient velocity is higher close to the ground the tower footprint is much more prominent inside the flow field at \( \frac{l}{R} = 1 \). As already seen in the side view (Fig. 5) the tower deficit recovers quickly as the flow velocity close to the ground is higher than in flat terrain. In the downstream development the deficit starts to fade similar to the flat terrain case. The shape is hard to compare as the incoming flow fields are pretty different. Overall, a bell–shaped deficit can not be seen as clearly as in flat terrain.

Using the method described in Sec. 3.4 an investigation on the mean wake centerline and its motion over 12 revolutions has been performed. The time averaged evolution of the wake centerline is depicted in Fig. 8 along with the amplitudes of the lateral centerline motions. In flat terrain the wake centerline is virtually oriented in wind direction and shows no significant deflection in lateral direction [17]. The fluctuation amplitudes of the wake position is almost constant up to about \( \frac{l}{R} = 6 \) and starts to increase substantially further downstream. The wake breaks up at this position (compare Fig. 5) and larger scale motions are observed as documented in Ref. [17]. This larger scale movement is usually described as meandering. Larsen [26] explains it the following way. Each time a certain deficit sheet is created at the rotor and starts to propagate downstream. As the inflow varies temporarily these sheets propagate non–equally and may run up to each other. As a result, the wake structure is non–homogeneous over time at a certain position in space. The propagating deficit sheets may create a larger scale spatial movement in the wake depending on the turbulent length scale, ambient turbulence and flow homogeneity, amongst others. Usually, meandering is related to length scales larger than the rotor area. This is not true for the investigated case suggesting that other effects like tip vortex interactions and instability are involved in the generation of large scale wake motions [17].

In contrast, for the present complex terrain case, the amplitudes are much smaller and the
wake propagates downstream more uniformly. A strong increase of the wake motion beyond \( l/R = 6 \) can not be observed \cite{17}. The more homogeneous flow field and the reduced fluctuations seem to suppress the meandering tendency in the wake. Visually, the lateral deflection of the wake centerline is stronger and oriented towards negative \( y/R \) values for the present complex terrain case (compare Fig. 8). It has to be mentioned, however, that the axes are not to scale and the time-averaged deflection amounts to less than 1°. This lateral deflection can be attributed to a very small orography-caused local yaw angle but also to a combination of rotor cone and tilt yielding to non-symmetric loading and vortex shedding of the rotor.

Fig. 9 displays the spatially averaged power spectral density \( S_{uu} \) at various downstream locations in the wake. The spatial average has been performed along the \( y \) axis over the complete rotor diameter. In this way the spectra are much smoother and better comparable to each other than just one point spectra which may be dominated by single and strongly local events. The
blue lines in the pictures depict data from the terrain simulations without turbine. The results were evaluated at hub height of the later turbine position. They can be interpreted as an undisturbed reference. The yellow and the red curves represent the results of the simulations including the virtual turbine and are given for two locations downstream of the rotor. Prominent peaks in the signal directly downstream of the turbine ($l/R = 0.25$) can be noticed. These peaks appear at the harmonics of the blade passing frequencies and have also be shown in Refs. [17], [13]. For a small distance downstream of the turbine ($l/R = 0.25$) increased amplitudes result in the high frequency domain if compared to the inflow spectra of the pure terrain simulations. With increasing downstream distance the peaks diminish quickly and the spectra recover almost to the state of the inflow. The trends in the spectra are similar in complex and flat terrain.

Figure 9: Wake spectra at two positions downstream of the turbine for flat (left) and complex terrain (right) compared to the spectra of the pure terrain simulations [17].

5. Conclusion and Outlook
In the present study numerical DES simulations were performed to investigate the impact of a complex terrain on the wake development of a virtual 2.4 MW wind turbine. For this purpose the orography at the planned WindForS test site near Stötten in Baden–Württemberg (Southern Germany) was considered. The test site is located at a flat plateau rearwards of an escarpment. To define the atmospheric inflow conditions for the simulations meteorological data for the prevailing wind direction and neutral stratification were evaluated. The mean boundary–layer profile was approximated by a power–law profile and prescribed at the inflow boundary of the computational domain. The measured turbulence intensity of $TI \approx 10\%$ was generated synthetically by means of a Mann box and fed into the simulations by a volume force approach. Firstly, pure terrain simulations were conducted to characterise the local inflow conditions for the virtual turbine. The results for the complex terrain were compared to flat terrain results to identify the impact of the orography. It turned out that due to the flow acceleration near the ridge of the escarpment the velocity near ground was increased at the position of the virtual turbine, i.e. the boundary–layer profile was enriched and the turbine is exposed to a much more uniform inflow compared to the situation in flat terrain where significant shear effects appear.

In a next step the virtual wind turbine was embedded in the flat and in the complex terrain simulations and the resulting wake characteristics were evaluated. Analysis of the wake deficit showed that for the present complex terrain case the enrichment of the wake is slightly delayed. This was attributed to the reduced local ambient turbulence caused by the flow acceleration near the ridge of the escarpment. Further, the time-averaged evolution of the wake centerline was evaluated along with the amplitudes of their lateral motion. It was observed, that due to the higher local turbulence the wake meandering was more pronounced in flat terrain.

It shall be noted that these findings in first place hold for the present special orography, turbine location and wind condition. For differing wind directions stronger disturbances caused by forest and flow separation near the ridge are to be expected. Further detailed studies will be
performed within the collaborative project WINSENT. Within this project two research turbines will be erected along with four met masts. Besides comprehensive field measurements detailed numerical models will be established and applied for flow field and aerodynamic studies.

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