Numerical study and LiDAR based validation of the wind field in urban sites

M von der Grün¹, P Zamre², Y Chen³, T Lutz², U Voß¹ and E Krämer²

¹ Hochschule für Technik Stuttgart - University of Applied Sciences, Faculty C, Schellingstraße 24, 70174 Stuttgart, Germany
² Institute of Aerodynamics and Gas Dynamics, University of Stuttgart, Pfaffenwaldring 21, 70569 Stuttgart, Germany
³ Stuttgart Wind Energy @ Institute of Aircraft Design (SWE), University of Stuttgart, Allmandring 5b, 70569 Stuttgart, Germany

E-mail: {maximilian.vondergruen, ursula.voss}@hft-stuttgart.de; {zamre, lutz, kraemer}@iag.uni-stuttgart.de; chen@IFB.Uni-Stuttgart.de

Abstract. Within the project "Windy Cities" the economic use of small wind turbines in urban areas is investigated in Tübingen, Germany. This test-site contains complex terrain, forested areas and various types of buildings making the local wind field more turbulent and complex. To avoid damages and reduced life times of small wind turbines caused by high turbulence a detailed prediction of the wind field is essential in the present study. This is done using CFD.

The scope of this study is the validation of the setup including terrain and vegetation. For this, on-site planar wind field LiDAR data are utilized to define the inflow boundary condition for highly resolved Detached Eddy Simulations (DES) using ANSYS Fluent. The required preprocessing steps of the LiDAR data are explained in detail and their assumptions, which are made to interpolate the data onto the numerical inflow plane. Since the inflow region is covered by forested zones a forest model is introduced with a local tree height adaption based on Laser scan data. LiDAR data, which are measured further downstream, are used to validate the forest model. Simulations with and without the considered forest are compared to investigate the influence of the forested region.

1. Introduction

An approach of renewable local power generation with short supply distances in cities can contribute to the worldwide trend to urbanism and the climate protection in future. Distributing offshore generated power over long distances to densely populated areas has the disadvantage that the power loss in long distance grids and lacking people’s acceptance lead to high energy costs and delayed implementations. Small wind turbines, which are mounted in urban terrain can help to overcome these problems. Their economic use in urban areas is investigated within the interdisciplinary Joint Graduate Research Training Group "Windy Cities".

In general a high energy yield for wind turbines is aspired, requiring high local wind velocities. On the other hand, high values of turbulent kinetic energy and turbulent intensity can cause damages at wind turbines and lead to reduced life times. Hence, a detailed knowledge about the local wind field is important. The wind field in urban areas strongly depends on the shape
of the buildings as Yang et al. [1] investigated. El Bahlouli et al. confirmed that on top of buildings the flow accelerates leading to higher energy yield [2]. Further studies confirmed that the roof type [3] and the building density influences the wind field and optimal locations for wind turbines [4]. Most of the studies considered just a single building or an arrangement of generic buildings [4] but not a real urban section. Very few of the studies considered complex terrain. As Schulz et al. [5] figured out, a complex topography may have a great impact on the local flow field, e.g. the flow accelerates on the top of a hill but flow inclination impact the turbine loads and performance. Letzgus et al. [6] pronounced that the vegetation and forests changes wind speed and wind direction, e.g. they decelerate the local velocity in the wake of forested zones. The simulations of Schulz and Letzgus considered rural areas without buildings. Besides the possibility of wind tunnel and on-site measurements, CFD is an increasingly established tool to predict local wind flows, with applications in pedestrian comfort, building aerodynamics and pollution distribution [7]. Urban areas, complex terrain and forested areas, especially with regard to urban wind energy exploitation, have been considered only in a few cases [8].

The aim of this study is to utilize on-site planar wind field LiDAR data to define the turbulent inflow boundary condition for highly resolved Detached Eddy Simulations (DES). The required preprocessing steps of the LiDAR data are explained in detail and their assumptions to interpolate the data onto the inflow plane of the domain. The university Campus Morgenstelle in Tübingen (Germany) is chosen for a detailed study to investigate the potential of small wind turbines. The real geometry of the buildings is included in the simulations. The inflow region is mainly covered by forested zones and the test site is located on a hilly terrain. Since both can have a great influence on the local wind field, as mentioned above, both scenic properties are considered in the simulations. Therefore, a forest model is implemented in ANSYS Fluent with a local tree height adaption. Since there is a lack of validation studies of urban simulations the forest model and the simulation setup in general are validated with LiDAR data measured further downstream. Besides the modelled vegetation the numerical setup includes actual geometry of the buildings and complex terrain to give a realistic and reliable overview of the windfield in cities and suburban areas, as shown in figure 5.

2. Methodology

The simulations are performed with the Ansys Fluent software using the Improved Delayed Detached Eddy Simulation (IDDES) in combination with the incompressible k-ω SST turbulence model according to the approach by Gritskevich [9]. DES is an economic combination of the Reynolds Averaged Navier-Stokes equations (RANS)-modelled boundary layer and Large Eddy Simulations (LES). It needs less computational resources compared to pure LES simulations. The IDDES model is based on the DDES model with an improved shielding function between the RANS and LES zone to avoid mesh induced separation of the flow [9]. This model has been validated in a previous study to give the best turbulence model for a single high-rise building on a flat terrain.

Since the inflow region towards the buildings is mainly covered by a forested zone, which has to be considered in the simulation, a forest model based on the approach of Shaw and Schumann [10] has been added to the solver. That enables the implementation of any kind of forest structure in the simulations. The model is specified by a source term in a spatially porous media which is added to the momentum equation of the Navier-Stokes equations. The additional terms for the x, y, z-momentum equation including the forest drag force are defined by

$$ F_w = -\rho c_d a(z) |u| u_i, $$

where $\rho$ is the density and $c_d$ is the drag coefficient which is set to 0.15 [10]. The variable $|u|$ describes the velocity magnitude and $u_i$ the velocity component in i-direction. The height-
depending parameter $a(z)$ represents the drag induced by the local foliage density of the trees leading to different velocity profiles within the forested area and in the wake behind the trees. The Leaf Area Index (LAI) describes the forest density and is defined by

$$LAI = \int_{z}^{h} a(z) \, dz,$$

(2)

where $h$ is the height of the tree or the forest, respectively. That means that every tree species has its own LAI according to its degree of foliation and consequently its own $a$-profile. Figure 1 shows profiles for different values of LAI, where LAI=2 represents a sparsely covered forest canopy and LAI=5 a very dense forest canopy in summer. The forest in the inflow region at the test site in Tübingen is a mixed forest with 56% conifers and 44% ratio of deciduous trees. The averaged LAI value according to this ratio is 3 which is taken for the simulation and the associated profile of $a$ is shown as the red line in figure 1. Bequet et al. [11] investigated the seasonal variation of LAI over the year for oaks and peaches. According to that study the LAI of oaks changes from 0.7 during the winter time to 2.7 in the summer time and that of peaches from 0.6 to 3.5 over the year [11]. However, for spruce and pines the seasonal LAI variation remains quite constant at 6 and 3, respectively [12]. For a detailed prediction of the (seasonal) wind flow the proper LAI has to be considered in the forest model.

![Figure 1](image1.png)  
![Figure 2](image2.png)

**Figure 1.** Profiles of $a$ over the dimensionless tree height $H_t$ for different LAI.  
**Figure 2.** Local dimensionless tree heights over the $x$- and $y$-coordinates of the domain.

The coordinates of the forested area are obtained from OpenStreetMap Data and directly projected onto the terrain used in the simulations. The local tree height of the forest is obtained by Laser scan data from the Landesamt für Geoinformation und Landentwicklung (LGL) (State Agency for Spatial Information and Rural Development) Baden-Württemberg. The Laser scan point cloud is split up into vegetation and ground marks which are divided into 10mx10m tiles. The values within one tile are averaged and the mean values are fed into the simulation. Figure 2 shows the distribution of the forest in the computational domain over the dimensionless $x$- and $y$-coordinate. The distribution of the local tree height $H_t$ is illustrated also in figure 2 showing a quite large deviation in height within the forested area. The Stuttgart Wind Energy (SWE) Institute conducted an on-site LiDAR measurement campaign at the test site in Tübingen. The measurement device was located at a high-rise
building, marked by the white point within the rectangle in figure 5. Three points in width
and four points in height (40, 140, 240 and 340 m) on a plane were measured in various
distances, so this data set is used for the inflow boundary condition and for the validation
further downstream. The influence of the terrain is considered already at the computational
inflow plane by the measurement of lateral depending wind profiles. This gives a more realistic
inflow condition than a 1D-data set from a single met mast. The three-dimensional velocity
components are determined from the measured line of sight velocity. In order to detect, sort out
and replace extrem and unphysical measurement data an extended version of a linear median
filter is applied which is widely-used in image data processing [13]. In the following the function
and the extensions of the filter will be explained briefly. The filter is applied by running through
the signal entry by entry. Assuming the following signal
\[ M(i) = [\ldots, 1 \ 2\ 102\ 4\ 5\ 6\ \ldots] \]  
with 102 as the number which should be replaced, so \( g(x) = 102 \).
Each value \( g(x) \) is replaced by the median \( g'(x) \) of the values in a window around \( g(x) \), here
the width of the window, marked with squared brackets is 3 and \( g'(x) = 4 \) and the signal turns to
\[ M(i) = [\ldots, 1\ 2\ 4\ 4\ 5\ 6\ \ldots] \]  
Figure 3 shows the measured velocity signal in streamwise direction of a measurement point
over the sampling time of 60 min. The black line shows the unfiltered velocity against the same
velocity (red line) filtered by the median filter, as explained above.

\[ M(i) = (g(x) - g_{\pm 1}(x)) \cdot w + g_{\pm 1}(x), \]

Since not only the outliers are filtered but also the small fluctuations of the velocity signal,
some extensions are added to the median filter. In order to avoid that even values with small
deviations compared to \( g(x) \) are replaced, a threshold value \( c \) triggers the replacement of \( g(x) \)
by \( g'(x) \)
\[ |g'(x) - g(x)| > c, \]  
which is set to 0.8 m/s. Additionally, a weighting function is applied to the filter. In case of
replacement the values within the window are updated by

![Figure 3. Velocity in streamwise direction u over time - unfiltered and filtered by the original median filter.](image1)

![Figure 4. Velocity in streamwise direction u over time - unfiltered and filtered by the extended version of the median filter.](image2)
where \( g_{\pm 1}(x) \) are the neighboring values and the weighting factor \( w \) is set to 0.1. Subsequently, the filter is applied using the new window elements. That means, that the qualitative fluctuations remain in the signal and the new value \( g'(x) \) is damped according to the weighting function. The updated signal versus the unfiltered signal are plotted in figure 4 which show a good improvement with more smaller fluctuations remaining in the signal. The median filter is applied to the signal of every measurement point and the signal is averaged over one hour. Since the LiDAR measuring device was not able to capture the signal properly at the upper points of the measurement plane at 340 m due to fog or low clouds and the lower points due to the vicinity of the forest, some assumptions are made and explained in the following. Schatzmann et al. [14] addressed the issues to extrapolate measured planar wind field data onto the numerical inflow plane but just gave a solution for linear wind profiles in urban areas. A previous simulation confirmed that the influence of the hilly terrain can be neglected at a height above \( z_{\text{hom}} = 330 \) m and lateral homogeneity can be assumed. The extrapolation scheme is divided into two parts depending on \( z_{\text{hom}} \) and a power law approach is taken for the overall velocity profile:

\[
U(z) = \left( \frac{z}{z_{\text{ref}}} \right)^{\alpha} \cdot u_{\text{ref}},
\]

where \( u_{\text{ref}} \) is the measured velocity at the reference height \( z_{\text{ref}} \) and the exponent \( \alpha \) depends on the surface roughness according to Davenport [15]. For \( z > z_{\text{hom}} \), \( \alpha \) is uniformly set to 0.21 due to the lateral homogeneity and \( u_{\text{ref}} \) is the velocity measured at \( z_{\text{ref}} = 340 \) m. For \( z < z_{\text{hom}} \) the lateral depending exponent \( \alpha(y) \) is adapted to the local terrain height and calculated by

\[
\alpha(y) = \frac{\ln \left( \frac{U(z_{\text{hom}})}{u_{\text{ref}}} \right)}{\ln \left( \frac{z_{\text{hom}}}{z_{\text{ref}}} \right)}
\]

The velocity \( U(z_{\text{hom}}) \) obtained from Eq. (7) and \( z_{\text{hom}} \) are used as boundary conditions for Eq. (8) to determine \( \alpha(y) \). In Eq. (8) \( u_{\text{ref}} \) is the velocity measured at \( z_{\text{ref}} = 240 \) m. The values between the three lateral measurement points are interpolated linearly and are fed into the simulation on the inflow plane.

3. Simulation Setup

The building geometry and the coordinates of the local terrain are also obtained from the LGL. In the preprocessing steps the building geometry is defeatured of all details larger than 0.2 m and incoherent surfaces are merged to solid geometries in order to ensure high quality meshing. The size of the domain is \((15.0 \times 13.5 \times 14.6) H_{\text{max}} \) according to the best practice guide for urban simulations [16], where \( H_{\text{max}} \) is the height of the tallest building. The domain height is adapted for complex terrain. Synthetic wind statistics by [17] at the test-site in Tübingen confirmed that the main wind direction is \( 245^\circ \) and consequently, the domain and the inflow plane are oriented towards that direction.

For the turbulence length scale \( L = 55 \) m is chosen. The grid resolution is 40 cells/L with additional refinement zones around all buildings with 80 cells/L. The building edges within possible detachment zones are resolved with up to 146 cells/L. The boundary layer of the terrain and around the buildings is fully resolved by fulfilling the \( y^+ \approx 1 \) criterion. The forested area is entirely meshed with the same grid resolution, so in each cell the drag force term is applied individually for a realistic flow inside and around the forest.

The simulations are carried out with a turbulence intensity of 10% according to a neutral Atmospheric Boundary Layer (ABL) and higher turbulence due to scattered trees and buildings in the inflow zone since the Lidar measurements are conducted in the late winter and the wheater was dominated by inversions. The simulations have been performed with ANSYS
Fluent 18.1. The Improved Delayed Detached Eddy Simulation (IDDES) in combination with the incompressible k-ω SST turbulence model was used according to the approach by Gritskevich [9]. The momentum, the k− and ω−equations are solved by the third order MUSCL-scheme, for the time discretization the second order Bounded Central-Differencing scheme is used. The roughness height $z_0$ was neglected in the simulations and the velocity was zero at the ground. The inflow turbulence are generated using a synthetic turbulence generator, the Vortex Method which is already implemented in Fluent based on the work of Mathey et al. [18] and Sergent [19]. As the inflow boundary condition experimental LiDAR values are filtered by the median filter, mentioned above, and extrapolated onto the numerical inflow plane according to the Eqns. (7) and (8). For the side and the upper surfaces of the domain the so-called ’symmetry’ boundary condition was used in Fluent, that means all variables are forced to be parallel to the boundary plane at the surface. For the outlet a pressure-outlet boundary condition is used. The terrain and the building surfaces are all treated as a no-slip walls. For the Courant-Friedrichs-Lewy (CFL) number 0.25 is chosen.

In the present work two cases were studied. The first case includes the forested area in the domain with local tree heights depending on $x$ and $y$. The drag force is calculated with the $a(z)$-profile depending on the local tree height for LAI=3 as shown in figure 1. The foliage density remains constant over the computational domain. The second case is without any modelled forested area to investigate the influence of the forest on the local wind field. For both cases the same setup is used as mentioned above.

4. Results
In the following section the computational results will be analyzed and discussed in detail. The inflow zone in the simulations contains forest vegetation, buildings and complex terrain. The results of the turbulent flow field are validated with on-site LiDAR wind data. Furthermore, the impact of the modelled forested zone is investigated on how it changes the wind direction and wind velocities. They will be compared to the simulation results which neglected the forested zone. The geometries are normalized by the maximal tree height within the forest $H_{\text{max}}$.

![Figure 5. Height(z) of the complex terrain with forested zones, buildings and instantaneous streamwise velocity u.](image-url)

Figure 5 illustrates the computational domain with complex terrain, building geometries and forested zones. In total 18 buildings (grey) are considered in the simulations. The iso-lines show...
the different heights of the terrain. The maximum difference in altitude amounts 96 m. Thus, neglecting the complex terrain would lead to poor results. The figure also shows a plane with the instantaneous velocity in streamwise direction, showing a highly turbulent flow induced by the buildings. Negative velocities indicate backflow zones of detached flows behind the buildings. The numbers one to four represent the forested zones and show their positions in the domain. The black arrow at the bottom left part of the figure indicates the flow entering the domain. Hence, the forested zones are located in the inflow and the result indicates the significance to consider the forest in the simulations. The white point within the rectangle represents the position of the LiDAR measurement device.

Figure 6 shows the simulated velocity magnitude (red line) against the one obtained by the LiDAR measurement campaign (black squares) over the height at different downstream locations. The LiDAR velocity is averaged for 60 min while the numerical velocity magnitude is averaged for 4 min. Figure 7 illustrates the placement of the evaluation lines in the topography from $x/H_{t_{\text{max}}}=-10$ to $x/H_{t_{\text{max}}}=-4$ and at $y=0$. The inflow plane is located at $x/H_{t_{\text{max}}}=-12$ and the inflow profile is based on LiDAR data, as explained above. An evaluation further downstream is not possible, because a minimal distance to the LiDAR measurement device is required to ensure good quality results. During the measurement campaign it was placed on the top of a building at $x/H_{t_{\text{max}}}=0$, as shown in figure 5. Area 1 in figure 7 illustrates the zone in which the forest model is activated but not the local tree height used in the simulations. Area 2 in figure 7 represents some of the real buildings considered in the simulations. The evaluation lines at $x/H_{t_{\text{max}}}$ at -6 and -4 are located in front and shortly behind in the wake of a building. Thus, also the flow around it can be analyzed and validated. For all locations a very good qualitative and quantitative agreement is achieved between the simulated and the on-site measured velocity magnitude. At the lower measurement point the velocity magnitude in the simulations is a bit larger than the measured velocity magnitude. A possible explanation is the reconstruction process which calculates the 3D velocity components from the line of sight velocity. This may struggle with a highly turbulent flow induced by high surface roughness and obstacles. Furthermore, LiDAR does not measure a value at a certain point but measures the values within a control volume which can have a size of several meters. This can be problematic if the desired measurement point is close to forested zones or buildings. Looking closer to the numerical velocity lines some characteristic phenomena are observed at
the ground. The line at $x/H_{t_{\text{max}}}=-10$ passes through the forested zone. The velocity magnitude inside the forest reflects the drag force according to the $a$-profile for LAI=3 in the model, see figure 1. At the ground the velocity is higher due to a lower drag force because the foliage density of trees is lower towards the ground. With increasing foliage the crown the velocity increases due to higher drag forces. At the top of the forest a slight increase of the velocity is observed because local tree heights are considered in the model. Compared to a forest model with an uniform tree height, the top of the forest would be a plane resulting in a more sudden increase of the velocity. However, the adaption of the local tree height causes a much rougher surface at the top decelerating the flow. At $x/H_{t_{\text{max}}}=-8$ the flow almost leaves the forest. The tree heights at the boundaries are much lower than in the center as shown in figure 2. Thus, the drag force induced by the forest model is lower at the boundaries resulting in higher ground velocities compared to a sharper velocity cut using a fixed tree height. But the influence of the forest is still visible in figure 6. Moving further downstream to $x/H_{t_{\text{max}}}=-6$ the forest is left behind and the vicinity of the buildings is reached. In front of rectangular buildings or obstacles a characteristic horse show vortex is formed [20] which is also the case here. The profile of the velocity magnitude in figure 6 is typical for these kind of vortices. The line at $x/H_{t_{\text{max}}}=-4$ is located in the wake, directly behind the building. It is obvious that the flow cannot follow the vertical edges of the building and is separated here. Hence, the velocities within the wake are much lower which is also confirmed by the corresponding velocity profile. With increasing $z$ the impact of the forest vanishes.

Figure 8 shows the streamwise velocity over height evaluated at $x/H_{t_{\text{max}}}$ from -10 to 0 which is located above a high-rise building. While the red line represents the velocity without any considered forested zone, the black line shows the velocity distribution for the same inflow conditions but with all forested zones included as illustrated in figure 5.

![Figure 8. Streamwise velocities plotted over height with considered forested zones (black) against results without forest (red).](image)

In the evaluation only the flow until $x/H_{t_{\text{max}}}=0$ is considered, because behind the high-rise buildings the flow is mainly affected by the buildings. In the centre of the forest at $x/H_{t_{\text{max}}}=-10$ the impact of the forest is quite significant. Without the forest the velocity profile adopts a simple power law. As mentioned above, the velocity curve inside the forest has a mirrored shape as the drag force implemented according to the $a$-curve in figure 1. A similar behaviour can be observed at $x/H_{t_{\text{max}}}=-8$. The influence of the forest here is smaller than at $x/H_{t_{\text{max}}}=-10$.
because it is close to the border of the forest and the local tree height is lower than within the center resulting in lower drag forces and higher velocities. Figure 9 illustrates the computational flow field of the streamwise velocity $u$ combined with the located evaluation lines and figure 10 shows the velocity $u$ but with the forest included in the simulations. As can be seen the flow field around the forested zone is much lower with negative streamwise velocities and crossflow within the forest which has also been observed by Letzgus et al. [6].

At $x/H_{t\text{max}}=-6$, in both cases a small recirculation zone at the ground in front of the building is observed in figure 9 and 10, which is due to the characteristic horse shoe vortex [20]. But with the forest included it is slightly less pronounced. Since it is still located in the wake of the forest, the velocity is much lower until $z/H_{t\text{max}}=1.3$. Looking at the flow field at the top of the building which is located between $x/H_{t\text{max}}=-6$ and -4, the local, accelerating influence of the buildings, which is also observed by El Bahlouli et al. [2], is on a much lower velocity level if the forested zone is considered in the simulations. The reason is that the flow which hits the building has a lower velocity in the forest case than without. This is confirmed by the evaluation plot at $x/H_{t\text{max}}=-6$. Especially in respect of mounting small wind turbines on that building this fact is very important because it would lead to an unpredicted lower energy output. The line at $x/H_{t\text{max}}=-4$ shows the velocities directly behind the building in figure 8. In the recirculation zone the forest has a negligible impact but above the building height $u$ is lower with a smoother increase for the forest case. This also affects the flow at $x/H_{t\text{max}}=-2$ leading to lower velocities in the forest case. The recirculation zone at the ground is generated due to a flat building following behind as shown in figure 9. Above the high-rise building at $x/H_{t\text{max}}=0$ the flow is accelerated due to the sharp edge of the building which is also confirmed by El Bahlouli et al. [2]. Compared to the previous building at $x=5$, the acceleration zone is formed in both cases. Since the effect of the forested zone decreases with increasing $x$, figure 8 shows just a little higher velocity at lower height for the forest case. Independently of $x$, the influence of the forest disappears at heights above $z/H_{t\text{max}}=2$. A general prediction at what height the impact of forested zones can be neglected is very difficult, because also the complex terrain has a large contribution to the local flow field.

5. Conclusion
In this study the windfield in complex urban terrain is investigated at a test-site in Tübingen. Therefore, a forest model is implemented in ANSYS Fluent which includes local tree height adaption based on Laser scan data, depending on $x$ and $y$ coordinates of the domain. The local forest drag force and the associated wind speed reduction is according to the foliage density profile and depends on all three coordinates. Measured on-site LiDAR data have been used to
define the velocity profile of the inflow boundary condition. The required steps to preprocess the LiDAR data and their assumptions are explained in detail. Therefore, a linear median filter is extended and adapted for LiDAR wind data to detect and replace outliers and unphysical measurement data.

Considering the modelled forested areas combined with complex terrain and real building geometries, simulations are performed. Their results are compared with on-site LiDAR data at various locations above forested zones and buildings. A very good qualitative and quantitative agreement is achieved for all locations. That means that besides the entire computational setup also the forest model is validated and shows good results. A further simulation is performed which neglected the forested zones to analyze the influence of forested areas on the local flow field. Its impact is quite significant, e.g. the flow separation zone combined with an acceleration zone above a building is on a much lower velocity level if the forest is considered in the simulations. But with increasing distance to the forest, the flow is more and more dominated by the buildings. On the top of a high-rise building a strong separation of the flow with high velocity gradients is observed. With regard to small wind turbines, the location has to be chosen carefully here. If it is mounted to low, directly on the roof top, the energy yield would be quite low, since there is a recirculation zone with low velocities. Increasing the height of the wind turbine, high velocity gradients lead to unbalanced loads and higher damages. A general statement is difficult to make because the location is always related to the specific terrain, building and vegetation.

Acknowledgments
This work was performed within the interdisciplinary Joint Graduate Research Training Group ”Windy Cities” in cooperation with the University of Stuttgart, the Hochschule für Technik Stuttgart and the Hochschule Esslingen. The authors also thank the Eberhard Karls University Tübingen for providing wind measurement data and the permission for the Lidar measurement campaign. The computational resources were provided by the bwUniCluster funded by the Ministry of Science, Research and Arts and the universities of Baden-Württemberg, Germany, within the framework program bwHPC and the High-Performance Computing Center Stuttgart (HLRS) within the project WEALoads.

References
[1] Yang A-S, Su Y-M, Wen C-Y, Juan Y-H, Wang W-S and Cheng C-H 2016 Applied Energy, 171 pp 213–30
[2] El Bahlouli A and Bange J 2018 Green Energy and Technology, pp 1–15
[3] Ledo L, Kossash P B and Cooper P 2011 Renewable Energy 36 pp 1379-91
[4] Yoshi R, Mochida A, Tominga Y, Kataoka H, Harimoto K, Nozu T and Shirasawa T 2007 J. Wind Eng. Ind. Aerodyn. 95 pp 1551-78
[5] Schulz C, Klein L, Weising P, Lutz T and Krämer E 2014 J. Phys.: Conf. Ser. 524 012134
[6] Letzgus P, Lutz T and Krämer E 2018 J. Phys.: Conf. Ser. 1037 072043
[7] Blocken B 2014 J. Wind Eng. Ind. Aerodyn. 129 pp 69-102
[8] Toja-Silva F, Kono T, Peralta C, Lopez-Garcia O, Chen J 2018 J. Wind Eng. Ind. Aerodyn. 180 pp 66-87
[9] Gritskевич M, Garbaruk A, Schütze J and Menter F 2012 Flow, Turbulence and Combustion 88 pp 431-49
[10] Shaw R H and Schumann U 1992 Boundary-Layer Meteorology 61 pp 47-64
[11] Bequet R, Campioli M, Kint V, Vansteenkiste D, Muys B and Ceulemans R 2011 Springer 25 pp 935-46
[12] Goude M, Nilsson U and Holmaström E 2019 European Journal of Forest Research 138 pp 1033-47
[13] Jähne B 2012 Digitale Bildverarbeitung (Berlin Heidelberg: Springer)
[14] Schatzmann M and Leitl B 2011 J. Wind Eng. Ind. Aerodyn. 99 pp 169-86
[15] Davenport A G 1960 Wind Loads on Structures (Ottawa: National Research Council of Canada. Division of Building Research)
[16] Franke J, Hellsten A, Schluens H and Carissimo B 2011 Int. J. Env. and Pollut. 44 pp 419–27
[17] Rau I M and Bigalke K 2007 Landesanstalt für Umwelt, Messungen und Naturschutz Baden-Württemberg
[18] Mathey F, Cokljat D, Bertoglio J P and Sergent E 2003 Int. Symp. on Turbulence, Heat and Mass Transfer
[19] Sergent E 2002 PhD thesis L’Ecole Centrale de Lyon
[20] Hucho W-H 2012 Aerodynamik der stumpfen Körper (Wiesbaden: Vieweg und Teubner)