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Table of Contents

Table of Figures

Table of tables

Executive Summary

This report documents the approach and methodology for dynamical downscaling of wind impacts, which is employed in the simulations performed for the YADES project. The key elements of this approach can be summarized as:

- ✓ High-resolution large-eddy simulation approach is the most suitable modelling technique for risk assessments strategies requiring detail gust predictions
- ✓ Large-eddy simulations need to be pre-computed for a representative set of meteorological conditions to form a data set
- ✓ Detailed high-resolution data in the database can be rescaled to estimate any prevailing large-scale meteorological conditions by using state information for example from a numerical weather-prediction model

1 Introduction

YADES is a H2020 framework project (funded under grant agreement 872931) whose objective is to incorporate a state-of-the-art research framework into the field of resilience analysis concerning Cultural Heritage (CH) areas, historic cities and related infrastructure that are vulnerable to Climate Change (CC) and other types of environmental hazards. Such hazards entail not only events with immediate impact such as earthquakes, floods, landslides, and violent storms, but also more frequent events that accumulate their risk over time acting as a continuous stressor on the structure.

Wind is an atmospheric stressor, which can inflict immediate hazard (during a storm) or exert its strain over extended periods of sustained but temporally intermittent loading that owes to its fluctuating and gusty i.e., turbulent nature. The challenge in predicting wind related hazards lies in the complex nature of atmospheric turbulence and the sensitivity of local wind conditions to the surrounding topographic details e.g., hills, buildings, vegetation, etc. This complexity makes it necessary to rely on high-resolution modelling approaches that can capture the meaningful differences in the application-specific flow physics. Large-eddy simulation (LES) is a modelling approach where the relevant turbulent motion is resolved both in space and time, exploiting simpler parametrization only for the small-scale motions that are universal in nature and, therefore, amendable to parametrization. In this project PALM LES model is used to carry out the turbulence simulations for the chosen cultural heritage and critical infrastructure pilot sites.

This report documents the downscaling approach and related modelling methods employed in the YADES project. Here, both theoretical and practical fundamentals are laid out. An example simulation layout and examples of downscaled results are presented at the end of the deliverable. The downscaled wind time series are subsequently utilized in the risk and damage analyses involving risk maps, and specific damage functions for both short- and long-term studies.

2 Methods and Procedures

This section presents the relevant theoretical and numerical developments required by the downscaling methodology for wind related hazards. First, the essential elements of the PALM LES model are introduced followed by a description of the atmospheric boundary layer (ABL) turbulence simulation procedures, which take into account the effect of the site-specific terrain and topography. Then, downscaling-specific practises to set up the computational model for a target site are discussed. Finally, the downscaling procedure itself is described.

2.1 PALM LES Model

The PALM LES model (Maronga et al., 2015; 2020) is a finite-difference flow solver for atmospheric and oceanic flows. The model is capable of resolving the effect of complex terrain, buildings and vegetation on the flow. PALM is based on the non-hydrostatic, filtered, Navier-Stokes-equations in the Boussinesq-approximated or anelastic form and it is designed to run efficiently in supercomputing environments. The dynamic solver core of PALM time-integrates the prognostic equations for the conservation of momentum, mass, energy, and moisture on a staggered Cartesian Arakawa-C grid. The effect of subgrid-scale turbulence on the resolved flow field is parameterized using a 1.5-order closure after Deardorff (1980) with modifications according to Saiki et al. (2000). Discretization in time is achieved by using a 3rd-order Runge-Kutta scheme in accordance with Williamson (1980) and spatial discretization for the advection terms is implemented with 5th-order advection scheme after Wicker and Skamarock (2002). The horizontal grid spacing is always equidistant, whereas gradual stretching is permitted in the vertical direction. The vertical grid spacing is typically set equidistant within the atmospheric boundary layer (ABL) and, to save computational time, the stretching is only applied above the ABL in the free atmosphere. The lateral domain boundaries of the computational model are by default cyclic, but advanced non-cyclic inflow and outflow boundary conditions are implemented as well. The current versions of PALM have been implemented with a LES-LES self-nesting capability (Hellsten et al., 2021). This feature is essential in downscaling applications where the effect of large-scale atmospheric turbulence on local urban wind conditions must be included. For further details on the model, see Maronga et al. (2015; 2020).

2.2 LES Modelling Approach

Wind downscaling usually requires LES data of very high spatial resolution, especially in urban and other built environments where the surface-layer wind flow is strongly influenced by the buildings, street canyons and other features of the built environment, which are typically of relatively small scale. For instance, resolving turbulent wind flow within a street canyon adequately requires a LES grid spacing of the order of one metre while in non-built environment with complicated terrain shape, about 5 m grid spacing is usually sufficient. On the other hand, the modelling domain must be larger than the large turbulent flow structures within the ABL. This usually means that the horizontal domain size must be of the order of ten kilometres or in some cases of hundred kilometres. It is impossible to cover such large areas with very high-resolution grid. Therefore, we concentrate the highest resolution into the areas of principal interest and their vicinity and use coarser resolution elsewhere. As the PALM model has constant horizontal grid spacing within a domain, we use an LES-LES self-nesting approach implemented in PALM (Hellsten et al., 2021). In this method the model set up consists of several LES-domains nested in each other and coupled dynamically. A smaller child domain with higher resolution is nested within its larger, lower-resolution parent domain. Child domains can act as parents for yet smaller child domain forming a cascade of nested domains. Child domains and cascades of children can also be set up parallel to each other. An example of a nested setup is given in Section 3. The outermost and largest domain of lowest resolution is referred to as the root domain. For the root domain, boundary conditions are needed on all boundaries, but for the child domains, explicitly set boundary conditions are needed only on the bottom boundary, which follows the terrain and building surfaces. This is because the boundary conditions for the other boundaries are interpolated from the parent solution at each time step as part of the coupling procedure.

The bottom surfaces of the domains follow the terrain and building surfaces. This information is input in the PALM LES model in the form of 2-D raster arrays including the terrain and building height for each vertical column of LES-grid cells. The raster data is input in the NetCDF format. The grid cells under the solid surface, terrain or building, are eliminated out from the numerical solution procedure, i.e., inactivated. Boundary conditions are set on all interfaces between active and inactive grid cells. The boundary conditions on horizontal grid-cell faces are based on the Monin-Obukhov similarity theory. Under neutral stratification these boundary conditions reduce to the logarithmic law of the wall conditions that are also applied to vertical solid surfaces. The effect of sub-grid-scale roughness is taken into account by an estimated roughness length that is set proportional to the grid spacing such that with lower resolution a higher roughness length is set. A more detailed description of the solid-surface boundary conditions is found in Maronga et al. (2015).

The effect of vegetation is modelled as a momentum sink term depending on flow velocity, prescribed canopy drag coefficient, and Leaf Area Density (LAD) distribution input as a three-dimensional array. A corresponding sink term is also added in the transport equation of the sub-grid scale turbulent kinetic energy. Details are found in Maronga et al. (2015).

The simulations are initialized by first running a precursor simulation for the root domain only for a sufficiently long time, typically several hours, to pass all initial transients and to achieve a statistically stationary flow state. The precursor run is initialized simply by specifying horizontally constant vertical profiles for the flow variables throughout the domain. The motivation to run precursor simulations without the nest domains is to save computing time and capacity. With the low-resolution root domain only, the time steps can be set considerably larger, following the Courant-Friedrichs-Levy (CFL) criterion, than with the full nested setup, and precursor simulation thus runs much faster. The actual LES run including all the nest domains is then started from the stored final time step solution of the precursor run. The actual run also needs a short adaptation time before the data sampling can be started because the higher-resolution solutions within the nest domains require some time to adapt to their higher resolution from their local lower-resolution initial states set by interpolating from their parent solutions.

As the nesting method allows the use of large root domains, we take the advantage of employing cyclic boundary conditions at the side boundaries. This is more straightforward than using non-cyclic inflow/outflow conditions combined with some method to generate turbulent motion at the inflow boundary. Obviously, the cyclic conditions do not usually fully reflect the real situations, but this does not introduce any significant error to the solution around the area of interest as the cyclic boundaries are set sufficiently far away from it. Near the cyclic boundaries, terrain shape and possible buildings must be flattened out. Top boundary conditions are set in a simplified way by just setting a slip-wall condition at the top boundary. The slip-wall conditions for the velocity field mean that the vertical velocity component is set to zero and the vertical derivative of horizontal components set to zero allowing horizontal flow (Neumann condition). Therefore, the ABL height in the simulations is dictated by the domain height. A more realistic way would be to specify the initial potential temperature profile such that the upper part of the domain features a temperature inversion layer, which forms a natural ceiling for the ABL. We have observed that the surface-layer results are not sensitive to the top boundary conditions and not even to the ABL height (Auvinen et al., 2020). The slip-wall method is computationally more affordable and avoids the solution of potential temperature in case of neutral stratification.

Unlike inflow condition, the cyclic boundary conditions do not drive the wind flow. Therefore, the wind flow must be forced in one way or another or else the wind flow would die out gradually. We apply a constant volume force in the upper part of the domain to maintain constant total momentum in the domain.

2.3 Downscaling Procedure

Our approach to downscale wind fields to very local scale and high resolution is based on fusing pre-computed high-resolution LES data and larger-scale information such as data from a Numerical Weather Prediction model (NWP) or observations from a nearby meteorological station. LES data provides the high-resolution information and brings in the small-scale effects of terrain shape, buildings, and vegetation. The larger-scale information provides the temporal large-scale state of the wind direction and speed at some selected point in the downscaling domain. This is hereafter referred to as state information.

Statistically stationary LES simulations must be carried out for a set of representative meteorological conditions. Typically, such set includes twelve 30-degree wind sectors to cover all mean-wind directions. The LES simulations are run with a nominal wind speed recorded and time averaged during the LES run at a reference point (or points) corresponding to the location(s) of the state information (for example a grid node of an NWP model or location of a meteorological station). It is assumed that the LES wind fields can be rescaled to any prevailing wind speed specified by the state information. The scalability is strictly justified only for neutrally stratified ABL, but we assume that the errors introduced by the scaling under non-neutral conditions are reasonably small, especially in heavy-wind conditions, which are the most relevant situations when it comes to wind hazards. We have so far limited the precomputations to neutrally stratified cases only. During the LES runs time and space dependent wind fields are output from each LES run for selected sub-domains depending on the purpose of the downscaling and stored to form a set of data units covering the representative meteorological conditions.

In the data-fusion phase the state information time series and the LES data are combined to obtain time series of three-dimensional wind field having high-resolution in both space and time. The temporal resolution of the state information is typically much lower than that of the LES. For instance, the wind observations are usually available as ten-minute averages. The temporal resolution of the state information depends on its source, and possibly also on the purpose of the downscaling. Typically, the state information provides the wind direction and speed in only one point in space for each state information time interval. For each state time interval, the best matching meteorological condition data unit is retrieved from the LES data set. This LES data is then rescaled using the ratio of the state wind speed of the current time interval and the nominal LES wind speed at the same spatial point. Downscaled wind forecasts can be produced this way to a given target site for example by employing wind data in a specified grid node of an NWP model as the state information. Unlike the NWP-based forecast, such downscaled forecast will include the various complicated effects from the local small-scale complexities of the terrain shape, built environment and vegetation depending on the level of detail of the LES simulations. An example of a downscaling application to mountainous terrain near Guadalajara, Spain from a previous project is given in Figure 1.

The fusion method involves the assumption of pseudo-stationarity because each LES data unit is a statistically stationary time-series of the particular meteorological condition it represents. Therefore, the final result is a time series made up by combining a number of stationary LES-data intervals of length equalling the state-information interval. The changes from one interval to another are discontinuous. This is not entirely realistic since also the large-scale changes of the meteorological conditions driving the small-scale dynamics are dynamic. However, this simplification is unavoidable as long as the downscaling is based on pre-computations.

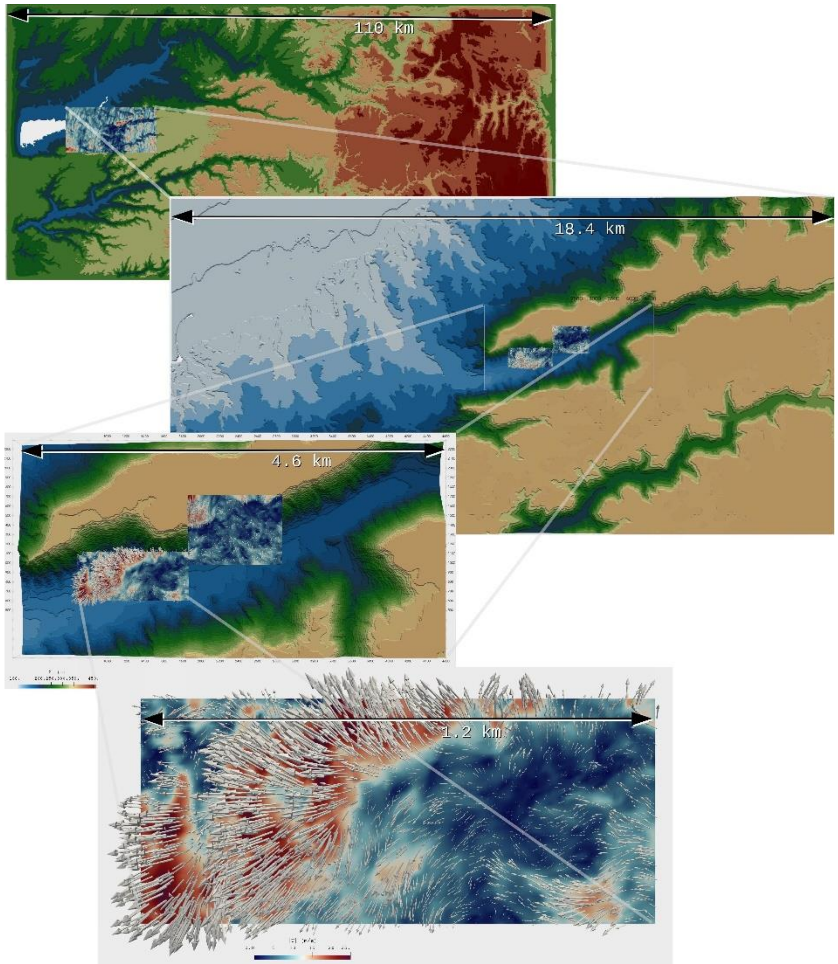

Figure 1. An example of a downscaling application to a mountainous-terrain site near Guadalajara, Spain. The terrain height in the whole domain 110 km by 55 km (the top picture) is shown by colours followed by zoom-in pictures and the target area (the bottom picture). The vector arrows show an instantaneous snapshot of the downscaled near surface wind. The higher-level mean wind in this situation is northerly (15 degrees). Note how the instantaneous surface wind is from almost opposite direction in parts of the site due to the complex terrain effects.

3 Application example: Rhodes critical infrastructure

The island of Rhodes (Greece) is highly touristic with significant cultural heritage, deriving the majority of its income from visitors during early April to late October. By virtue of being an island, it is highly sensitive to disruption of operations in its port, airport, and public utility facilities. To explore such critical infrastructure of Rhodes the LES modelling setup covers the whole island and two target areas, see Figure 2. The selection of critical infrastructure to be studied and the problem formulation has been designed in collaboration with Environmental Reliability and Risk Analysis (ERRA) and National Technical University of Athens (NTUA). The island is in the middle of the root domain with enough sea area around it to allow the use of cyclic boundary conditions without any significant artificial effects. Total size of the root domain is 61400 m × 76800 m × 2880 m. Nested sub-domains with more accurate resolution were used for the target areas of the civilian airport and the Kattavia wind park, and in addition for the meteorological-station site in Lindos. Table 1 gives the dimensions and specifications of the root domain and all nested domains. In this case, no urban or other densely built target sites are involved. Instead, the effects of terrain shape are of interest in this case. Therefore, buildings and vegetation are not modelled.

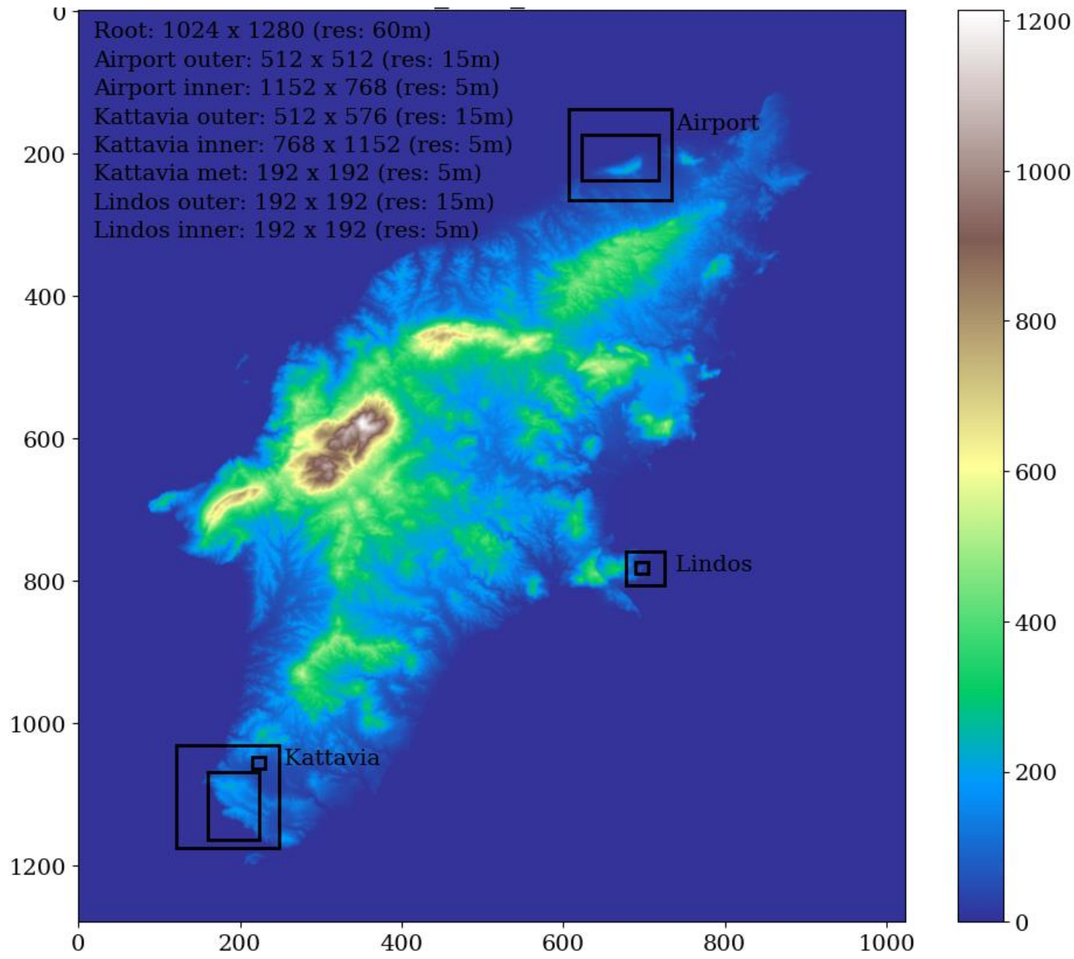

Figure 2. Rhodes root domain and nested domains. Kattavia target site consists of two inner nest domains. One for the wind park and another, smaller one for the meteorological station.

Table 1. Rhodes root and nest domain dimensions and specifications. Numbers of grid points in each direction are denoted by nx, ny and nz and the grid spacings by Δx, Δy and Δz. Lx, Ly and Lz are the domain dimensions and z0 is the sub-grid-scale surface roughness length.

Domain	Id	*nx*	*ny*	*nz*	*Δx, Δy* (m)	*Δz* (m)	*Lx* (m)	*Ly* (m)	*Lz* (m)	*z*0 (m)
Rhodes island	ROOT	1024	1280	96	60	30	61440	76800	2880	0.5
Airport outer	N02	512	512	96	15	10	7680	7680	960	0.2
Airport inner	N03	1152	768	128	5	5	5760	3840	640	0.1
Kattavia outer	N04	512	576	96	15	10	7680	8640	960	0.2
Kattavia inner	N05	768	1152	128	5	5	3840	5760	640	0.1
Kattavia met	N06	192	192	64	5	5	960	960	320	0.1
Lindos outer	N07	192	192	64	15	10	2880	2880	640	0.2
Lindos inner	N08	192	192	64	5	5	960	960	320	0.1

Rhodes airport is selected as one of the target sites in YADES due to its importance for the island and its challenging wind conditions under certain meteorological situations. The airport is located between the sea and a relatively steep-sloped ridge about 270 m high parallel to the runway, see Figure 3. Under certain meteorological situations, the ridge causes difficult gusty wind conditions over the runway and along the final approach path thus making landings difficult, even dangerous. Such wind conditions occur mostly in wintertime while low pressures pass over Rhodes. Under such conditions the airport must be closed. This work examines the flow conditions in the final-approach areas at both ends of the runway. The aim is to develop an operational model for predicting the landing conditions for safe and efficient airport operation. LES-modeling results are collected from both ends of the runway from the final-approach path over a length of about 2 km and up to 150 m altitude with a spatial data-recording resolution of 10 m in the *x*- and *y*-directions and 5 m in the *z*-direction. Wind-velocity components are recorded in all these points with 2 s temporal resolution. These LES results will be downscaled using both local wind observations and NWP data as state information. Using NWP data as state information, short-term downscaled wind predictions can be produced. This downscaled wind information can be used to operationally model the landing wind conditions. Furthermore, it is expected to lead to a deeper understanding of the dynamics of severe local wind episodes. The resulting LES-data set can also be used for downscaled climatological predictions by employing climate model predictions as the state information. Such predictions could reveal the role of climate change in the future operability of Rhodes airport.

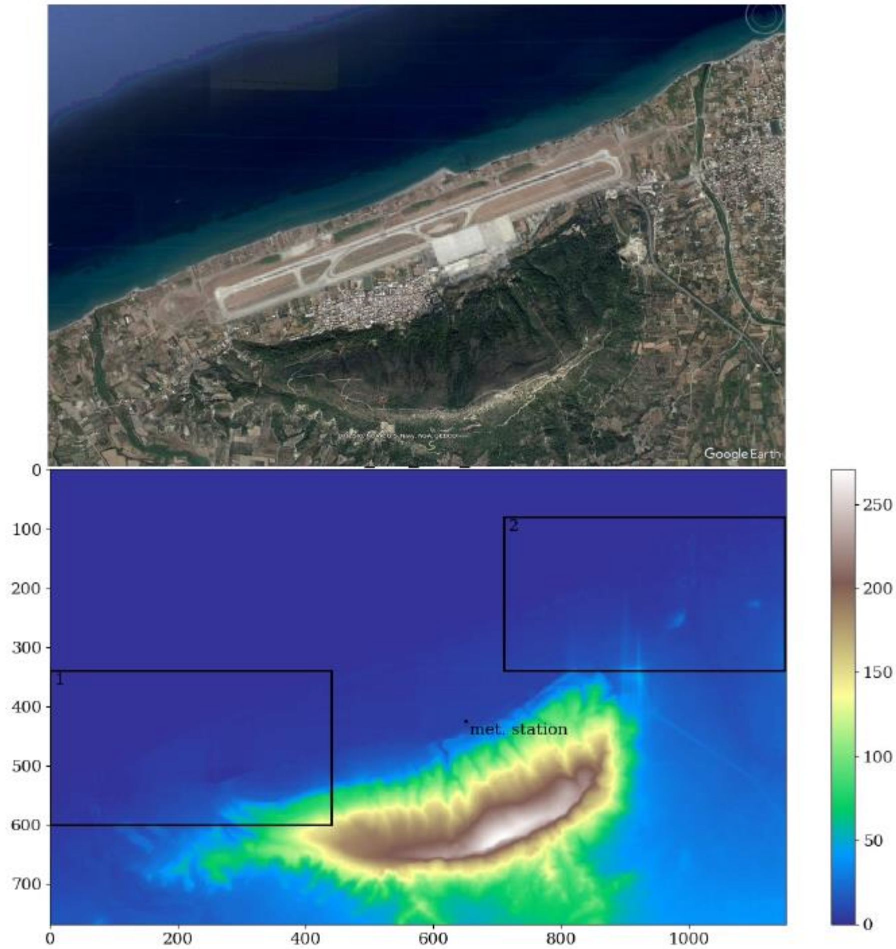

Figure 3. The location of Rhodes airport on the Google Earth satellite image (upper) and the airport inner nest domain with data-recording domains covering the latest about 2 km of the final-approach paths of the runways 06 and 24 and the meteorological station (lower). Terrain height (m) is shown by colour in the lower figure.

In the southern part of the island is located one of the most important energy-production sites of Rhodes, the Kattavia wind park, and the starting point of the main power line that extends to the northern part of the island. The Kattavia wind park is located in an area with very demanding wind conditions. The energy production capability of the site has suffered from several outages due to featherings (shutdowns) of wind turbines due to exceedances of the maximum allowed wind speed, and even due to wind-induced collapse of power-line towers. There are currently 15 relatively small wind turbines in the area, but they are planned to be replaced by larger and more efficient power plants in the future. As the technical information of the future turbines is not available for this study, we use the technical information of the NREL 5-MW reference wind turbine (Jonkman et al., 2009). Its hub height is 90 m and rotor-disk diameter 126 m. Wind turbines of the size in question must be placed at least 600 m (five disk diameters) apart from each other to avoid excessive wake interference. No plan of the wind park's future layout is currently available, so, for modeling purposes, seven turbines are virtually positioned in the park area in accordance with the layout shown in Figure 4. The wind-velocity data for each turbine is collected in a cubical output domain covering the rotor disk at all yaw angles with a 5 m × 5 m × 5 m spatial output resolution and with temporal resolution of 2 s. In addition, wind data is collected with 25 m horizontal, 5 m vertical and 2 s temporal resolutions in two output domains covering parts of the power line near the turbines 5, 6 and 7, see Figure 4. Within these domains, the power line crosses relatively steeply varying terrain and thus is expected to be exposed to strong wind hazard.

The LES wind-velocity data is also collected at the meteorological measuring station of both target sites (airport and Kattavia) in the form of vertical profile with 5 m resolution, so that the LES results can be rescaled according to the state information as described in Section 2.3. The meteorological-station site in Lindos is also included as a backup station for possible cases with missing data in airport or Kattavia stations.

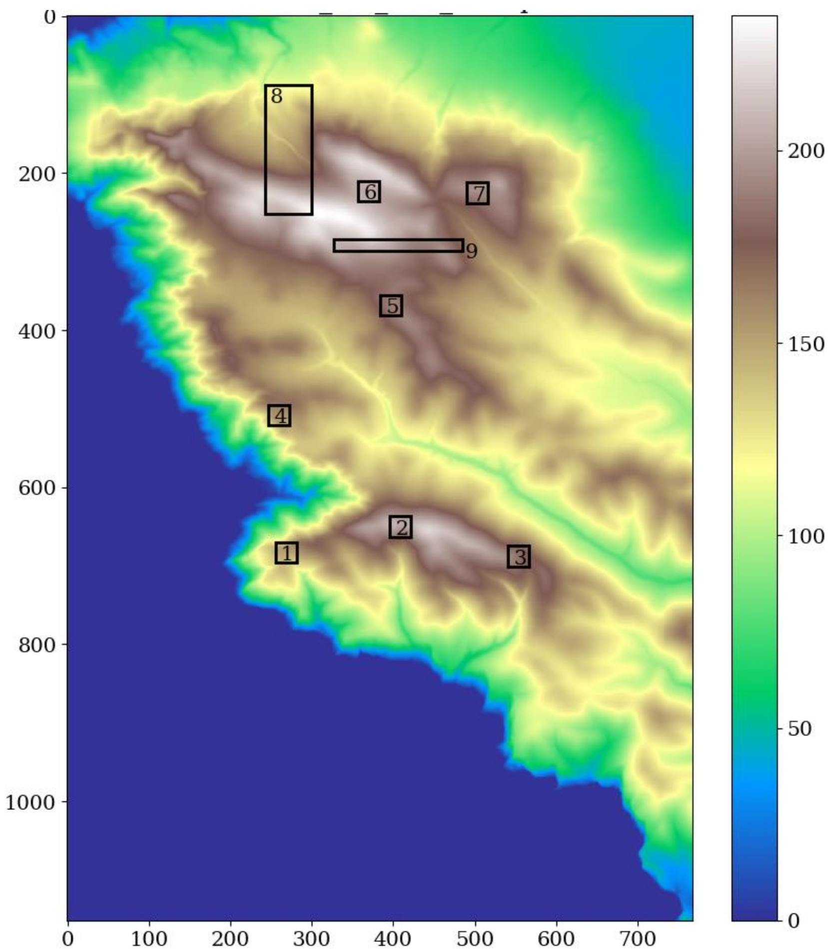

Figure 4. The virtual positioning of seven NREL 5-MW wind turbines at the Kattavia wind park (squares 1-7) and two selected parts along the power line (rectangles 8 and 9). Terrain height (m) is shown by colour.

For each target site LES modelling result contains a collection of turbulent wind speed datasets for each 30-degree wind sector. The datasets contain high-frequency time series for all wind components. The spatial shape and size of the output domains depends on the application. The spatial variability of wind characteristics is demonstrated in Figure 5 by showing a two-hour section of downscaled wind speed data in three different locations separated by just a few hundreds of metres from each other. The differences in the mean wind speed and turbulent fluctuations between the points are due to the complex terrain effects.

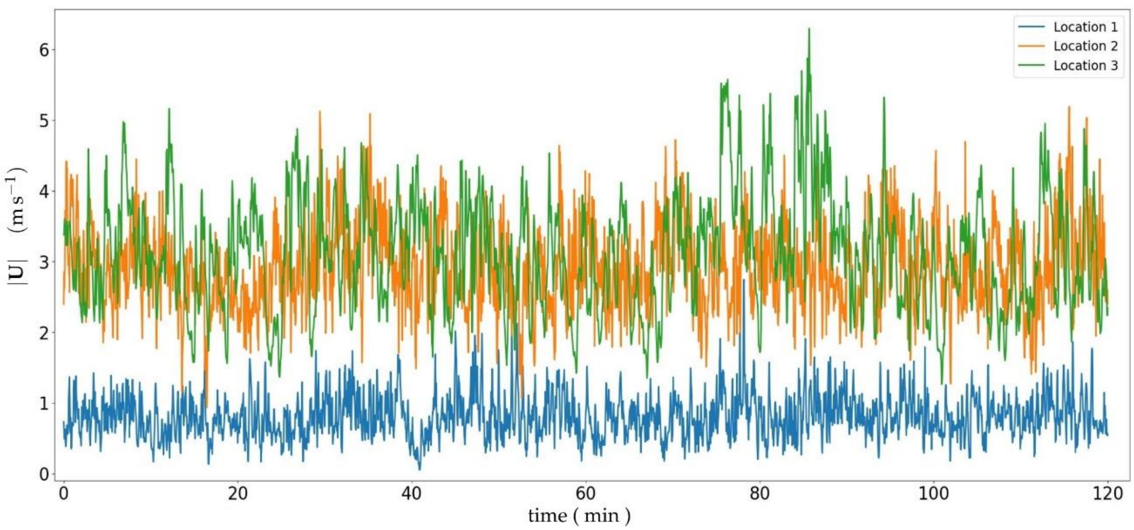

Figure 5. An example of downscaled wind speed timeseries for three different locations close to each other. The differences in the mean wind speed and turbulent fluctuations between the points are due to the complex terrain effects.

4 Conclusion

This report describes our wind downscaling approach and related methods utilized in the YADES project and gives an application example. The downscaling is based on pre-computed high-resolution LES data sets and larger-scale state information, which may be wind observation data, wind data from a numerical weather prediction model (NWP) or climate modelling data.

Complex terrain shape, built environment, and forest canopies tend to make the wind characteristics spatially highly variable, complex, and dependent on the details of the surface morphology. Such variability cannot be predicted by NWP models or any large-scale models. Moreover, observations do not usually capture such variability, because meteorological stations are sparsely located. Therefore, downscaling to high spatial and temporal resolutions is necessary to assess and understand wind-related risks of various assets.

The results are expected to enable the accurate calculation of wind hazard for cultural heritage sites, allowing users to explore not only issues of physical damage, but also of the all-important indirect losses due to loss of functionality due to operation disruption.

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