Ploto

D3.2

Report on the dynamical downscaling of climate and atmospheric impacts 1st version

Project name

Deployment and Assessment of Predictive modelling, environmentally sustainable and emerging digital technologies and tools for improving the resilience of IWW against Climate change and other extremes

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List of abbreviations and acronyms

Abbreviation	Meaning
ABL	Atmospheric Boundary Layer
AFDJ	Galati Lower Danube River Administration
AUTh	Aristotle University of Thessaloniki
BME	Faculty of Transportation Engineering and Vehicle Engineering
BSZL	Freeport of Budapest Logistics Ltd
CFL	Courant-Friedrichs-Levy criterion
COP	Common Operational Picture
CORDEX	Coordinated Regional Climate Downscaling Experiment
EURO-CORDEX	The European branch of the international CORDEX
EZM	European Zooming Model system
FMI	Finnish Meteorological Institute
GCM	Global Climate Model
HadGEM2	Hadley Centre Global Environment Model version 2
HRAP	Holistic Risk Assesment Platform
ICHEC	Irish Center for High-End Computing
ICON	ICOsahedral Nonhydrostatic (the global NWP model of Deutcher Wetterdienst)
ICON-EU	Nested regional ICON model for Europe region
IWAT	IWW Assesment Tool
IWW	Inland Water-Way
IMS	Incident Management System
LAD	Leaf-Area Density
LES	Large-Eddy Simulation
LU	Land Use
MAV	Hungarian Railway Services
MOHC	Met Office Hadley Centre
MPI-M	Max Planck Institute for Meteorology
MPI-ESM-LR	Max Planck Institute Earth System Model Low Resolution
NetCDF	Network Common Data Form
NWP	Numerical Weather Prediction model
OMS	Operational Meso-scale modelling System
PDF	Probability Density Function
RACMO	Regional Atmospheric Climate MOdel
RCA4	Rossby Centre regional Atmospheric model version 4
RCM	Regional Climate Model
RCP	Representative Concentration Pathway

RORO	ROll in / ROll out
RSOE	National Association of Radio Distress-Signalling and Infocommunications
SPW MI	Service Public de Wallonie
SRTM	Shuttle Radar Topography Mission
TKE	Turbulent Kinetic Energy
UAV	Unmanned Aerial Vehicle
UDG	Danubius University of Galati
ULiege	Université de Liège
UM	University of Maribor
UTC	Coordinated Universal Time
WP	Work Package

Executive Summary

This report, titled "D3.2 -- Report on the dynamical downscaling of climate and atmospheric impacts 1st version", presents the downscaling approaches and methods developed and employed for large-scale climatological and meteorological data in the PLOTO project Task 3.3. The large-scale data originates from Regional Climate Model (RCM) predictions for the future climate scenarios and from Numerical Weather Prediction (NWP) model data for short term forecasts. The selection of the climatological data from the EURO-CORDEX database has been reported in the deliverable report D3.1. The short-term data to be downscaled is obtained from the ICON-EU NWP system. Downscaling of the future climate projections addresses the STO 2 of PLOTO "Reliable quantification of climatic, hydrological and atmospheric stressors", and the short-term downscaled forecasting addresses the STO 3 "Development of a forecasting module to provide high-resolution tailored weather and precipitation forecasts".

We describe also the PLOTO use cases and their relevant weather vulnerabilities and hazards as a basis for selecting the data to be downscaled and designing the sets of resulting downscaled data.

As the resolutions of the RCM and NWP models are relatively low, they cannot capture any effects of local small-scale features of specific sites of interest like fine-grained terrain shape, buildings and trees. Therefore, the data must be downscaled to local scale and high resolution so that the effects of the local features are properly captured.

We apply two downscaling approaches. For wind data, we apply an approach based on precomputed very high resolution Large-Eddy Simulation (LES) data and data fusion. For other meteorological variables of interest: temperature, relative humidity, cloud cover and precipitation we apply high-resolution meso-scale modelling. We also present two examples of downscaling. All the downscaling tasks for all use cases, their specific features and the results will be presented in the report D3.3.

The downscaled RCM data for future-climate scenarios will be used as input to Task 3.6 for the assessment of the site-specific climate risk parameters and stressor indicators. In WP4, downscaled climatic projections will be used for infrastructure resilience assessment. The short-term downscaled forecasting systems developed here will be used in Task 3.4 to obtain tailored forecasts for the use case sites for the needs of dynamical data assimilation in Task 3.5 and in WP6 to support IWAT, Decision support system and Enhanced Visualization Interface.

1. Introduction

1.1 Project information

The project entitled **"Deployment and assessment of predictive modelling, environmentally sustainable and emerging digital technologies and tools for improving the resilience of IWW against climate change and other extremes (PLOTO)"** aims at increasing the resilience of the IWW and the connected hinterland infrastructures, especially under adverse conditions, such as extreme weather, accidents, and other kinds of hazards. In doing this, downscaled climate change scenarios will be combined with simulation tools and actual data, to provide operators an integrated tool able to support more effective management of their infrastructures at strategic and operational levels.

PLOTO project consists in the deployment and assessment of predictive modelling, environmentally sustainable and emerging digital technologies, and tools for improving the resilience of IWW against climate change and other extremes. An integrated tool is set up to allow relevant authorities to improve the efficiency of their infrastructures management. This tool is a combination of downscaled climate change scenarios with simulation tools and actual data. Six complementary avenues will be considered to achieve this integrated tool that will support relevant authorities and their operators for more effective management:

- Measure and use high-resolution modelling data for the determination and assessment of the climatic risk of the selected transport infrastructures and associated expected damages.
- Use existing data from various sources with new types of sensor-generated data (computer vision) to feed the used simulator.
- Utilise tailored weather forecasts (combining seamlessly all available data sources) for specific hot spots, providing real-time early warnings with corresponding impact assessment.
- Develop improved multi-temporal, multi-sensor UAV- and satellite-based observations with robust spectral analysis, computer vision and machine learning-based assessment for diverse transport infrastructures.
- Design and implement an integrated resilience assessment platform environment as an innovative planning tool that will permit a quantitative resilience assessment through an end-to-end simulation environment, running "what-if" impact/risk/resilience assessment scenarios. The effects of adaptation measures can be investigated by changing the hazard, exposure, and vulnerability input parameters.
- Design and implement a Common Operational Picture (COP), including an enhanced visualisation interface and an Incident Management System (IMS).

The PLOTO integrated platform and its tools will be validated in three case studies in Belgium, Romania and Hungary.

1.2 Purpose of the deliverable

Downscaling of the future climate projections addresses the STO 2 of PLOTO "Reliable quantification of climatic, hydrological and atmospheric stressors", and the short-term downscaled forecasting addresses the STO 3 "Development of a forecasting module to provide high-resolution tailored weather and precipitation forecasts". The purpose of this deliverable report D3.2 is to describe the downscaling approaches, methods and procedures. Wind data is downscaled based on high-resolution

Large-Eddy Simulation (LES) modelling and data fusion while other meteorological variables: temperature, relative humidity, cloud cover and precipitation are downscaled based on high-resolution meso-scale modelling. This report describes not only the methodology for downscaling the RCM-predicted future climate data, but also a methodology for producing short term (for instance 24-72 hours) downscaled forecasts to the target sites by automatically on-line downscaling predictions of Numerical Weather Prediction Model (NWP). The motivation for the downscaling is to bring in the local effects of local small-scale features, such as fine-grained terrain shape and even buildings and trees. Such effects can be important when assessing the risks and vulnerability of assets, functions and operations, and they are not at all captured by RCMs and NWPs. This report presents and explains the methodology, providing two preliminary examples. Final outcomes for all use cases will be part of Deliverable D3.3 with the detailed downscaling tasks per use cases and a description of the specific features in the procedures.

1.3 Intended audience

The primary audience of this deliverable report consists of the PLOTO partners involved in the tasks exploiting the final downscaled data and results obtained using the methods reported here, see Sec. 1.4. The secondary audience is the whole PLOTO consortium. And as the dissemination level of this report is “Public”, it is open to any interested audience.

1.4 Structure of the deliverable and its relation with other work packages/deliverables

The Deliverable is structured as follows:

Section 1. Describes PLOTO’s aim, as well as this document’s purpose, intended audience and structure.

Section 2. Describes the context and general methodology of this Deliverable.

Section 3. Describes the modelling approaches and techniques for the downscaling.

Section 4. Presents the target sites of each use case and the use-case specific relevant climatic stressors, which in turn determine the detailed specification of the data to be downscaled.

Section 5. Presents preliminary examples of the downscaling procedures and results.

Section 6. Concludes the Deliverable by summarising the main outcomes.

The outcomes of Task 3.3 will be used as input to Tasks 3.4, 3.5, 3.6, as well as WP4 and WP6, as described in Section 2.

2. Methodology

This deliverable report (D3.2) is the second part in the "trilogy" of D3.1, D3.2 and D3.3. D3.1 described the Regional Climate Model (RCM) predicted climate data to be downscaled to very high local resolution. D3.2 reports the first part of the Task 3.3 work, the downscaling methods an d procedures while D3.3 will report the final outcomes of the tasks per use cases and a description of those specific features in the procedures not included in this report D3.2. Temporally Task 3.3 spans from M10 up to M28.

The downscaled climate model data for future-climate scenarios will be used as input to Task 3.6 for the assessment of the site-specific climate risk parameters and stressor indicators. In WP4, downscaled climatic projections will be used for infrastructure resilience assessment. The short-term downscaled forecasting systems developed here will be used in Task 3.4 to obtain tailored forecasts for the use case sites for the needs of dynamical data assimilation in Task 3.5 and in WP6 to support IWAT, Decision support system and Enhanced Visualization Interface.

The methodology is based on Task 3.1 and 3.2, whereas the end user needs are defined in WP2. In Task 3.1, relevant RCM data for future climate scenarios were selected and extracted from the EURO-CORDEX database, while in Task 3.2 high-resolution land-use maps and surface parameters were produced. These data are needed as input data for the meso- and local scale modelling for the downscaling methods and applications described in this report.

The main part of the work of Task 3.3 is carried out in close collaboration between AUTH and FMI involving also partners with strong use-case specific knowledge and expertise such as ULIEGE, SPW MI, RSOE, BME, MAV, BSZL, AFDJ, UDG and UM.

Downscaling of the future climate projections addresses the STO 2 of PLOTO "Reliable quantification of climatic, hydrological and atmospheric stressors". The short-term downscaled forecasting addresses the STO 3 "Development of a forecasting module to provide high-resolution tailored weather and precipitation forecasts".

3. Modelling Methods and Procedures

3.1 Wind downscaling to local site scale using high-resolution LES

This section presents the relevant theoretical and numerical developments required by the downscaling methodology for wind related risks and 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 orography and topography. Next, downscaling-specific practises to set up the computational model for a target site are discussed. Then, the downscaling procedure itself is described. Finally, the state information (data to be downscaled, e.g. RCM wind data for the future climate) employed for driving the downscaling procedure is presented.

3.1.1 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 can resolve the effects 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. Recently, PALM has been equipped 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.

3.1.2 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 from 1 to 2 m 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 coverage must be from about hundred square kilometres up to several hundreds of square kilometres. It is impossible to entirely cover such surface areas with a very high-resolution grid having grid spacings of the order of one metre. 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 domains forming a cascade of nested domains. Child domains and cascades of children can also be set up parallel to each other. As an example of a nested setup the use case C (Wallonia) setup is shown in Figure 1. 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 can be 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 vegetation data must be obtained for instance from a DSM or other inventory. As an example, in this work we model the trees as described above in the use case C, but not in use cases A and B, since we do not have separated or separable building- and trees data available. In those cases, the trees must be treated as solid objects.

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 relatively low-resolution root domain only, the time steps can be set considerably larger, usually by one order of magnitude, 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 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 are 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.

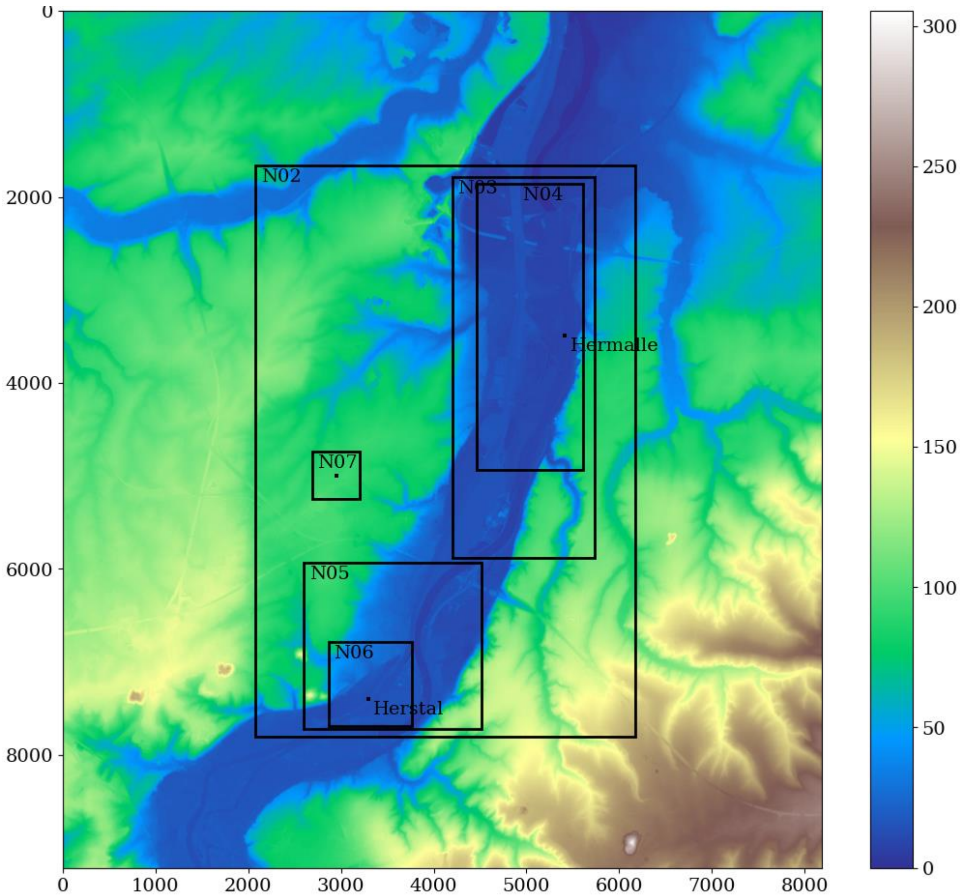

Figure 1: The root and nested domains for the use case C (Wallonia). The color indicates terrain height. The rectangles with the domain-ids like N02 show the horizontal locations of the nested child domains. N04 and N06 are the highest-resolution

domains having 2 m grid spacings. The spots Hermalle and Herstal are the meteorological stations and the spot in N07 is the RCM referencing point. The horizontal size of the root domain is 16 384 m by 18 432 m.

3.1.3 Wind downscaling procedure – general description

Our approach to downscale wind fields to local scale and very high resolution is based on fusing pre-computed high-resolution LES data and larger-scale information such as data from a Regional Climate Model (RCM) or a Numerical Weather Prediction model (NWP) or observations from a nearby meteorological station depending on the purpose of the downscaling. LES data provides 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, i.e. the referencing point. This large-scale information is hereafter referred to as state information.

Statistically stationary LES simulations must be carried out for a set of representative meteorological conditions. Typically, such a 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 the referencing point (or points) corresponding to the location(s) of the state information, a selected grid node of a climate model or 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, but this is only in order to save computational cost and storage space. The downscaling approach itself is not limited to neutrally stratified conditions. 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 fields 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, wind observations are usually available as ten-minute averages, and archived RCM results may be available every six hours for example. 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 time interval, the best matching meteorological condition data unit is retrieved from the precomputed 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, the referencing point. The LES referencing wind speed is time averaged over the same time interval as the state information referencing wind speed to ensure that they correspond to each other. Downscaled wind forecasts can be produced this way to given target sites, for example by employing wind data in a specified grid node of an RCM or an NWP model as the state information. Unlike the RCM data or 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.

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 time interval. The changes from one interval to another are discontinuous. This is not entirely realistic since naturally 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 precomputed LES. On the other hand, this is not a problem in wind hazard studies in which only high-wind conditions and their occurrence and frequency are of interest and the dynamic changes of the state are not of interest.

3.1.4 Downscaling of ICON-EU weather-prediction model short term predicted wind data – technical description

Automatized and operational short-term forecasting of downscaled wind can be used to support operational preparedness with potential application to the early-warning module of IWAT.

The Numerical Weather Prediction (NWP) model ICON-EU (Zängl et al., 2015) is chosen as the on-line source of the larger-scale, but frequently updated, weather forecast to drive the operational downscaling system. This choice is made because ICON-EU is a state-of-the art NWP model which provides continuously updated meteorological data for the entire Europe. The online data repository and the open-access data sources offer the most suitable framework for the presented short-term wind forecast downscaling system. The flowchart shown in Figure 2 offers an operational layout for the operational downscaled wind prediction tool. A precursor for this system has originally been developed within the PANOPTIS-project (www.panoptis.eu) and adapted and further developed here for the needs of PLOTO.

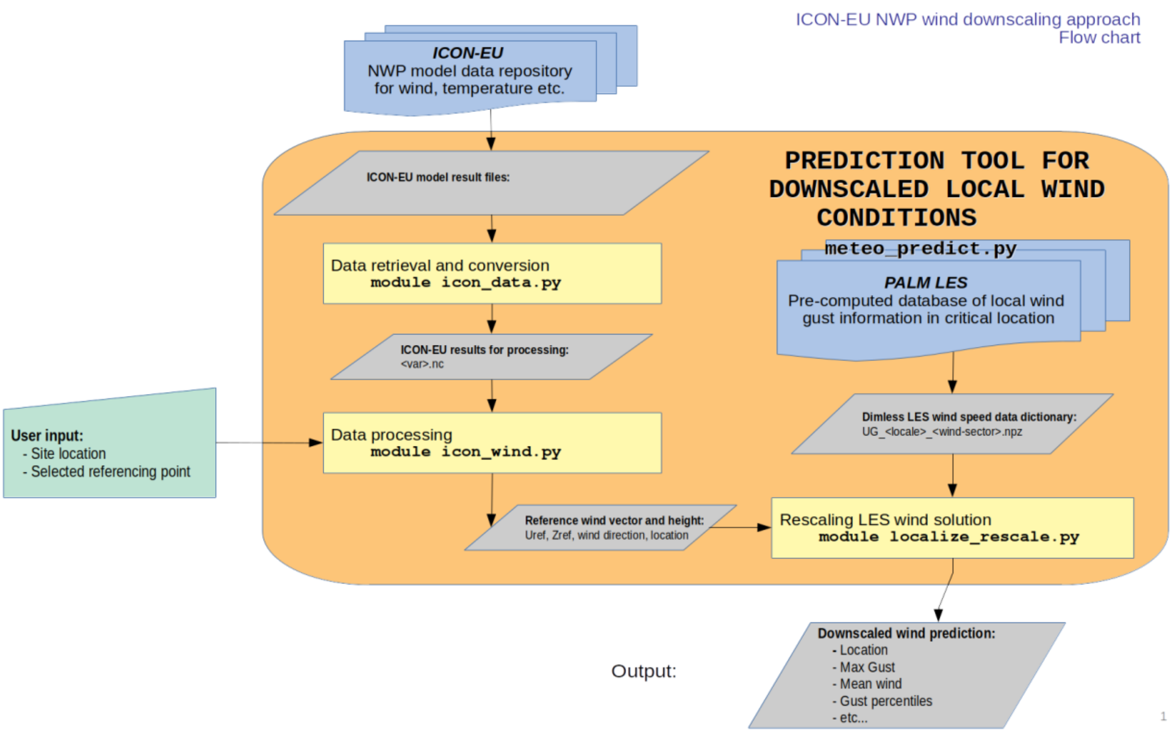

Figure 2: Flowchart describing the downscaling procedure for short-term wind prediction. The method utilizes open-access ICON-EU NWP model outputs for wind data, which is also used to determine dominant wind direction and speed at surface level. This determines which wind sector LES data subset is chosen from the pre-computed LES data set and how it is rescaled to correspond with the NWP-forecasted conditions.

The ICON-EU data repository is seen on the top of the left branch in Figure 2. Every 24 hours the system monitors the ICON-EU data repository and looks for the next ICON-EU forecast data to be downscaled. When the data becomes available it calls the downscaling system `meteo_predict.py`. As a first step, the script invokes a module `icon_data.py` which automatically retrieves the new set of the most recent ICON-EU forecast data files which describe the meteorological state of Europe. The ICON-EU data files are subsequently decompressed and converted from grib2 to NetCDF-format.

As a next step, module `icon_wind.py` interprets the received forecast data, aims into the area of the chosen PLOTO use case site and determines the representative surface wind condition predicted for the next 72-hour period (which is also the time period for the downscaled wind gust and meteorological state forecast). We use the ICON-EU wind data at 10 m level from terrain surface, because the next higher level at which wind data is freely available on-line is at 900 hPa pressure-level, corresponding to roughly 900 m height measured from the sea level depending on the ambient surface air pressure. This is too high for our present LES domains. Ideally, the reference wind would be right above the surface layer, say roughly at 200 m height, but as mentioned above, such data is not freely available from ICON-EU. The problem in using the surface wind at 10 m height is that while the LES model resolves terrain shape-, building- and vegetation effects on wind, the NWP model ICON-EU does not. Therefore, the LES-model 10 m wind may not correspond to the ICON-EU 10 m wind. In this case we avoid this problem by setting the wind referencing point of the LES model in the middle of a relatively large plain area. Moreover, we intentionally ignore modelling of buildings and trees around the referencing point to make it better correspond to the NWP model. Then the system goes on to produce a downscaled forecast. In this case, the obtained ICON-EU surface mean-wind vector is used by the module `localize_rescale.py` first for selecting the best corresponding 30-degree wind sector from the pre-computed LES result dataset stored in an operational server at FMI. Subsequently, the `les_rescale.py` module rescales the data by the ratio of the current ICON-EU wind speed and the nominal time averaged wind speed recorded in the referencing point in the LES pre-computations as described in Sec. 2.1.3. Finally, after completing the current 72-hour period forecast, the wind-prediction tool automatically sends the forecast to the PLOTO system. The forecast may contain for example the following information for each monitoring site:

- Maximum gust speed (m/s);
- 99th percentile gust speed (m/s);
- Mean wind speed (m/s) and its direction;
- Standard deviation of wind speed (m/s).

3.1.5 Downscaling of RCM-predicted future climate wind data – technical description

The procedure to downscale the RCM wind data for the future climate projections is in principle similar to that of the ICON-EU NWP data. However, in terms of programming it is a simpler procedure because no on-line data fetching, and continuous automatic operation are needed. Instead, the wind data from more than one RCMs for the target site is downloaded from the EURO-CORDEX database beforehand. The downscaling is then performed off-line for the selected RCMs and RCP scenarios.

Again, 10 m level wind data is used because the next lowest available RCM data level, 850 hPa pressure level, is too high for our LES setups. The problem of using 10 m wind described in Sec. 2.1.4 also applies in this case and the approach to avoid the problem is the same. For the use case C, we use the nearest RACMO and RCA RCMs' grid point as the referencing point as shown in Figure 1 (middle of N07). This point is surrounded by a fairly flat area, thus there are essentially no complex-terrain effects, and we also intentionally ignore modelling buildings and trees in the child domain N07 surrounding the referencing point to make the LES-predicted and averaged wind in this point better correspond to the RCM-predicted wind.

Relevant EURO-CORDEX RCM data (Kotlarski et al., 2014) has been selected for the present work by Lehtonen et al. (2023). This includes several wind variables somewhat depending on the RCM-GCM model combination. Out of the available wind variables, the most interesting and useful ones for the present work are the daily maximum 10 min averaged wind speed and daily maximum gust speed. Unfortunately, these wind speeds come without wind direction information. Therefore, we use instantaneous wind-velocity components given every six hours to estimate the wind direction of the daily maximum wind-speed events. However, not all RCM-GCM-model combinations provide such wind-component information. Therefore, we will only use those model data which include both the every-6-hour component data and the daily maximum 10 min averaged and gust wind speeds, see Table 1. This is because the wind direction information is crucially important for the downscaling. The unknown wind direction corresponding to the maximum gust speed is estimated by the direction of the maximum 6-hour instantaneous wind speed. Naturally, this is somewhat uncertain, but this is the best that can be done with the available data. It is important to understand that this is not a drawback of the wind-downscaling method, but a drawback of the EURO-CORDEX database.

The RCM data spans from the beginning of the year 2006 to the end of 2099 or 2100 depending on the individual model run. In addition, we have also historical data spanning from the beginning of 1971 to the end of 2005.

Table 1: RCM-GCM pairs of which results will be downscaled.

RCM	Horizontal resolution	Number of vertical levels	Driving GCM
RACMO22E	0.11 deg	40	MOHC- HadGEM2-ES
RACMO22E	0.11 deg	40	ICHEC-EC-EARTH
RCA4	0.11 deg	40	MOHC- HadGEM2-ES
RCA4	0.11 deg	40	ICHEC-EC-EARTH
RCA4	0.11 deg	40	MPI-M-MPI-ESM-LR

To give an example of a detailed downscaling procedure, the algorithm employed for the preliminary results on use case C in Sec. 4.1 is described below. It is important to note that the details of the procedure depend largely on the application and the purpose of the downscaling. For instance, in this first relatively simple example the focus is only on the daily gust wind-speed maximums found over the river surface not in producing full 3-D time dependent downscaled fields although it is fully possible. However, this full 3-D time downscaling would take much more computing time and disk storage space.

- For each LES-computed wind sector *WD* data set:
    - find the highest 10 min time averaged referencing wind speed $V_{max10rLES}$ from the LES time series at the referencing point using sliding-window averaging of the wind speed and the corresponding wind direction and record them;

  - find the local instantaneous maximum wind gust speed $V_{maxgRiverLES}$ over the river surface 0 m < z <= 9 m and calculate the ratio $R_{gLES}(WD) = V_{maxgRiverLES} / V_{max10rLES}$;
  - record the local direction $WD_{maxgRiverLES}$ of the peak wind gust.
- Scan through the RCM time series:
  - for each day, estimate the wind direction $WD_{max10RCM}$ corresponding to $V_{max10RCM}$ by the day's highest-speed instantaneous wind vector output every 6 hours (because nor $WD_{maxgRCM}$ neither $WD_{max10RCM}$ are available as explained above);
  - downscale $V_{max10RCM}$ by multiplying it by $R_{gLES}(WD_{max10RCM})$ to obtain V_{maxgDS} as the result.

In this procedure, the downscaling is made for the RCM-predicted daily maximum 10 min averaged wind speed, not to the daily maximum gust speed. This is referenced to the maximum 10 min averaged LES-predicted wind speed at the referencing point (the selected nearby RCM grid node). The RCM-predicted daily maximum gust speed is a parameterized value which is not as straightforward to associate with the LES-predicted wind speed at the referencing point.

3.2 Downscaling of other meteorological parameters to local site scale using meso-scale modelling

This section covers the developments required by the downscaling methodology for other meteorological parameters to local site scale using meso-scale modelling.

3.2.1 MEMO mesoscale atmospheric model

The mesoscale meteorological model MEMO (Moussiopoulos et al., 2012), which constitutes a main part of the EZM (European Zooming Model) system (Moussiopoulos N., 1995), is used for producing grid meteorological model simulations. MEMO is a three-dimensional, non-hydrostatic, prognostic mesoscale model for the simulation of mesoscale air motion and inert pollutant dispersion at the local-to-regional scale, over complex terrain, allowing multiple nesting.

The MEMO model is capable of efficiently producing simulated datasets of hourly meteorological parameters, such as wind speed and direction, temperature, turbulent kinetic energy (TKE), incident solar radiation, cloud cover (diagnostically) and relative humidity, as well as turbulence parameters like surface roughness, Monin-Obukhov length and friction velocity for each grid point and at multiple heights above ground level in a 3-dimensional geographical grid, covering the target region. These high-resolution downscaled datasets offer flexibility in terms of data extraction. Another important feature of MEMO is that it is also capable of simulating local circulation systems, such as mountain-valley winds, sea/lake breezes, as well as the urban heat island. These mesoscale atmospheric processes also affect local-to-regional scale dispersion phenomena. Therefore, MEMO is consideredas a suitable scientific tool to generate such comprehensive meteorological data for the needs of meteorological downscaling, as well as atmospheric pollutant dispersion.

3.2.2 Mesoscale modelling approach

For the initialisation of MEMO, a number of vertical profiles of the key meteorological variables originating from the ICON-EU (Zängl et al., 2015) operational numerical weather prediction model are used. Such profiles are assimilated into the model calculations on a 3-hour basis. The grid structure of ICON global model is based on an icosahedral (triangular) grid of the earth's sphere. The forecast data are also provided in standard packages on an icosahedral (triangular) grid. Regarding the ICON-EU calculations, there is a tightly coupled two-way interaction between the ICON-EU regional model and the global ICON.

The native model grid has a horizontal grid spacing of 6.5 km, the output grid a grid spacing of 0.0625° (~ 7 km). In the vertical, ICON-EU relies on 60 levels up to a height of 22.5 km. Besides, the ICON-EU forecasts are available up to 120 hours from the four model runs at 00, 06, 12 and 18 UTC and up to 30 hours from the model runs at 03, 09, 15 and 21 UTC. The time interval for the forecast period up to 78 hours is one hour, while the forecast periods between +81 and +120 hours are covered by a 3-hourly time interval.

More specifically, the downloader module of the automated module undertakes the transfer of the ICON-EU data, processes them (the ICON-EU data files are initially decompressed and, as a second step, converted from grib2 format into ASCII), and stores them in a dynamic data pool, also part of the HRAP infrastructure, which is kept updated at all times. The scheduler selects only the most recent dataset for input to the MEMO model. Each of these processes keeps a separate event log and diagnostic files accessible through the HARP repository.

The Operational Meso-scale modelling System (OMS) has been configured for three pilot areas in Belgium (Wallonia), Hungary (Budapest) and Romania. The configuration of the MEMO grid for all areas is shown in Table 2, while Figures 3-6 depict the domain extents and the topography layer providing a high-resolution representation of the topography for the model domain for all under consideration.

Table 2: Specification and dimensions of OMS domains.

Wallonia				
Coarse Grid			**Units**	**UTM zone**
UTM Coordinates (X,Y)	662274	5568490	m	
Number of cells in X,Y-direction	120	120	Cells	
X,Y size of each cell	2000	2000	m	
Grid total extent (X,Y)	240000	240000	m	
Fine Grid				31 U
UTM Coordinates (X,Y)	685702	5616158	m	
Number of cells in X,Y-direction	120	120	Cells	
X,Y size of each cell	250	250	m	
Grid total extent (X,Y)	30000	30000	m	
Budapest				
Coarse Grid			**Units**	**UTM zone**
UTM Coordinates (X,Y)	352109	5257038	m	
Number of cells in X,Y-direction	72	72	cells	
X,Y size of each cell	2000	2000	m	
Grid total extent (X,Y)	144000	144000	m	
Fine Grid				34 T
UTM Coordinates (X,Y)	352109	5257038	m	
Number of cells in X,Y-direction	144	144	cells	
X,Y size of each cell	250	250	m	
Grid total extent (X,Y)	36000	36000	m	
Romania				
Coarse Grid			**Units**	**UTM zone**
UTM Coordinates (X,Y)	635546	5002753	m	
Number of cells in X,Y-direction	240	240	cells	35 T
X,Y size of each cell	1000	1000	m	
Grid total extent (X,Y)	240000	240000	m	
Fine Grid				
[redacted]				

As regards the required high resolution topographical input data, they were derived from the satellite elevation datasets of NASA's Shuttle Radar Topography Mission – SRTM/90 m database (http://www2.jpl.nasa.gov/srtm/). Besides, thematic layers of land use data were obtained from the Corine Land Cover 2006 (http://www.eea.europa.eu/data-and-maps/data/corine-land-cover) database, which includes 44 land use (LU) types, which were reclassified to the seven LU types used in MEMO applications, namely water, arid land, few vegetation, farmland, forests, suburban and urban.

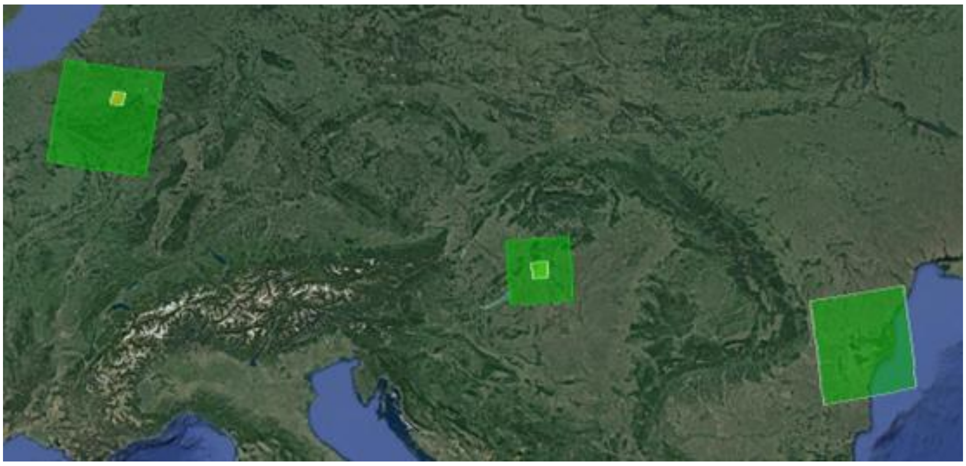

Figure 3: Locations of the three pilot domains on the European map.

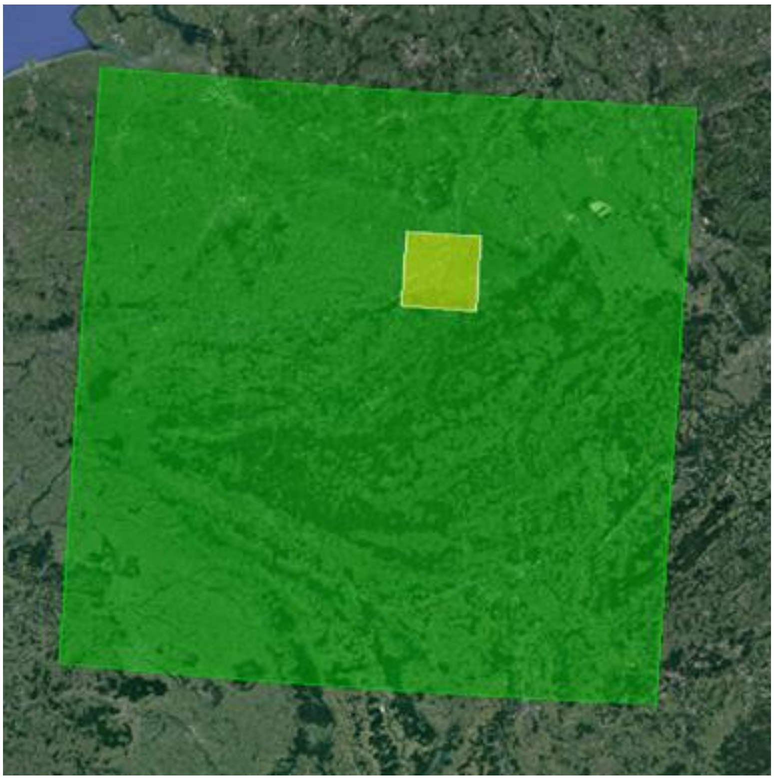

Figure 4: Definition of mesoscale nested grid for the domain of Wallonia.

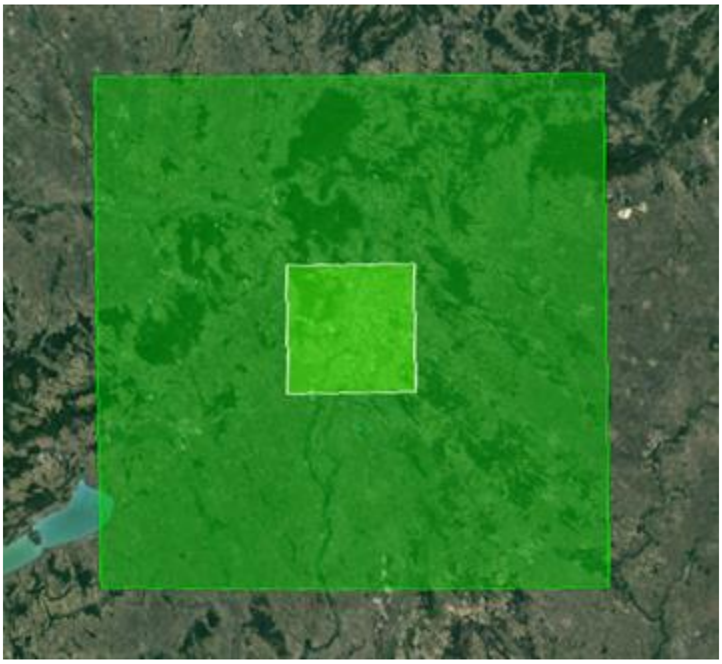

Figure 5: Definition of mesoscale nested grid for the domain of Budapest.

Figure 6: Definition of mesoscale grid for the domain of Romania.

The meteorological mesoscale module, based on MEMO and ICON-EU models, provides functionality for downscaling several meteorological parameter fields which, amongst other, include temperature, humidity, incident solar radiation, relative humidity, precipitation, cloud cover and of course wind intensity and direction. More specifically, model results are provided at an hourly basis for the current hour, as well as for the next three (3) hours as short-term predictions. After the simulations process has been completed, model results are processed in an automated way and a range of maps are produced for a number of predefined variables with the aid of suitable post processing tools based on the object-oriented scripting language Python. Table 3 depicts the specification of the mesoscale modelling approach output.

Table 3: Specification of the output of mesoscale modelling approach.

Parameter (unit)	Time reference	Spatial Resolution	Vertical Reference
Temperature (^{0}C)	1 h	250 m	2 m
Relative Humidity (%)			
Wind Speed (m/s)			
Wind direction (^{0})			
Precipitation (mm)			Surface
Cloud Cover (%)			-

For downscaling future climatic series of the above variables, a combination of sampled dynamical downscaling and statistical downscaling is used. The first part of this approach involves a selection of 100 monthly periods chosen within a period of 100 years covered by the EURO-CORDEX database and is performed separately for each of the three use case areas. The selection of the periods follows a climate classification scheme previously applied by Favre et al. (2014). The corresponding downscaling runs are currently in progress and will be reported in the final version of this deliverable.

The statistical downscaling part of the approach involves a construction of synthetic PDFs of the main meteorological variables based on the mapping of the sample dataset of dynamical simulations, using appropriate weight factors. In any case, the construction of a complete downscaled series for the entire 100-year period is computationally infeasible and will not be undertaken in the frame of this task. What is targeted instead, is to obtain consistent PDFs of occurrence able to represent probabilities of events with extremely long recurrence intervals, which could nevertheless significantly contribute to the total hazard. It should be noted that to this end, extracting statistics from EURO-CORDEX series alone will not suffice since the recurrence intervals could well exceed by a large margin the total length of the available series.

3.3 Treatment of the catchment-area scale data

The RCM-predicted catchment-area scale precipitation data collected for hydrological analyses and shown in the report D3.1 (Lehtonen et al., 2023) needs no downscaling. Instead, it is used as such directly from EURO-CORDEX database. The catchment is a cumulative process feeding water into the river from the whole large catchment area. Thus, it depends on spatially and temporally integrated cumulative precipitation within the area. Downscaling would bring no added value in such data and would also be computationally too heavy a task.

4. Use cases

4.1 Target sites and site-specific climatic stressors and data to be downscaled

This section presents the target sites of each use case and the use-case specific relevant climatic stressors, which in turn determine the detailed specification of the data to be downscaled.

4.1.1 Use case A: Danube delta

The delta of Danube in Romania is a large area (see Figure 7). Wind is downscaled only for the Sulina area (Figure 8). Sulina is the area which is the very mouth of the middle branch of the delta of Danube on the shore of Black Sea. There, ships enter and exit the narrow river, and the area is quite windy. There is a small town of Sulina and a small port.

Figure 7: Aerial view of the whole Danube delta area (Google Earth, Data SIO, NOAA, U.S. Navy, NGA, GEBCO, Image Landsat/Copernicus, Image ©2024 CNES/Airbus, Image ©2024 Maxar Technologies).

Figure 8: Aerial view of the Danube delta in Sulina area (Google Earth, Image ©2024 CNES/Airbus).

Downscaled wind data will be used to estimate the high wind gusts to which ships are exposed while entering and exiting the river. Heavy gusts may pose a safety risk for the ships manoeuvring into the narrow river and out to the Black Sea. Principally, RCM-predicted future climate wind data for RCP-scenarios (primarily RCP4.5) will be downscaled for further risk and other analyses. This downscaling procedure is similar to that for the use case C given as a preliminary example in Sec. 4.1. Additionally, a downscaled and automatized short-term forecasting system can be developed based on downscaling NWP data.

Precipitation is downscaled to a high-resolution grid over the lower catchment area covering the St. George, main and Sulina branches (Figure 7). This will serve to estimate level fluctuations and flush flood events that are associated with the risk of overflows or low levels. Temperature and cloud cover series estimated at the same a very high resolution will be used to assess icing probabilitie s on water surface as well as on port assets. The high-resolution terrain and land cover used will ensure that these effects can be reported on a near-per-asset base, taking into account radiative and latent heat fluxes.

4.1.2 Use case B: Port of Budapest

Budapest Port or the Csepel Freeport is located behind the eastern bank of Danube a few kilometres downstream from the center of Budapest. It includes two bays and four pier sections as shown in Figure 9 (left). It is the principal port of Hungary. It can handle dry cargo, containers, breakbulk, RORO, refined petroleum products and crude oil. More than 2000 ships carrying 1,200,332 tonnes of cargo visited the port in 2021 (https://www.marineinsight.com/know-more/ports-in-hungary).

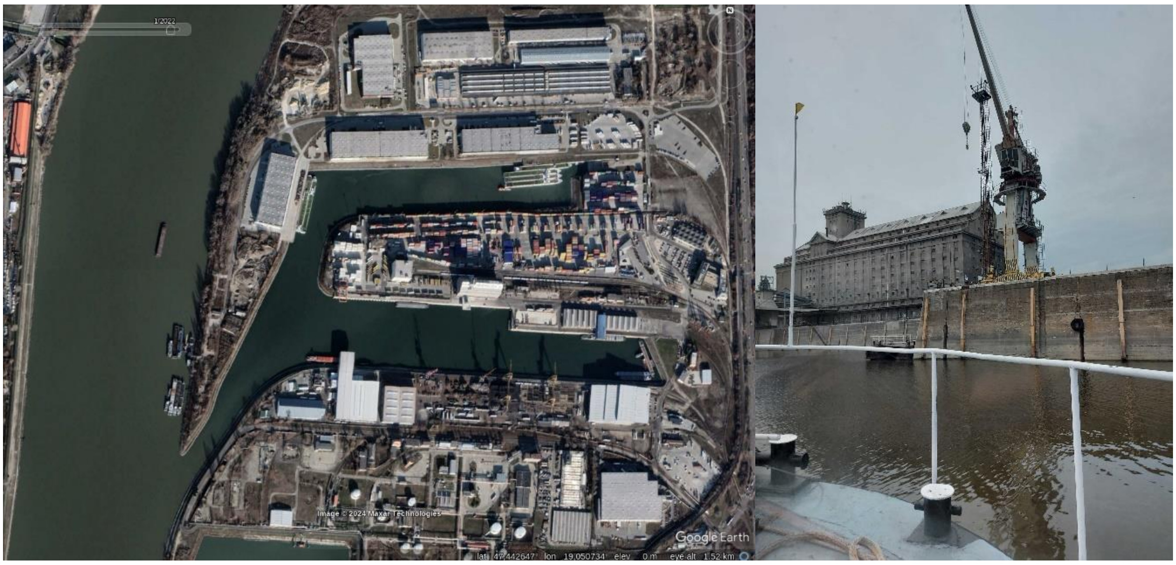

Figure 9: Left: aerial view of the port of Budapest (Google Earth, Image ©2024 Maxar Technologies). Right a view just off one of the pier sections showing an old warehouse (© Antti Hellsten) as an example of large buildings potentially influencing the local wind conditions.

Downscaled wind information is needed to identify the local exceedances of the wind-speed safety limits of the conventional ship loading and unloading operations in the Budapest port. Here, conventional means loading and unloading by cranes in contrast to roll in / roll out (RORO) type operations. For this purpose, we will store the instantaneous LES-predicted wind-speed components with high 0.33 Hz frequency covering the piers of the port and also the three Vaisala WXT 536 weather stations installed in the port area. This precomputed LES data will then be used for wind downscaling as described in Sec. 2.1.3 and in Sec. 4.1. This way we will obtain downscaled wind information about the exceedance frequency in future climate projections, principally RCP4.5, and also downscaled information for near term forecasting. The downscaling is expected to bring in remarkable added value since the climate-model data and weather-prediction model data do not include any effects of local terrain shape, buildings and vegetation in the wind, especially the maximum gusts, and these missing effects are brought in from the precomputed LES data by means of the downscaling procedure.

Upstream measurements of water levels will be combined with precipitation estimates downscaled over the coarse area in order to identify exceedances of operational level limits in the day-to-day timescale, while precipitation downscaled over the fine domain will help identify flush flooding potential over local assets in smaller timescales, of the order of tens of minutes. Icing potential that could affect crane and RORO operations will be estimated on the basis of downscaled moving-average series of temperature and cloud cover in the high-resolution domain.

4.1.3 Use case C: River Meuse near Liege

The area of interest in the use case C is a section of the river Meuse (Maas) passing the city of Liege in Wallonia, Belgium and reaching downstream towards north up to the border between Belgium and the Netherlands (Figure 10). In this area the river consists of two branches near each other. The eastern branch is the natural river which is not navigable, and the western branch is a man-made channel (Albert canal) for ships to navigate. This branch flows partially above the surrounding terrain between dikes. Both branches have several ship locks in this area and there are several ports and smaller ship-loading piers in the area.

Figure 10: Left: aerial view of the river Meuse area near Liege. Right: closer views of part of the study locations. (Google Earth, Image ©2024 Maxar Technologies)

Downscaled wind information is needed for two specific purposes in this use case.

One purpose is to estimate the wave formation on the river surface in order to estimate the risk of overtopping past the riverbanks. The wave formation is mainly dependent on the time-averaged surface wind speed and the fetch length, which in turn depends on the wind direction relative to the river-bed direction. The wave formation itself will be separately modelled by ULiege using the downscaled average 10 m wind-speed and direction information over the whole modelled section of the riverbed, see Figure 1.

The second purpose is to estimate the high wind gusts to which ships are exposed to while manoeuvring on the river. The most critical manoeuver is U-turn and the most critical vessel type is the container ship as their face area is typically quite large. The bulk vessels typically operated on rivers have only small wind-exposed face area and they are thus less sensitive to gusts. The tallest container ships operated on Meuse reach up to about 9 m above the water line. Therefore, we store instantaneous LES-predicted wind-speed components with high frequency of 0.33 Hz above the river surface up to at least 11 m height covering whole modelled section of the riverbed, see Figure 1. This precomputed LES data will then be used for downscaling as explained in Sec. 2.1.5 and Sec. 4.1.

Probability of exceedance of operational level limits and probability of overflow/breach events will be estimated on the basis of downscaled precipitation over the coarse domain. Such exceedances can directly affect traffic and manoeuvring operations due to overheight and draft limitations. The temporal resolution of this parameter is one hour, allowing the hydrological models to adequately resolve the propagation of flood fronts throughout the region. Icing potential will be calculated for river and terrestrial areas around Liege using the high-resolution domain. Such effects are expected to impact road traffic, river surface and near-shore assets.

5. Preliminary results

5.1 Example of future climate wind downscaling to river Meuse (use case C)

A preliminary result for the use case C (Wallonia) is presented here as an example. The example is for long term future climate analysis, i.e. downscaling of the RCM data from the EURO-CORDEX-database. Near-term forecasting, i.e. on-line downscaling of ICON-EU NWP model data will be presented in the report D3.3. Both wind downscaling applications for the use case C are based on the same LES-runs.

The horizontal extent of the whole LES domain, see Figure 1, is made relatively large in order to set its outer boundaries far away from the areas of interest. This way simple and easy-to-use cyclic boundary conditions can be applied on the outermost, i.e. the root domain. The root domain horizontal dimensions are 16 384 m and 18 432 m, and its height is 1024 m counted from the lowest terrain point within the root-domain. In fact, the domain should extend even further north since the river is of interest up to the border of the Netherlands, but we had to restrict the domain size as shown in Figure 1 because we had no land use data covering the Netherlands side. Grid spacing in the root domain is 16 m in all directions. This is too low a resolution to resolve the local effects from e.g. buildings. Therefore, resolution is focused around the areas of interest using the LES-LES self-nesting capability of PALM (Hellsten et al., 2021). The resolution is refined in three stages. First there is an intermediate nest domain N02 with 8 m grid spacing and including two nested domains N03 and N05 each having 4 m grid spacings. Finally, N03 includes N04 having 2-m grid spacing and similarly N05 includes N06 also having 2 m grid spacing, see Figure 1. The finest resolution nested domains N04 and N06 cover most of the river sections of interest. However, some parts of the river are only covered by N03 and N05 having 4 m grid spacing. This is because otherwise the model setup would have become computationally too heavy. There is also one more nested domain N07 having 4-m grid spacing within N02. This covers the RCM referencing point (Lon = 5.619494 deg, Lat = 50.701488 deg) for downscaling and for both RCMs: RACMO22E and RCA4. The surroundings of this point feature fairly flat terrain, thus the LES wind at z = 10 m height from the local terrain surface in this area should correspond well to the RCM-predicted 10 m wind. In reality, there are some buildings in this area, but we intentionally neglect them in the LES model to make the LES and RCM predictions better correspond to each other around the referencing point. The referencing point is also shown in Figure 1. Buildings and trees are modelled only in the high-resolution nest domains N03, N04, N05 and N06. In the root and N02 the resolution is too low to include buildings and trees. There, their effects are modelled simply by means of increased roughness length z_0 in the surface boundary condition. In the root domain we set z_0 = 0.3-m and in N02 and N07 it is 0.1-m while N03 and N05 it is 0.07-m and 0.03-m in N04 and N06.

Time and space dependent wind-velocity components are output at 0.33 Hz frequency over the river surface covering from bank to bank the whole section of interest. The horizontal spacing of the output grid is four metres. Vertically the output starts from the river surface and reaches up to 11 m above the surface with the vertical spacing of 2 m within the nests N04 and N06. In N03 and N05 the vertical spacing of the output grid is 4-m. The output grids are defined as a large number of relatively small patches in the LES model but for the sake of convenience all the output data is post processed into a single structured 4-D array which contains time dependent wind-velocity component data in the above-described points above the river surface and a fill value elsewhere. A separate averaged 10-m wind 2-D array is provided as well as a result of post processing.

We carry out the LES runs for 12 30-degree wind sectors under neutral stratification and store all the above-described results for all the wind sectors in a data set for downscaling. Furthermore, we store the wind component data in the referencing point in N07 at z=10-m above the local terrain surface and in the two meteorological stations Hermalle (z = 9-m, Lon = 5.690157-deg, Lat = 50.727968-deg) and Herstal (z = 30-m, Lon = 5.628044-deg, Lat = 50.658395-deg). The station data will be used to validate the present downscaling methodology.

Here we present a simple example of a downscaling of local peak gusts over the river surface in just one RCM-predicted future-climate scenario (the scenario RCP4.5 modelled by the RCA4 driven by the GCM MPI-ESM-LR, i.e. the model combination given on the last line of Table 1). The data spans the period from 1.1.2006 to 31.12.2100. In this very preliminary demonstration case, we only analyse a small subsection of Albert canal, a 1.1 km long section downstream from Pont d'Oupeye. This short section is covered from bank to bank from the water surface up to 9-m height. Complete results will be provided in D3.3.

These preliminary results indicate that the RCA4 LES-downscaled gust wind speed V_{maxgDS} over the river surface (along the limited-length domain of this example) are systematically lower than the RCA4 parameterized daily maximum wind gust speed. Table 4 gives the averages, 95th and 99th percentiles and numbers of exceedances of 14, 20 and 25 m/s threshold values of the daily maximum gust speed over the river section over the whole time period from 1.1.2006 to 31.12.2100.

Table 4: Some statistical measures of the daily maximum gust wind speed during 1.12006 - 31.12.2100 based on RCP4.5 and RCA4 RCM driven by the GCM MPI-ESM-LR climate modelling. RCA4-parametrized versus LES-downscaled daily maximum gust speed

	RCA4 parametrized gust	RCA4 LES-downscaled gust
Average	11.7 m/s	9.3 m/s
95th percentile	21.1 m/s	17.0 m/s
99th percentile	25.1 m/s	21.3 m/s
Number of exceedances, 14 m/s	10 754	4463
Number of exceedances, 20 m/s	2510	599
Number of exceedances, 25 m/s	357	75

The RCM cannot capture the orographic effects of the relatively narrow river valley on the wind statistics. This is probably the main reason for the overestimation. The RCM result represents wind flow over plain terrain rather than wind conditions within the valley. Another reason for the over-estimation seems to be that at least in this case the RCA4 model's gust parameterization gives clearly higher gust factors (maximum gust wind speed divided by the ten-minute averaged wind speed) compared to our fine-resolution LES.

5.2 Example of downscaling of other meteorological parameters to Budapest (use case B)

Dynamical downscaling is implemented in the module developed by AUTh to provide downscaled versions for temperature, relative humidity, cloud cover and precipitation at a resolution of 250 m (use cases B and C) or 1000 m (use case A). Currently the Operational Mesoscale System provides continuous current-hour nowcasts of these fields based on input from the regional scale model ICON-EU, which are archived and pre-processed to create a repository of medium-term situations that will be subsequently used for hazard analysis. Operational output of the system for all use cases is accessible through an online dashboard available at http://hydra.meng.auth.gr/ploto/. The user can choose to visualize the current downscaled fields per use case and per parameter, while a choice is provided between the low (coarse) and high (fine) resolution domains. In addition to online visualization, the dashboard offers functionality to download the downscaled fields in various raster formats, including GeoTIFF and NetCDF, suitable for processing by GIS, analysis or visualisation tools.

In Figures 11 to 14, sample hourly downscaled fields are shown for the coarse and fine domains of Budapest (use case B). In the case of temperature and relative humidity, it is evident that the process of downscaling manages to resolve the influence of local topographical (terrain elevation) and surface type. These results highlight the added value of using a process-based model to resolve information that would be unavailable from any other lower-resolution model. Moreover, the wide range of temperatures resolved over the fine domain indicates that the downscaled fields provide qualitatively important information for hazard assessment, since the local extrema can deviate significantly from the overlying base-state variables and thus contribute to the long tails of occurrence distributions.

In the case of cloud cover and precipitation, the increase in detail as introduced by downscaling is less pronounced compared to thermal variables, but still important to resolve local effects. In particular, solar radiation is directly affected by local cloud patterns and can result in variations in surface forcings, e.g. shaded vs exposed surfaces in respect to the icing potential. Precipitation is adequately resolved even in the coarse domain, which was selected to accommodate most of the catchment area relevant for hydro-hazard assessment. Nevertheless, the additional structure resolved in the fine domains can also be of use in cases when information on instantaneous or peak precipitation can affect runoff in relation to topsoil status etc.

In addition to surface maps of nowcasted fields, the Operational Mesoscale System can provide 24-hour next-day forecasts over the same area and using the same resolution. The added value of this product is to support operational preparedness with potential application to the early-warning module of IWAT. In Figure 15, sample forecast timeseries of temperature is shown, calculated for the location of the S3 meteorological station in the Budapest port area. Since the coarse and fine domains overlap over the central area, in principle one can extract this information both from the large domain (which directly incorporates input from the regional-scale model) and the smaller nested domain (which incorporates input from the coarse domain), as demonstrated in Figure 15. In practice, only the fine domain output will be relevant for the case of day-to-day operations.

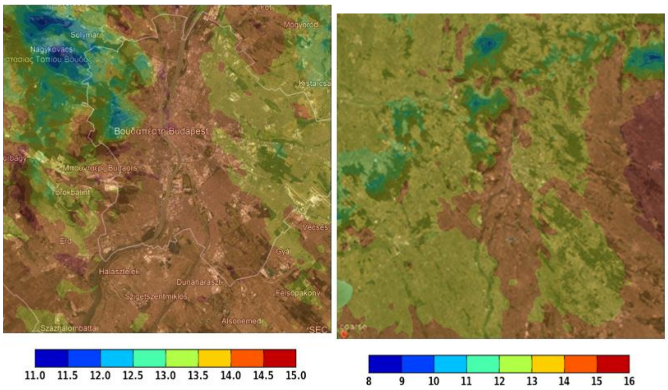

Figure 11: Sample surface temperature nowcast fields for the coarse (left) and fine (right) domains of Budapest.

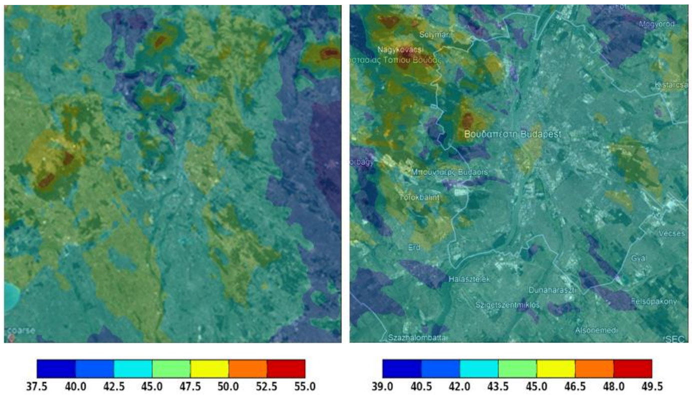

Figure 12: Sample relative humidity nowcast fields for the coarse (left) and fine (right) domains of Budapest.

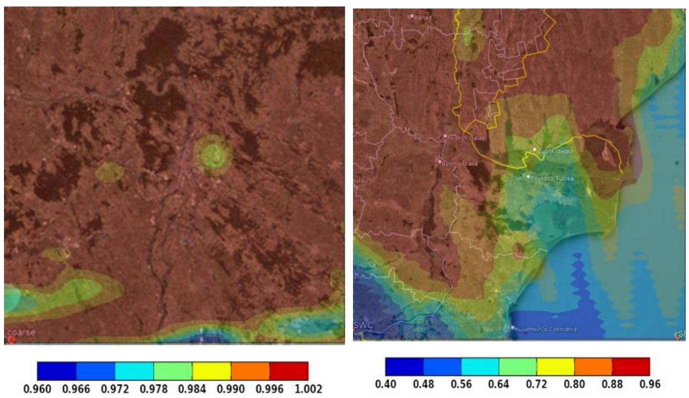

Figure 13: Sample cloud cover nowcast fields for the coarse (left) and fine (right) domains of Budapest.

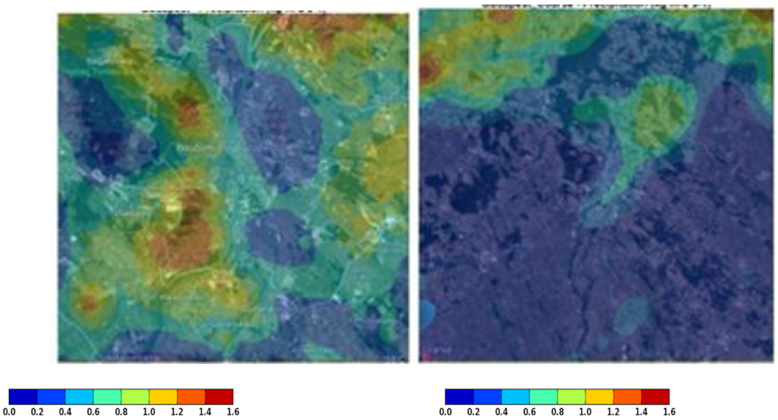

Figure 14: Sample precipitation nowcast fields for the fine (left) and coarse (right) domain of Budapest.

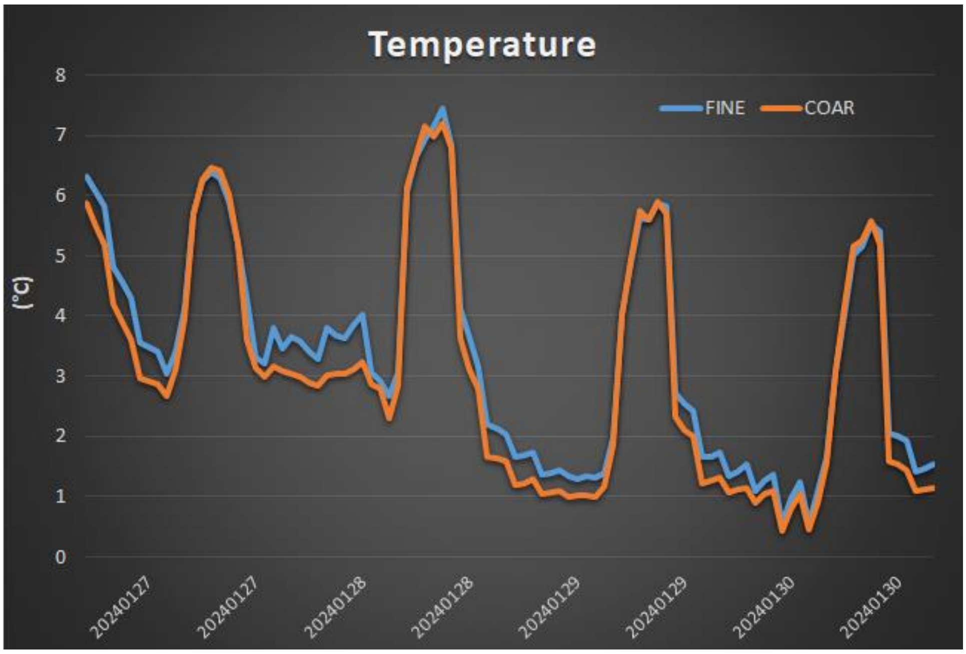

Figure 15: Forecasted time series of temperature calculated for the location of the S3 meteorological station in the Budapest port area.

6. Conclusions

This deliverable report presents the downscaling approaches and methods employed for large-scale climatological and meteorological data in the PLOTO project. The large-scale data to be downscaled is on one hand RCM-predictions for the future climate scenarios and on the other hand NWP-model data for short term forecasts. The climatological data consists of several pairs of RCMs nested into GCMs and driven by three greenhouse-gas emission scenarios (representative concentration pathways, RCP): RCP2.6, RCP4.5 and RCP8.5. This data is extracted from the EURO-CORDEX database (Kotlarski et al., 2014) for the PLOTO use-case relevant areas, see Lehtonen et al (2023). Temporally the time series span from the beginning of the year 2006 up to the end of2099 or 2100 depending on the model run. In addition, respective historical data spanning from the beginning of 1971 to the end of 2005 has been extracted from the EURO-CORDEX database by Lehtonen et al. (2023). The short-term NWP data used in this work is obtained from the ICON-EU NWP modelling system (Zängl et al., 2015).

As the resolution of the climatological and meteorological data is relatively low. The RCM and NWP models cannot capture any effects of local small-scale features of specific sites of interest like fine-grained terrain shape, buildings and trees. Therefore, the data is downscaled to local scale and high resolution such that the effects of the local features are properly captured.

We apply two downscaling approaches in this work. For wind data, we apply an approach based on precomputed very high resolution Large-Eddy Simulation (LES) data and data fusion. For other meteorological variables of interest: temperature, relative humidity, cloud cover and precipitation we apply high-resolution meso-scale modelling. These approaches and methods are described in the report.

The downscaled RCM data for future-climate scenarios will be used as input to Task 3.6 for the assessment of the site-specific climate risk parameters and stressor indicators. In WP4, downscaled climatic projections will be used for infrastructure resilience assessment. The short-term downscaled forecasting systems developed here will be used in Task 3.4 to obtain tailored forecasts for the use case sites for the needs of dynamical data assimilation in Task 3.5 and in WP6 to support IWAT, Decision support system and Enhanced Visualization Interface.

The report also describes the PLOTO use cases and their relevant weather vulnerabilities and hazards. Finally, two preliminary application examples of downscaling are given.

7. References

Auvinen, M., Boi, S., Hellsten, A., Tanhuanpää, T. and Järvi, L.: Study of Realistic Urban Boundary Layer Turbulence with High-Resolution Large-Eddy Simulation. Atmosphere 2020, 11, 201. https://doi.org/10.3390/atmos11020201, 2020.

Deardorff, J.W.: Stratocumulus-capped mixed layers derived from a three-dimensional model, Boundary-Layer Meteorology, 18, 495-527, 1980.

Favre, A., Philippon, N., Pohl, B., Kalognomou, E. A., & Lennard, C: DIAGNOSTIC DE LA VARIABILITÉ INTERANNUELLE DES SORTIES CORDEX-AFRICA SUR LE SECTEUR DE L'AFRIQUE DU SUD. In 27ème Colloque de l'Association Internationale de Climatologie (pp. 131-137). Association Internationale de Climatologie, 2014.

Hellsten, A., Ketelsen, K., Sühring, M., Auvinen, M., Maronga, B., Knigge, C., Barmpas, F., Tsegas, G., Moussiopoulos, N., and Raasch, S.: A nested multi-scale system implemented in the large-eddy simulation model PALM model system 6.0, Geoscientific Model Development, 14, 3185–3214, https://doi.org/10.5194/gmd-14-3185-2021, 2021.

Kotlarski, S., Keuler, K., Christensen, O. B., Colette, A., Déqué, M., Gobiet, A., Goergen, K., Jacob, D., Lüthi, D., van Meijgaard, E., Nikulin, G., Schär, C., Teichmann, C., Vautard, R., Warrach-Sagi, K., and Wulfmeyer, V.: Regional climate modeling on European scales: a joint standard evaluation of the EURO-CORDEX RCM ensemble. Geoscientific Model Developlment, **7:** 1297–1333, doi:10.5194/gmd-7-1297-2014, 2014.

Lehtonen, I., Hellsten, A., Auvinen, M., Barmpas, F. and Tsegas, G. High-resolution surface parameter maps, based on climate scenarios and available data. PLOTO deliverable report D3.1, 2023.

Maronga, B., Gryschka, M., Heinze, R., Hoffmann, F., Kanani-Sühring, F., Keck, M., Ketelsen, K., Letzel, M. O., Sühring, M., and Raasch, S.: The Parallelized Large-Eddy Simulation Model (PALM) version 4.0 for atmospheric and oceanic flows: model formulation, recent developments, and future perspectives, Geoscientific Model Development, 8, 2515–2551, https://doi.org/10.5194/gmd-8-2515-2015, 2015.

Maronga, B., Banzhaf, S., Burmeister, C., Esch, T., Forkel, R., Fröhlich, D., Fuka, V., Gehrke, K. F., Geletič, J., Giersch, S., Gronemeier, T., Groß, G., Heldens, W., Hellsten, A., Hoffmann, F., Inagaki, A., Kadasch, E., Kanani-Sühring, F., Ketelsen, K., Khan, B. A., Knigge, C., Knoop, H., Krč, P., Kurppa, M., Maamari, H., Matzarakis, A., Mauder, M., Pallasch, M., Pavlik, D., Pfafferott, J., Resler, J., Rissmann, S., Russo, E., Salim, M., Schrempf, M., Schwenkel, J., Seckmeyer, G., Schubert, S., Sühring, M., von Tils, R., Vollmer, L., Ward, S., Witha, B., Wurps, H., Zeidler, J., and Raasch, S.: Overview of the PALM model system 6.0, Geoscientific Model Development, 13, 1335–1372, https://doi.org/10.5194/gmd-13-1335-2020, 2020.

Moussiopoulos, N. "The EUMAC Zooming Model, a tool for local-to-regional air quality studies," Meteorology and Atmospheric Physics, vol. 57, no. 1–4, pp. 115–133, 1995.

Moussiopoulos N., Douros I., Tsegas G., Kleanthous S. and Chourdakis E.: An air quality management system for policy support in Cyprus, Hindawi Publishing Corporation, Advances in Meteorology 2012, doi:10.1155/2012/959280, 2012.

Saiki, E.M., Moeng, C.-H., and Sullivan, P.P.: Large-eddy simulation of the stably stratified planetary boundary layer, Boundary-Layer Meteorology, 95, 1-30, 2000.

Wicker, L.J. and Skamarock, W.C.: Time-splitting methods for elastic models using forward time schemes, Monthly Weather Reviews 130, 2088-2097, 2002.

Williamson, J.H.: Low-storage Runge-Kutta schemes, Journal of Computational Physics 35, 48-56, 1980.

Zängl, G., D. Reinert, P. Ripodas, and M. Baldauf: The ICON (ICOsahedral Non-hydrostatic) modelling framework of DWD and MPI-M: Description of the non-hydrostatic dynamical core. Q.J.R.Meteorol. Soc., 141, pp. 563–579, 2015.