

Urban Climate Under Change [UC]² – A National Research Programme for Developing a Building-Resolving Atmospheric Model for Entire City Regions

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Abstract

Large cities and urban regions are confronted with rising pressure by environmental pollution, impacts of climate change, as well as natural and health hazards. They are characterised by heterogeneous mosaics of urban structures, causing modifications of atmospheric processes on different temporal and spatial scales. Planning authorities need reliable, locally relevant information on urban atmospheric processes, providing fine spatial resolutions in city quarters or street canyons, as well as projections of future climates, specifically downscaled to individual cities. Therefore, building-resolving urban climate models for entire city regions are required as a tool for urban development and planning, air quality control, as well as for design of actions for climate change mitigation and adaptation. To date, building-resolving atmospheric models covering entire large cities are mostly missing. The German research programme “Urban Climate Under Change” ([UC]²) aims at developing a new urban climate model, acquiring three-dimensional observational data for model testing and validation, and testing its practicability and usability in collaboration with relevant stakeholders to provide a scientifically sound and practicable instrument to address the above mentioned challenges. This article provides an outline of the collaborative activities of the [UC]² research programme.

Keywords: urban climate, air quality, urban planning, climate change, building-resolving atmospheric model, large eddy simulation, observational data, model validation, applicability tests, data management

1 Introduction

Large cities and urban regions are highly sensitive to impacts caused by storms, heat and cold waves, droughts, heavy rainfall, episodes of increased air pollution, as well as to combinatorial effects of such events, since they cause health problems, fatalities and economic damages (SMITH *et al.*, 2014). In 2016, about 54.5 % of the global population was estimated to live in urban settlements (UNITED NATIONS, 2016). In Germany, the degree of urbanisation has already reached 75 % in 2014, and will presumably reach 83 % in 2050 (SCHÖN and MÜLLER, 2016). Due to regional consequences of

global climate change, problems caused by hazardous atmospheric events are expected to intensify in future decades and make extra efforts mandatory (IPCC, 2014). A key challenge for cities is dealing with many conflicting interests, e.g., between rising needs for living space for increasing numbers of city dwellers on one side, and necessary actions for adaptation to impacts of climate change on the other side. According to Russo *et al.* (2014), the disastrous effects of the 2003 and 2010 heat waves in Europe reveal that large, densely populated areas are likely to face increasing risks by adverse effects in the future. This demonstrates the particularly high need for effective actions in urban regions.

The long-term nature of existing urban infrastructure, in combination with long lead times for planning of new urban infrastructure, impede to address impacts of increasing air temperatures and changing precipita-

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tion patterns coming along with climate change (e.g. OECD, 2010). Therefore, planning authorities responsible for urban development need reliable, locally relevant information on projections of future climate specifically downscaled to individual cities in order to implement effective mitigation measures, such as increasing urban green or enhanced albedo of urban surfaces (see e.g., GROSS, 2012; SCHUBERT and GROSSMAN-CLARKE, 2013). It is essential to know how climate responds at city scales, how climate is affected by human influences, and about the role of natural climate variability and changes in the near future (GRIMMOND et al., 2010).

Urban structures cause modifications of atmospheric processes on different scales (see e.g. ARNFIELD, 2003, for a comprehensive review). Large cities show a broad spectrum of temporal and spatial scales with specific atmospheric processes that need to be resolved by numerical atmospheric models (see e.g. SCHERER et al., 2019, for a detailed discussion). Micro-scale processes need to be considered both by experimental research and numerical model simulations, e.g. for micro-scale simulations of wind comfort in cities (GROSS, 2014) or dispersion of air pollutants emitted into the urban canopy layer (UCL). Changes in local climates are often greater in magnitude than projected changes of global climate, since artificial materials, urban morphology, and emissions of air pollutants due domestic, commercial and transport activities exert strong effects on urban atmospheres (GRIMMOND et al., 2016). Research of local-scale (also called neighbourhood scale) atmospheric processes addresses atmospheric environments in street canyons and city quarters, i.e., in the UCL and the urban boundary layer (UBL). However, basic assumptions of standard one-dimensional schemes applied for investigating the UBL no longer hold valid, when dealing with horizontal resolutions of one kilometre or less, making new schemes accounting for interactions between three-dimensional urban-surface heterogeneity, the UCL and the UBL necessary (CHEN et al., 2012). Meso-scale atmospheric processes affect energy fluxes and balance over larger cities (ARNFIELD, 2003), thus urban atmospheric studies have to consider the UBL, the PBL, and the entire troposphere. Regional- to synoptic-scale weather situations and climate conditions, as well as long-distance transport of air pollutants are also relevant for urban atmospheric environments, and thus need to be included in urban studies.

Since atmospheric processes acting on different spatial scales are not independent from each other, it is not sufficient to study them separately, at least, if accurate data and reliable information are required for decision-making. So far, only few studies have explicitly followed multi-scale approaches spanning from micro-scales to global scales (for a review see, e.g., EMEIS, 2015). Output of GCMs was dynamically downscaled with regional and urban climate models to a resolution of three (KUSAKA et al., 2012) respectively one kilometre (LEMONSU et al., 2013). CONRY et al. (2015) performed one-way dynamical downscaling from global

(Community Atmosphere Model) to regional climates (Weather Research and Forecasting Model; see e.g. SKAMAROCK and KLEMP, 2008; CHEN et al., 2011), proceeding further to micro-scale climates by using, e.g., the ENVI-met model (BRUSE and FLEER, 1998). The study illustrated the problem that atmospheric models able to fully couple building resolving micro-scales to meso- or even macro-scales are not yet generally available. A spatial resolution of 50 m in predicting UHI effects was achieved by FRÜH et al. (2011) with a dynamical-statistical downscaling approach, in combination with interpolation of micro-scale model output. However, the model was only operated in offline mode. CONRY et al. (2015) stated that no multi-model nesting was so far used to downscale the output of a GCM to gain input data for a CFD model resolving micro-scale resolutions of 0.5 to 10 m.

One-way nesting of numerical models using model grids of different extents and resolutions is a commonly applied strategy for downscaling of meso- or macro-scale atmospheric processes to smaller scales. Unfortunately, urban climate models like ENVI-met are only able to resolve micro-scale processes at buildings and trees by fine grids in small city quarters, but are not able to use spatially distributed atmospheric forcing data. Instead, they only employ vertical profiles of atmospheric variables aggregated for the entire model domain. This limits their usability for urban-scale studies. Upscaling of micro-scale processes to larger urban areas, city districts or even to entire cities is not possible by one-way nesting or forcing.

To date, building-resolving atmospheric models that are applicable for entire large city regions are mostly missing. Existing models are limited in several ways. Some of them use coarse model grids, such that buildings and their effects on micro-scale atmospheric processes are not resolved, while others are only able to cover smaller urban areas, or cannot be used for long-term integration required for urban climate studies. RANS models fully parameterise turbulence, and thus are not able to explicitly resolve the effects of turbulence generated by buildings and trees on dispersion of heat and air pollutants, among other limitations. LES models do have these capabilities, but currently none of the LES models fully implements accurate schemes for physical and chemical processes under complex urban boundary conditions (see MARONGA et al., 2019, for a detailed discussion). Furthermore, existing urban climate models cannot be seamlessly combined with large-scale numerical models used for weather forecasts or regional climate projections. MILLS et al. (2010) stated that an integrated computer modelling framework is needed to bridge the range between the purpose meteorological data are needed for, the prediction of consequences of climate change, the diversity of urban structures and their rapid development and, above all, the different spatial and temporal scales.

In the framework of the [UC]² research, urban climate models are defined as numerical models that are

able to resolve atmospheric modifications caused by urban fabric, land use and human activities, which result in differences between cities and their surroundings with respect to weather, climate and air pollution. Although climatological statistics usually refer to aggregated values for 30-year periods, atmospheric modifications in cities (e.g. changes in air temperature and humidity, wind, radiation, concentration of air pollutants) can often be inferred from observed or simulated data for very short time periods as long as weather changes do not mask them. For this reason, urban climate models are often applied for weather conditions with low pressure gradients, and thus low wind speeds, and for sunny conditions leading to pronounced, micro-scale differences in atmospheric variables. By addressing one or a few selected meteorological situations, relevant aspects of the urban climate are addressed, and in combining results of several situations, the urban climate can be described. This approach overcomes the problems of long-term numerical integrations over many years or even decades that would require huge computing and data storage capacities. This is particularly relevant for applied studies where such capacities are mostly missing.

Before an urban climate model can be applied to real-world problems, it is essential to evaluate its performance using comprehensive, highly accurate observational data sets on weather and climate, as well as on air quality in cities. Various aspects constrain scale- and problem-specific implementation of urban climate observation networks (MULLER et al., 2013), thus such data sets are rarely available until now, particularly if multi-annual or multi-decadal time series from long-term observations are required. GRIMMOND et al. (2010) emphasized the need for operational urban meteorological networks within and around cities balancing resolution and practicability, as well as the need for LTO data sets.

Since June 2016 a new research programme entitled “Urban Climate Under Change” ([UC]²) is funded by the BMBF for a first period of three years to address the above-mentioned challenges. This article presents an overview on the collaborative activities of the entire [UC]² research programme, while three further articles discuss the specific research and development tasks for model development (MARONGA et al., 2019), acquisition of observational data for model evaluation (SCHERER et al., 2019), and development of requirements of a modern urban development and planning as well as applicability tests for both the new urban climate model and observational methods (HALBIG et al., 2019).

2 Aims and objectives

The [UC]² research programme aims at development, evaluation and application of an innovative, highly efficient and user-friendly urban climate model for entire cities called PALM-4U (PALM for urban applications, read: PALM for you). The model is based on the LES code PALM (RAASCH and SCHRÖTER, 2001; MARONGA

et al., 2015). It enables simulations of atmospheric processes for large city regions of up to 2000 km² with grid-resolved buildings and complex topography, as well as simulations for a large variety of regional climates. The PALM-4U model is applicable for a wide range of scientific and real-world problems related to urban development and planning, air quality control, reduction of greenhouse gas emissions, human comfort, and for adaptation to regional consequences of global climate change. Thus, users from different areas of target applications are involved in development and testing of the PALM-4U model to ensure its practicability and usability. The compilation of a users’ requirements catalogue ensures incorporation of their needs into model development. Practice partners are testing the practical and user serviceability of the new urban climate model by using test applications and case studies. With particular respect to users’ needs in city authorities, the PALM-4U model can be run on large massively parallel computers, as well as on local computers with limited resources. Model documentation, tutorials and free access to model source code are provided to the scientific community and the general public.

In addition, users of urban climate models, e.g. practitioners in urban planning and development, often do not have sufficient expertise, tools and IT infrastructures. Therefore, a web-based GUI for setting up the model, implementing planning scenarios, defining input data, conducting simulations, and for analysing and visualising model output data complements the PALM-4U model.

Testing and assessing the performance of the PALM-4U model demands comprehensive, accurate observational data sets on weather, climate and air quality in large cities. Thus, existing atmospheric data sets were compiled and processed, and new observational data sets were acquired by LTOs and measurements during twelve IOPs (two winter and two summer IOPs in three cities). For this purpose, new measurement concepts and analysis tools are developed and tested. Observational data also serve for applications in urban planning and air quality control, among others.

3 Structure of the research programme

The [UC]² research programme is organised as shown in Fig. 1 to reflect and address the broad spectrum and the complexity of the research and development tasks.

Three research modules (A–C) were implemented to take over specific tasks, i.e., development and testing of the PALM-4U model (A), acquisition of observational data for model evaluation (B), and testing the practicability and user serviceability of the PALM-4U model (C). Besides their individual tasks, the three modules intensively collaborate with respect to model validation (interface between A and B) and applicability tests of both the model (interface between A and C) and observational methods (interface between B and C).

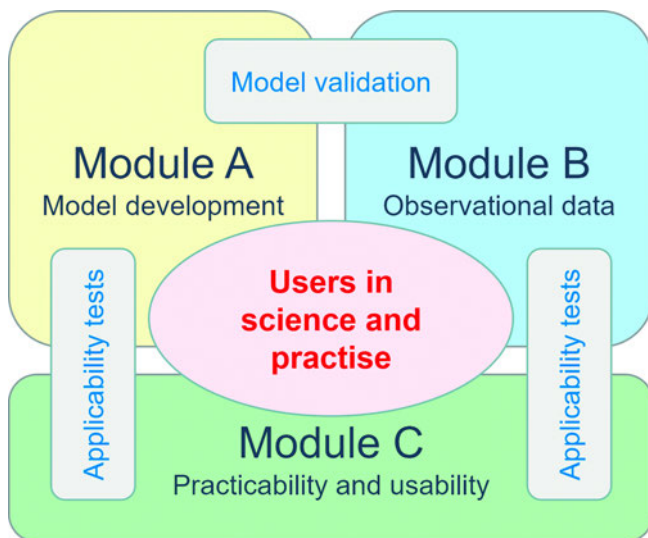


Figure 1: Overview on the structure of the [UC]² research programme.

In total, 30 subprojects are part of the [UC]² research programme with partners from universities, research institutes, private companies and governmental authorities.

3.1 Overview on the research modules

The research tasks allocated to module A are carried out by a consortium called “*Model-based city planning and application in climate change*” (MOSAİK; MARONGA et al., 2019; www.uc2-mosaik.org; accessed on March 8, 2019). The MOSAİK partners are developing and testing the new urban climate model PALM-4U, which is able to operate in both RANS and LES mode. The LES mode enables estimating turbulence-induced fluctuations (e.g. peak concentrations of air pollutants or wind gusts) for the first time with an urban climate model. The PALM-4U model, which was publically released on October 31, 2018, is able to simulate atmospheric processes (both physics and chemistry) for entire cities not only for neutral atmospheric conditions but also for non-neutrally stratified atmospheres. This is particularly important since atmospheric stability strongly varies within cities over short distances, depending on topography, land use, season, and time of day (NORDBO et al., 2013), and has strong effects on flows and dispersion of heat (RAMAMURTHY et al., 2007), water vapour and air pollutants (GAO et al., 2016; YASSIN, 2013), particularly near the ground.

The research tasks allocated to module B are carried out by the consortium “*Three-Dimensional Observation of Atmospheric Processes in Cities*” (3DO; SCHERER et al., 2019; www.uc2-3do.org; accessed on March 8, 2019). The 3DO partners compiled existing and are acquiring new atmospheric data sets from ongoing LTOs, and have carried out specific measurements during four IOPs in each of the cities of Berlin, Hamburg and Stuttgart. Observational data from LTOs and

IOPs will be used for model validation and applicability tests. Observations do not only cover the atmosphere near the ground but also the entire planetary boundary layer (and partly beyond) over the three cities and their surroundings.

The two consortia “*Climate Models for Practice*” (KliMoPrax) and “*Review of practical and user serviceability of an urban climate model to foster climate proof urban development*” (UseUclim) are jointly responsible for module C (HALBIG et al., 2019; www.uc2-klimoprax-useuclim.org; accessed on March 8, 2019), together with further partners from city authorities in Bonn, Berlin, Essen, Hamburg, Karlsruhe, Munich, Stuttgart, Chemnitz, Dresden and Leipzig, as well as the private planning company SWECO GmbH. Identification of user requirements for the PALM-4U model, both for its functionality and practical usability of the GUI, and of specific application examples to be used for applicability tests, as well as evaluation of practicability and serviceability of the PALM-4U model are the major tasks of module C.

3.2 Programme co-ordination

Each of the consortia is co-ordinated by one of the principal investigators (PI). The MOSAİK project is co-ordinated by G. GROSS and B. MARONGA, Leibniz University Hannover, while the 3DO project is co-ordinated by D. SCHERER, Technische Universität Berlin. The two projects forming module C are co-ordinated by F.-A. WEBER, Research Institute for Water and Waste Management at RWTH Aachen (KliMoPrax) and J. CORTEKAR, Climate Service Center Germany, Hamburg (UseUclim). The two consortia of module C have agreed upon a joined co-ordination team.

The entire [UC]² research programme is co-ordinated by D. Scherer, who is supported by the co-ordinators of the other project consortia. Since collaboration between the modules is complex but essential for the success of the [UC]² research programme, a number of programme-wide activities are carried out or scheduled, respectively. These activities include programme meetings, a website (www.uc2-program.org; accessed on March 8, 2019), as well as central PR activities complementing the websites and the PR activities of the three modules. The programme co-ordination is also responsible for organising specific meetings on programme-wide topics like data management, model validation and applicability tests. The project co-ordinators are jointly evaluating the progress of research and development within the [UC]² research programme, and are discussing upcoming requirements for new research and development activities.

3.3 Data management

Data management is highly complex since the [UC]² research programme uses and produces a multitude of data sets of different thematic layers, data structures

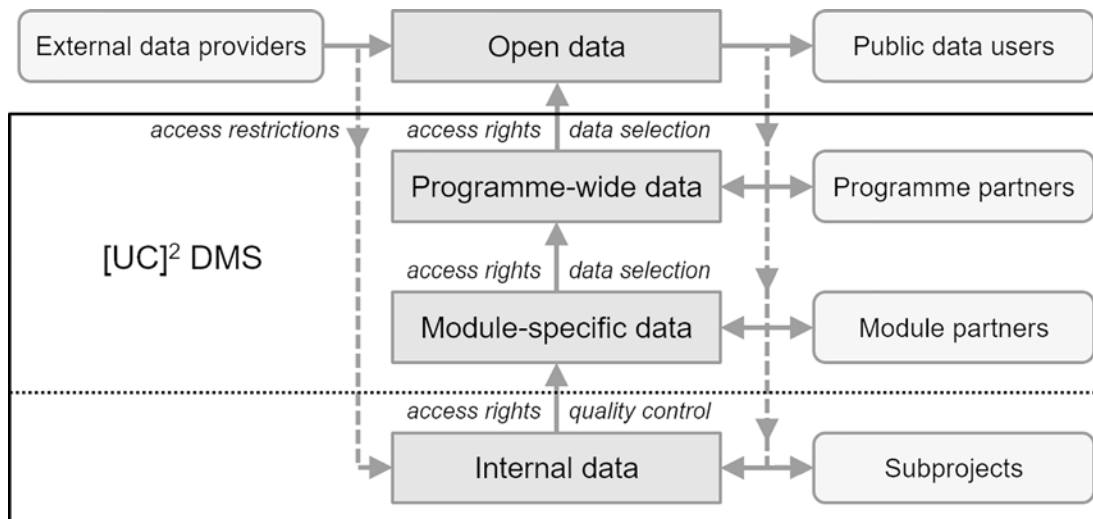


Figure 2: General data flow within the [UC]² research programme.

and file formats, as well as partly very large data sets exceeding tenths of Terabytes. Fig. 2 illustrates the data flow within the [UC]² research programme. A new DMS was developed and is used as repository for module-specific and programme-wide data sets for collaborative research.

In addition, a programme-wide working group on data management was implemented, which developed and continues to improve concepts and regulations for data management issues. The working group has released a [UC]² data policy (www.uc2-program.org/uc2_data_policy.pdf; accessed on March 8, 2019), as well as a [UC]² data standard enabling automatic exchange of data from numerical model simulations, wind tunnel experiments and observations. Seven different licence types are introduced: MOSAIK Licence, 3DO Licence; KliMoPrax Licence, UseUCLim Licence, [UC]² Restricted Licence, [UC]² Research Licence, [UC]² Open Licence. All data sets shall be made available under the [UC]² Open Licence, if not prevented by access restrictions, after the end of the [UC]² research program, i.e., May 31, 2019.

All data sets shared within the [UC]² research programme, with the scientific community and the general public follow standard data formats like NetCDF (www.unidata.ucar.edu/software/netcdf/; accessed on March 8, 2019). Data sets comprise meta-data that follow general scientific conventions like the CF Metadata Conventions version 1.7 (<http://cfconventions.org/latest.html>; accessed on March 8, 2019), which is based on the conventions of the COARDS (<http://ferret.pmel.noaa.gov/Ferret/documentation/coards-netcdf-conventions>; accessed on March 8, 2019). In addition, the SAMD product standard (https://icdc.cen.uni-hamburg.de/fileadmin/user_upload/samd_docs/samd_product_standard_v1.0.pdf; accessed on March 8, 2019) developed by the BMBF research programme “High Definition Clouds and Precipitation for Advancing Climate Predictions” (HD(CP)²; <http://hdcp2.eu>; accessed on

March 8, 2019) was considered as far as possible. The [UC]² data standard integrates data from observations, physical and numerical modelling, and also considers the needs of the established user community of the PALM model.

As shown in Fig. 2, subprojects provide existing static and atmospheric data sets from former or ongoing research activities, or produce new data sets as part of research and development within the [UC]² research programme, either by observational methods or by numerical model simulations. In addition, GIS data on terrain topography, building geometries and properties, and tree cadastres, are provided by some of the practise partners, or are publically available (e.g. digital elevation models derived from space-borne RS data). These data sets are regarded as internal data, which don’t have to follow the [UC]² data standard, and may be solely used by the subprojects themselves or a limited number of science or practise partners. Internal data are complemented by data from external sources, which may either be open data or do impose access restrictions, and are thus only available to certain partners.

A selection of data relevant for module-specific or programme-wide research activities is uploaded by the subprojects to the DMS after rigorous quality control. Data are formatted and licenced as specified by the [UC]² data standard. Data sets licensed under the [UC]² Research Licence or the [UC]² Open Licence will be made available to public data users, and are thus allowed to be stored in external data repositories.

A platform for sharing data, information, knowledge, and efficient tools for communication is required to manage the large number of persons involved in the [UC]² research programme, particularly since persons join and leave the subprojects at arbitrary times. Therefore, the [UC]² research programme uses a so-called Knowledge Base, which is a web-based dynamical platform integrating data and document repositories, a reference management system, tools for providing detailed

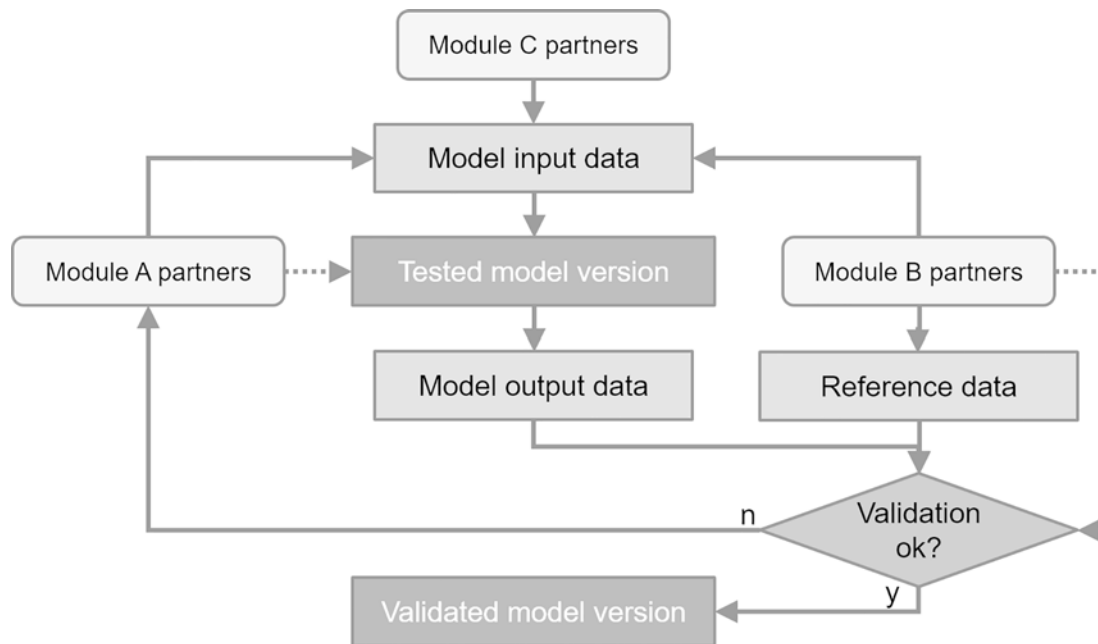


Figure 3: Concept for validating the PALM-4U model. Solid lines show the flow of data and information. Dotted lines indicate the respective partners responsible for performing model simulations and validation routines. Module C partners include the practise partners.

information on researchers, subprojects, modules, and working groups, as well as various communication tools (FEHRENBACH et al., 2015).

4 Model validation and applicability tests

Partners from modules A, B, and C as shown in Fig. 1 are jointly performing model validation and applicability tests for PALM-4U and observational methods. These collaborative activities are ongoing, and shall be finished at the end of the [UC]² research programme in May 2019.

4.1 Model validation

Partners from the modules A and B are mainly responsible for model validation as collaborative effort. Fig. 3 illustrates the general flow of data and information for validating the PALM-4U model. The partners perform technical and plausibility tests (internal validation) of single PALM-4U components, i.e., routines for resolving fluid dynamics, for parameterisation of thermodynamic processes (radiation, energy balance at the surface, boundary layer processes, etc.), and for air-chemistry computations. The entire model will be validated following established guidelines and procedures like the VDI Guideline 3783/9 (VDI, 2017), or the CED-VALLES approach developed by the COST Action 732 (FRANKE et al., 2011). According to these guidelines, model validation is part of model evaluation, which targets to assess a model's accuracy, i.e., to quantify deviations between results from model simulations and reference data from observations or physical experiments.

In the [UC]² research program, model results will also be compared against data from wind-tunnel experiments and results from further numerical models. This action will involve both the RANS and the LES mode of the PALM-4U model. The evaluation will also include a scientific analysis of the model validation results since deviations between model results and reference data may also stem from uncertainties in the input data or reference data, which therefore need to be thoroughly analysed. Knowing a model's accuracy with respect to individual variables does not imply that a model would be fit for any purpose. This is, however, an even more complex task since purpose-specific requirements on data accuracies must also be known. This task will remain for follow-on research activities

A working group on model validation was established as programme-wide activity for developing a concept for model validation, and for co-ordinating the entire process of model evaluation. The concept, which is still under development, specifies that both winter and summer simulations will be performed for the entire city regions of Berlin, Hamburg and Stuttgart using model grids of 15 m or finer. The PALM-4U simulations for Berlin and Stuttgart will be forced by real-case weather data produced by a meso-scale numerical model for time periods of two consecutive days (one day for model spin-up), for which appropriate reference data from field measurements are available. The two-way self-nesting option of the PALM-4U model (see MARONGA et al., 2019) will then be applied for simulations at very high spatial resolution of 1 m in domains that cover the so-called IOLs, which are comprehensively studied by the 3DO partners either by LTO or IOP measurements (see SCHERER et al., 2019). The high-resolution simulations

Table 1: Problem areas and application types addressed by the [UC]² research programme.

Problem area	Application type	Method	Description
Urban development and planning	Environmental impact assessment	M+O	Comparison of planned scenarios with the current situation as baseline
	Land-use plans	M	Area-based suitability testing for different types of land uses including delineation of areas for nature conservation (exclusion of certain types of land use)
Air quality control	Disaster risk management	M+O	Atmospheric dispersion modelling and observation of toxic air pollutants from instantaneous sources (e.g. fires, explosions)
	Action plans	M+O	Design of action plans and implementation of individual actions, e.g. as part of early-warning systems
Climate change mitigation	Monitoring of greenhouse gases	O	Long-term observations of concentrations and fluxes of greenhouse gases for detection and quantification of significant long-term trends
	Strategic environmental assessment	M+O	Comparison of planned components of a strategic plan for climate change mitigation with the current situation as baseline
Climate change adaptation	Risk assessment	M+O	Analysis of past and future natural hazards and risks using data from long-term observations and modelling studies
	Effectiveness control	O	Monitoring of environmental variables serving as indicators of the effectiveness of actions for adaptation to impacts of global climate change in cities

M: numerical and physical modelling; O: observation

will be performed in the LES mode, while the city-wide simulations will be performed either in the RANS or LES mode.

The PALM-4U model requires highly detailed and accurate input data for initial and boundary conditions for a specific simulation. These data sets are either static (e.g. GIS and RS data on topography, land cover, building geometry) or dynamic (atmospheric data). In addition, the 3DO partners provide input data on times and locations of observational data available from measurements at stations, vertical profiles, trajectories, or as gridded RS data from ground-based, aerial or satellite platforms. The PALM-4U model is then able to produce output data for these locations at full temporal resolution, which is of utmost importance to study e.g. turbulence phenomena without storing all data for each time step, which is not possible due to limited data storage capacities. PALM-4U simulations usually require time steps in the order of 1 s, while the number of grid points is in the order of 10⁹ points, such that a one-day simulation would require several hundredths of Terabytes for each variable.

Depending on the model domain, static and dynamic input data require resampling or interpolation from general data sources. The partners will perform both ideal- and real-case simulations, and compare model output data with reference data obtained either from wind tunnel experiments or from field observations. Data already used for testing the model will not be used in model validation. Whenever applicable, model and reference data

will be normalised, and deviations between model output and reference data will then be evaluated, depending on variable, errors and uncertainties in reference data. The evaluation will also include a qualitative discussion on application-specific requirements on model accuracy. Module A and B partners will prioritise variables that are essential for practical applications as identified by module C partners. A major challenge of model evaluation will be to assess the different sources of uncertainties, i.e., errors in input and reference data sets and model imperfections. A report on model evaluation and a suite of reference data sets will document the results.

4.2 Applicability tests

The [UC]² research programme aims at provision of new and improved tools to be used for a wide range of real-case applications (see Table 1). A number of real-case examples of future applications were chosen and are investigated by module C to test the applicability of the PALM-4U model, of observational methods, or a combination of both. Practice partners in local authorities and other focus groups involved in urban development and planning are future users of the PALM-4U model. Supported by scientific staff and computing power of module C, they are testing the practical and user serviceability of the PALM-4U model and the GUI by an iterative process (see HALBIG et al., 2019). The tests revealed and will continue to do so till the end of the [UC]² research programme, whether the users' qualifications,

skills, and IT infrastructures are sufficient to operate the PALM-4U model for specific applications by using the GUI, as well as GIS and observational data from a large variety of sources. This allows to identify future requirements for user qualification and training, IT infrastructures, and services eventually to be provided by third parties. A continuous and permanent dialogue between the partners involved in module C and with the research partners of modules A and B takes place along all process steps.

As far as possible, GIS and observational data that are freely available or part of operational measurements are used for the application examples. Thus, applicability tests will help to identify which of the existing data sources provide sufficient, accurate data for certain application types with respect to temporal and spatial coverage. Applicability tests will also provide information on required time for data acquisition and analysis, and associated costs. Application examples located in one of the three cities studied by module B may also use data that are acquired by module B. Therefore, IOP planning in module B also reflected requirements on specific observations stemming from application examples. Module C compiled a catalogue of user requirements, which are, however, not yet specifying quantitative, application-specific demands on data accuracies, neither for GIS and observational data nor for results from model simulations. This remains to the future.

5 Conclusions and perspectives

The [UC]² consortium, although operating only since June 2016, has been able to implement a highly ambitious research programme for integrated urban climate research combining investigations on weather, climate and air quality (see [BARLOW et al., 2017](#)). Research and development activities combine theoretical and experimental studies by physical and numerical models with state-of-the-art observational methods. Involvement of practitioners from municipal authorities or private companies document the transdisciplinary nature of the [UC]² research programme. The partners will make the results and products of the [UC]² research programme freely available to potential scientific and practical users, since they provide an excellent basis for a multitude of further research and application projects.

The MOSAIK project provides excellent opportunities to further improve the new urban climate model PALM-4U, which offers to serve as tool for a multitude of scientific and practical applications due to its computing efficiency and novel techniques. Due to the expected performance of the PALM-4U model, which will be distributed as open source software, the partners anticipate a rapidly increasing user community in the future.

Already now, the [UC]² research programme has further extended the scientific and technical infrastructures for LTOs of atmospheric processes using highly inno-

vative measurement techniques in Berlin, Hamburg and Stuttgart, which will in large parts be maintained by the 3DO partners as long-term infrastructures. Atmospheric data sets from LTO and IOP measurements will be publicly available for these cities after completion of the research programme. These data sets exhibit high potential for applications in urban weather and climate, air quality, climate protection and adaptation to climate change.

The broad experience of the scientific and municipal partners in the KliMoPrax and UseUCLim consortia ensures that the research and development efforts in modules A and B are guided by practice-oriented user requirements. The PALM-4U model shall be integrated in existing climate services to assist decision making in urban planning projects and related fields of application. The contribution of module C to transfer products and results to potential user groups is thus of great importance.

Despite the achievements described above, there are still open questions that need to be addressed by future research. First of all, the PALM-4U model is currently not designed for simulating strong precipitation events, which is, however, a highly important field of application. Second, reference data for validating the model under weather conditions with high wind speed have not been acquired during the IOPs carried out by the 3DO project, since the focus of these measurements was to study weather situations leading to most pronounced urban atmospheric modifications. Third, the PALM-4U model's uncertainties need to be quantitatively characterized for specific fields of applications. This requires information on application-specific users' demands on accuracies, suitable reference data of high accuracy for each of the application fields, and PALM-4U simulations for specific weather conditions during which the respective aspects (e.g. heat waves, thunderstorms, high levels of air pollution) can be studied in detail. Compound phenomena like heat waves and droughts also need to be considered, which make such analyses even more complex. Finally, the [UC]² research programme could already identify that the static GIS data sets on micro-scale terrain topography, building geometries and properties, and tree cadastres available for the individual cities are highly heterogeneous and incomplete with respect to the demands of the PALM-4U model. Since sophisticated models like PALM-4U generally depend on accurate input data, uncertainties in simulation results are partly also stemming from deficiencies in input data. Therefore, new cost-efficient methods for deriving accurate and complete static input data from various data sources are required, as well as new analysis methods that allow to quantify how errors in input data propagate to the simulation results, and thus could limit the model's applicability.

The partners plan to initiate a so-called “*Urban Climate Model Intercomparison Project*” (UCMIP). The UCMIP could either be implemented as a component of a second phase of the [UC]² research programme or as an independent follow-up project.

Appendix – Abbreviations

BMBF	German Federal Ministry of Education and Research
CF	Climate and Forecast Metadata Conventions
CFD	Computational Fluid Dynamics
CEDVAL	Compilation of Experimental Data for Validation of Microscale Dispersion Models
COARDS	Cooperative Ocean/Atmosphere Research Data Service
COST	European Cooperation in Science & Technology
DMS	Data management system
GCM	General circulation model
GIS	Geographic information system
GUI	Graphical user interface
IOL	Intense observation location
IOP	Intense observation period
IT	Information technology
LES	Large Eddy Simulation
LTO	Long-term observation
NetCDF	Network Common Data Format
PALM	Parallelized Large Eddy Simulation Model for Atmospheric and Oceanic Flows
PBL	Planetary boundary layer
RANS	Reynolds-Averaged Navier Stokes
RS	Remote sensing
SAMD	Standardized Atmospheric Measurement Data
UBL	Urban boundary layer
UCL	Urban canopy layer
UHI	Urban heat island

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