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Project MOSAIK: Model-based city planning and application in climate change – development of the new urban climate model PALM-4U

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Abstract

MOSAIK is one of three modules of the nation-wide program “Urban Climate Under Change” ([UC]^2)[A], altogether with 30 sub-projects, funded by the German Federal Ministry of Education and Research (BMBF). The central goal of [UC]^2 is the development, validation and application of a modern, efficient and user-friendly urban climate model. The MOSAIK projects are responsible for the development of the new urban climate model, with its core based on the modern, highly parallelized and optimized large-eddy (turbulence-resolving) simulation model PALM. New features to-be-implemented are: Reynolds-averaged-Navier-Stokes-type turbulence parameterizations for fine and coarse spatial resolution; nesting with large-scale models and self-nesting to focus on specific areas like small city quarters (so-called zoom function); an energy balance solver for all relevant urban surface types, as well as an indoor climate and energy demand model for buildings; an urban chemistry model; a multi-agent system in order to study environmental effects on large groups of people. Further aspects of MOSAIK are the preparation, supply and management of required input data for the model evaluation, e.g. maps of building height, vegetation coverage or land-surface elevation. Finally, a graphical user interface will be developed, enabling a user-friendly operation of the new urban climate model – named PALM-4U.

1. Overview

With the growing economical importance of cities, the people's “natural” environment for working, accommodation and recreation is an urban settlement. A growing city population is associated with a replacement of nature spots, a concentrated consumption of resources,

A Program website: http://www.uc2-program.org/.

[UC]^2 Urban Climate Under Change
Stadtklima im Wandel

a high energy demand, and increased air pollution. The interactions between urban areas and the atmosphere have received growing attention in urban climate research in the last decades [1]. The main challenges in the 20th century were the urban heat island problem [2] and urban air quality issues [3], both affecting human health and comfort. It is therefore necessary to include these aspects in sustainable and future-oriented city planning, especially under consideration of local and regional impacts of climate change, leading to increased threats of heat waves and declining air quality [4]. Urban climate models (UCMs) are the tool of choice to estimate effects of the city morphology – such as building density, degree of soil sealing, façade greening, etc. – on air quality and thermal/wind comfort for urban residents.

Within the joint research project MOSAIK[B] – as part of the three-year nation-wide program “Urban Climate Under Change” ([UC]^2) funded by the German Federal Ministry of Education and Research – a new modern and user-friendly UCM of unprecedented spatial resolution and computational performance will be developed. The highly parallelized and optimized large-eddy simulation (LES) model PALM[C] will serve as the core of the new model PALM-4U (reads PALM *”for you”* and ”*for U*rban applications”), which shall be applicable on massively-parallel computers as well as on city planners' local PCs and workstations.

Features that will be added to the PALM core in order to make PALM-4U a full UCM are: Reynolds-averaged-Navier-Stokes (RANS) type turbulence parameterizations for fine and coarse spatial resolution; an energy balance solver for all relevant urban surface types, an indoor climate and energy demand model for buildings, and an urban chemistry model; a multi-agent system (MAS) for studies of environmental effects on large groups of people; grid nesting to allow forcing by larger-scale models, and self-nesting to enable a magnifying-lens function that allows planners with limited computer resources to perform high-resolution studies for specific areas of interest, e.g. small city quarters or single streets. These features will allow both simulations with very high spatial resolution (down to 1m) for large cities or long climate projections, as well as more focused applications with coarser resolution, and exemplary periods or specific areas. With its LES core, PALM-4U is the first UCM with LES mode, allowing for a direct quantification of turbulence-induced fluctuations (e.g. peak concentrations or wind gusts).

PALM-4U will be able to provide maps of urban climate and bio-climate standard products including physiological equivalent temperature (PET) and universal thermal climate index (UTCI), but in addition the MAS will also help to identify areas for humans with high stress potential based on the individual characteristics of the agent, such as the

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B In German: **MO**dellbasierte **S**tadtplanung und **A**nwendung **I**m **K**limawandel.
In English: Model-based city-planning and application in climate change.
Project website: http://www.uc2-mosaik.org/

C PALM website: https://palm.muk.uni-hannover.de/

walking path and speed, age, clothing, etc.. These hotspots cannot be determined from standard maps, because they do not take into account peoples' behavior.

The new model requires local surface information with very high resolution of building topography, vegetation, soil moisture etc., which can be derived from sources like satellite data, aerial imagery, and existing municipal data. A special focus will be the data input/output formats and data interfaces to PALM-4U in order to support standards of (future) city planning. Data will be stored in an online data management system in a consistent format, including a standard data catalog for typical weather and climate scenarios as well as for high-risk situations such as rainfall extremes and heat waves. An intuitive web-based user interface will allow to define input data and model setups, to carry out the simulations, and to analyze and assess model output data.

2. PALM-4U development

2.1 RANS and LES mode

State-of-the-art urban flow and dispersion modeling is based on RANS models, where turbulence on all scales is filtered out and fully parameterized. This approach limits the accuracy and universal applicability of such models and leads to known deficiencies in building wakes [5] and urban weak wind regions [6]. However, RANS models typically are computationally least expensive, which is the main reason they are and will be used for practical applications.

The computational advances in recent years have made the application of LES affordable for practical urban modeling applications [7]. In such models, relevant scales of turbulent motion are explicitly resolved, i.e. LES is capable of capturing the inherent unsteadiness of turbulent flow and dispersion in the urban canopy [8]. As the base model PALM is an LES model, it already includes a subgrid-scale model to parameterize the unresolved part of the turbulence in LES mode. For the RANS mode, the subgrid parameterizations need to be extended to cover a broader range of unresolved turbulence, and these formulations need to be scale dependent, since the model will operate under different spatial resolutions (10^0-10^2m). For coarser resolutions, building and vegetation effects must be parameterized as well, since these objects are not explicitly resolved.

2.2 Grid nesting

To evaluate the turbulent flow in an urban area, all relevant processes that affect the local environment need to be considered in a simulation, covering a wide range of spatial scales from the local scale (e.g. effects of single trees or buildings) up to the regional (e.g. urban heat island) or even the synoptic scale. Resolving all these scales in one simulation requires a large model domain (10-100 km) and a fine grid (1 m), which is still hard to handle in terms of the available computational resources.

The alternative is to apply the grid-nesting technique [9, 10], where the regional processes are simulated on a coarse grid for a large model domain, and the local processes are simulated on a fine grid only for the domain of interest. Different nesting methods will be implemented: (i) large-scale nesting enables to force PALM-4U with externally derived meteorological data from e.g. numerical weather prediction or climate models, or measured data; (ii) recursive PALM-4U self-nesting enables a magnifying-lens feature for small areas, e.g. to study effects of a building on the local environment.

2.3 Surface energy budget

The local temperature within a complex urban environment is determined by the texture of the urban surfaces as well as by the atmospheric conditions. These site conditions – the properties of soil, vegetation, surface/wall materials, atmosphere – have to be considered by means of a surface energy budget model, in order to calculate the temperature of each urban surface element based on its individual properties such as surface albedo, heat capacity and conductivity, etc.. As the surface temperature is a key element for urban climate, particular attention must be paid to the proper calculation for very different surfaces and soil properties. The surface energy budget model in PALM-4U will be able to consider e.g. bare soils, paved roads and places, crashed rocks and gravel, trees and other vegetation including shadow effects, parks, water bodies of variable depth, building façade and roof greening.

2.4 Urban radiation and building parametrization

Radiative fluxes at urban surfaces and between buildings are parametrized for the entire range of resolutions (10^0-10^2m). The fluxes are required in the energy balance of the urban surfaces, for the direct human radiative exposure, and in air chemistry applications. At each urban surface element, fluxes of the diffuse longwave as well as the diffuse and direct shortwave radiation are calculated. This approach will include the casting of shadows, and the radiation exchange within the urban canopy, e.g. reflection of shortwave radiation between buildings. Furthermore, an effective building/street representation in the form of urban street canyons (“double-canyon effects parametrization” (DCEP) as implemented in COSMO-CLM, see e.g. [11]) will be implemented for non-building-resolving resolutions. These street canyons are characterized by: building and street width, orientation of the canyon, building-height distribution.

2.5 Indoor climate and energy demand

A holistic building model [12, 13] will be implemented to PALM-4U, responsible for the combined calculation of indoor climate (e.g. indoor temperature and air quality) and energy demand (e.g. for heating, cooling, lighting and ventilation), based on an extensive building database that includes: (i) building properties such as geometry, material, available windows, and ventilation models; (ii) occupants' behavior, based on (stochastic) models that consider window opening and use of solar control, occupants profiles regarding attendance, and internal heat gains; (iii) a person description, including metabolic rates and clothing values; (iv) the HVAC (Heating, Ventilation and Air Conditioning) energy supply system, based on characteristic line models (considering the applicable standards) for different air-conditioning concepts, including operation strategies for the energy supply system. The building model is based on an analytic solution of Fourier’s equation, and it dynamically interacts with the energy balance solver for the building surfaces, i.e. the calculated indoor temperature depends on the outside-wall temperature, and vice versa.

2.6 Urban chemistry and air pollution

Poor air quality in urban areas, due to strong anthropogenic emissions combined with poor city ventilation, has a negative effect on human health and well-being. In order to apply PALM-4U for air quality analysis and mitigation studies, the transport and chemical transformation of atmospheric pollutants – in the gas phase and in the form of aerosols –

need to be implemented. This is realized by the kinetic pre-processor KPP[D] (e.g. used in the Weather Research & Forecasting Model WRF), which generates the required chemistry code for PALM-4U, based on the selected pollutants to be simulated. The implemented chemistry modes will be of different complexity: (i) a more simple chemistry scheme for the computationally more expensive LES mode; (ii) a more complex chemistry for the RANS mode of PALM-4U. Besides the chemistry schemes, additional modules and input are required, such as photolysis (dissociation of molecules by solar radiation), boundary conditions, or anthropogenic and biogenic emissions.

2.7 Multi-agent system (MAS)

Quality of life in cities is associated with wind comfort, heat stress, radiative exposure, and air pollution. In order to obtain a general view of the environmental load, the spatial distribution of relevant meteorological parameters are used for a mapping of human-stress zones in urban areas. However, such a conventional (Eulerian) approach neglects the wide spectrum of urban-resident characteristics including socio-economic data.

By means of an MAS to be embedded in PALM-4U in the form of the Lagrangian particle approach already available in PALM, individual stress levels based on local atmospheric conditions can be determined for specific groups of people with particular attributes as e.g.: age, size, skin sensitivity, health, clothing, etc. Together with socio-economic data – such as the age distribution, work or leisure activities, and frequenting of paths in a specific urban area – comfort areas, heavy loaded places and optimized walking paths can be estimated.

One focus of the MAS is on the thermal well-being of the urban residents in different temporal and spatial contexts, estimated via a human energy balance that uses equivalent temperatures such as PET or UTCI to describe the integral thermal environment of the human body. Further focus is on the local exposure of urban residents to UV radiation, derived by an exposure model that takes into account: (i) complex geometry of a resident as well as clothing habits; (ii) anisotropy of radiative fluxes; (iii) shading by buildings.

2.8 Code verification and performance tests

One part of the PALM-4U development is the verification and validation of new code components. This includes code revision as well as functionality tests of each component and their interactions. Further, performance tests (benchmarking) on supercomputer systems are necessary to ensure that the high efficiency of the PALM code, with respect to computing time and scalability of the code on large numbers of processor cores, is maintained by PALM-4U. An essential goal of MOSAIK is to demonstrate that PALM-4U is able to run with limited computer resources – as it is the case e.g. in city-planning applications. This will be demonstrated on a project workstation, packed with an affordable number of processor cores. Besides these more technical tests, a verification of PALM-4U against the VDI[E] requirements, and a comparison with results from existing UCMs will be accomplished.

D KPP web page: http://people.cs.vt.edu/~asandu/Software/Kpp/

E In German: Verein Deutscher Ingenieure; in English: Association of German Engineers. See https://www.vdi.de/

3. PALM-4U operation

3.1 Preparation and management of input and output data

The steering of PALM-4U requires certain input data – terrain height, building height/distribution, surface albedo, percentage of impervious/vegetated surfaces – in order to appropriately estimate the effects of city morphology and surface properties on the urban (micro-)climate. Such data are derived from communal, federal and state geo-data (e.g. cadastral information), and remote sensing imagery. The latter offers an area-wide source of information about the land surface texture, derived by false-color aerial imagery or satellite data. Elevated surface parameters (e.g. green roofs, vegetation volume) require a very high-resolution digital elevation model – e.g. derived from laser-scan data. This source of data nowadays exists for most German cities.

Additional data required for the surface energy balance solver is the soil water content for all pervious surfaces, as a key parameter for percolation and evaporation. The soil water content will be provided by the water balance model STORM [14].

All input and output data, required and produced within MOSAIK, will be administrated by a central data management system. This will allow an easy exchange of the relevant data throughout the entire $[UC]^2$ project. An important prerequisite for the proper functionality of the data management system is the pre-definition of consistent data formats/standards and metadata.

3.2 Graphical user interfaces for PALM-4U operation

A user-friendly graphical interface will be developed, enabling prospective users of municipal administrations and private enterprise companies for climate consulting to easily apply PALM-4U as well as to evaluate the model output, provided that a certain basic knowledge is available.

The second user-friendly tool to be developed is a software package for the initialization and forcing of PALM-4U with data from meso-scale atmospheric models of the German Weather Service (Deutscher Wetterdienst). A scenario catalogue will be included, covering various weather situations or climate projections to choose from.

4. Final remark

PALM-4U will be available as Open Source software to all interested users, consultancies, and the public authorities. The German Weather Service plans to use PALM-4U for future commercial and research investigations of urban environments in Germany.

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Project partners

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