Urban Climate 56 (2024) 102059

Contents lists available at ScienceDirect

Urban Climate

journal homepage: www.elsevier.com/locate/uclim

A city-scale turbulence-resolving model as an essential element of integrated urban services

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ARTICLE INFO

Keywords:
Integrated urban services
PALM modeling system
Urban air quality
Urban thermal comfort
Turbulence-resolving model development
Storylines and simulations

ABSTRACT

Large-eddy simulation (LES) models, such as the PALM modeling system in this study, are actively used for urban micro-climate modeling. We consider urban LES in a broader context as a mature high-resolution model for integrated urban services (IUS), which is an initiative of the World Meteorological Organization that provides a modeling component for urban decision-support systems. A decision-support system requires iterations of quantitative information from knowledge providers and qualitative expert assessments from communities of practice. We present two pilot PALM-aided IUS from the "Turbulent-resolving urban modeling of air quality and thermal comfort" (TURBAN) project. One pilot has its focus on an air quality service contributing to a decision-support system of the port of Bergen, Norway. Another pilot contributes to air quality and thermal comfort services in the city of Prague, Czech Republic. Co-production sessions with stakeholders identified critical enablers for urban LES in IUS. We present integration and interpretation of the modeling information within the decision-making process with a "storylines and simulations" (SAS) approach based on a web-based geoinformation system (WebGIS).

1. Introduction

Each city is unique. Each city is created by an intricate interplay of geographical, morphological, climatic, and ecological conditions that shape its urban physical environment (Oke, 2006). Societal factors contribute too. Each city has its own unique historical trajectory and develops a unique set of socio-economic features. Urban features translate into urban morphology augmented by architectural solutions and, eventually, to specific urban microclimates. On a global scale, cities play a central role in human civilization controlling energy and material flows, environmental pollution, and climate change (Creutzig et al., 2019). This global role of cities

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https://doi.org/10.1016/j.uclim.2024.102059
Received 22 April 2024; Received in revised form 16 June 2024; Accepted 5 July 2024
Available online 11 July 2024
2212-0955/

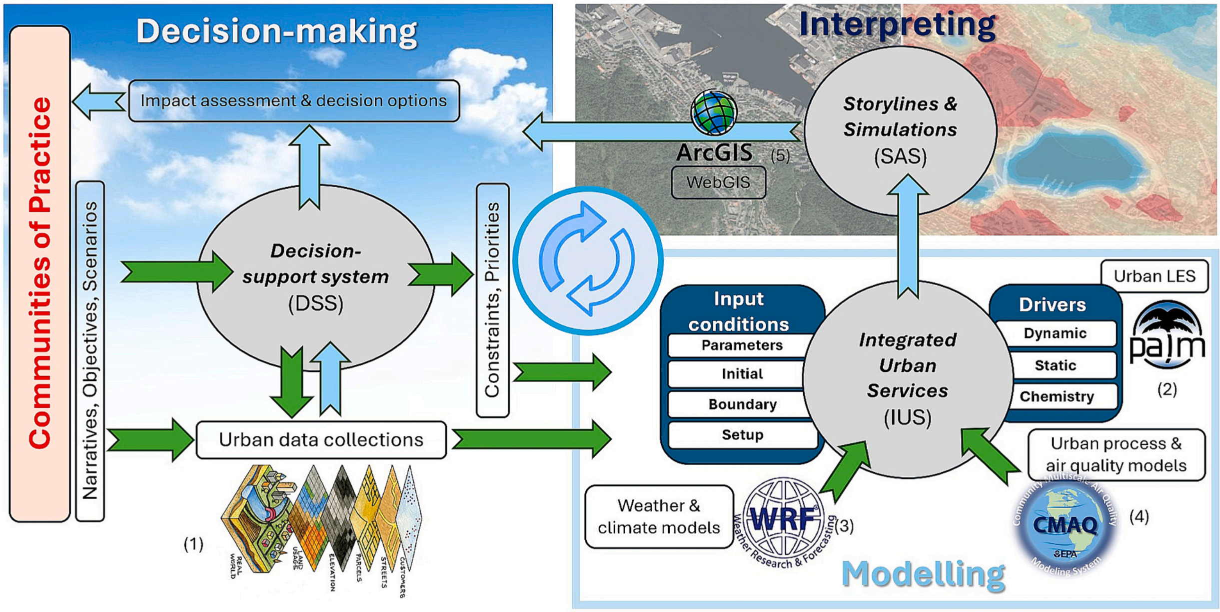

Fig. 1. A methodological framework for urban decision-making explored in the TURBAN project. The decision-making block includes a decision-support system (DSS) created by communities of practice (the port of Bergen, the city of Prague). DSS identifies the needs, sets up constraints and priorities, organizes urban data collection, and suggests decision options and solutions. DSS issues requests for modeling information. The integrated urban hydrometeorological modeling services (IUS) in the modeling block prepare input conditions, simulation parameters and drivers, and ensure seamless data flow between models of different class: weather and climate models exemplified by the Weather Research and Forecasting (WRF) model; air quality models – by the Community Multiscale Air Quality (CMAQ) model; urban large-eddy simulation (LES) and other computational fluid dynamics models – by PALM. The interpreting block includes storylines and simulations (SAS) approach. SAS translates IUS modeling results to knowledge understood by the DSS stakeholders. A Web-based Geo-Information System (WebGIS) provides an advanced technological platform for SAS, here ESRI ArcGIS solutions are used. The background image is taken from our WebGIS storytelling for Bergen. The loop symbol between the blocks highlights the need for co-production between technology experts and community stakeholders. The graphical icons are taken from: (1) https://roundup.getdbt.com/p/data-lineage-layers-collaborative; (2) https://palm.muk.uni-hannover.de/trac; (3) https://www.epa.gov/cmaq; (4) https://www.mmm.ucar.edu/models/wrf; (5) https://www.arcgis.com/index.html.

raises the significance of environmentally responsible urban governance. To improve urban governance, communities of practice (urban stakeholders at any level of governance) need a holistic decision-support system (DSS) that incorporates geographically resolving urban models and data analysis (González et al., 2013). A mature DSS organically combines qualitative (narrative scenarios and expert opinions) and quantitative (observational data analysis and computer modeling) components. The latter, quantitative, component is naturally provided by Integrated Urban hydrometeorological and air quality modeling Services (IUS) (Baklanov et al., 2020, 2018; Grimmond et al., 2020). The IUS results could be efficiently communicated back to the DSS stakeholders with a "Storyline and Simulations" (SAS) approach (Houet et al., 2016). This approach "fuzzilizes" the data analysis and simulation results (Alcamo, 2008) making the potentially useful information usable and used (Lemos et al., 2012).

Urban uniqueness and complexity have so far impeded efforts to develop DSS that organically simulate urban physical and societal environments in interaction (Caldarelli et al., 2023). It is perhaps not surprising that we see numerous reincarnations of much-criticized technocratic "smartening" of cities that hand decision-making to information technology systems (Jiang et al., 2022). The IUS initiative of the World Meteorological Organization (WMO) could be a game-changer (WMO, 2019). At present, a typical IUS includes a downscaling modeling chain operating at global to regional meteorological scales down to a horizontal spatial resolution of about 1 km (Esau et al., 2021; Mahura et al., 2024). The IUS chain inherits the lack of coupling to models operating at arguably the most important urban scales which are finer than 1 km. A seamless extension of models across this scale barrier - the meteorological "terra incognita" (Wyngaard, 2004) - is hampered by the apparent inability of turbulence parameterizations to represent processes at microscales over complex surfaces (Rai et al., 2019). Mesoscale atmospheric models include urban processes through subgrid-scale parameterizations of different complexity. Parameterizing requires a universal representation of atmospheric dynamics and air-land/air-sea interactions. Cities lack such universality.

Not all is hopeless, however. Analysis of observations reveals that atmospheric motions on smaller scales of three-dimensional turbulence are more universal than quasi-two-dimensional large-scale motions. The lack of universality on meso-meteorological scales (1 km to 100 km) makes the urbanization modeling schemes dependent on numerous poorly defined and hardly accessible case-specific parameters (Ching et al., 2018; Masson et al., 2020a; Nuterman et al., 2021). Moreover, sophisticated urbanization schemes might not deliver the expected performance in capturing urban atmospheric interactions, energy and mass fluxes, and pollution transport (Grimmond et al., 2011). Contrary, universal energy scaling is found in the inertial (Kolmogorov) subrange under very different atmospheric conditions both in spatially homogeneous (Larsén et al., 2016) and complex urban (Fortuniak and Pawlak, 2015; Roth, 2000) environments. This universality on turbulence scales could be used for the benefits of urban modeling. The urban LES models, at least in principle, explicitly resolve atmospheric motions larger than those in the inertial subrange. In this sense, the urban LES models resolve the unique and complex part of the atmospheric environment, whereas its more universal part remains parameterized.

We recognize that a strict LES criterion - the explicit resolution of turbulent eddies within a part of the inertial subrange of scales, usually <50 m (Cuxart, 2015) - may not always be satisfied in simulations for applied IUS. Turbulence within the urban canopy layer is also under-resolved in a typical LES application. Auvinen et al. (2020) recommend a resolution with 20 model levels within the urban canopy, which is currently unattainable in applied urban LES. Still, one may take advantage of the universality of small-scale turbulence in the urban canopy and roughness layers (Kanda et al., 2013; Macdonald, 2000; Roth, 2000; Wood et al., 2010). With these cautions in mind, we will still refer to this class of models as urban LES resolving at least the largest structures in the urban atmosphere (Christen et al., 2007). Barthlott et al. (Barthlott et al., 2007) observed that the large coherent structures occupied 36% of the total time of observations carrying about 44% of turbulent momentum and 48% of turbulent heat fluxes. Thus, it is arguable that explicit modeling of large-scale turbulent structures makes urban atmospheric processes and flows more tractable.

The benefits of urban LES can be summarized as follows. Urban LES: (i) resolve the most energetic/dispersive turbulent motions in the atmospheric boundary layer; (ii) are able to simulate internal boundary layers, local turbulent flows above and to some degree within the urban canopy, and impact of surface heterogeneity on atmospheric eddies; (iii) are aware of spatial locations of the pollution sources and able to advect extreme concentrations within turbulent air pockets. The most important shortcomings of the urban LES models are (i) sheer computational cost that rapidly increases with resolution refinement in three dimensions; (ii) ad hoc initialization methodology that does not allow to capture configurations and properties of instant turbulent eddies; and (iii) deficit of initialization data at fine spatial resolutions.

Computer simulations constitute however just a part of the decision-making process. “To make a decision we need to know the problem, the need and purpose of the decision, the criteria of the decision, their subcriteria, stakeholders and groups affected, and the alternative actions to take” (Saaty, 2008). Not all modeling information could be useful for and used in DSS. “Knowing more does not guarantee that we understand better” as Saaty (2008) ported it. As we will demonstrate in our study, urban stakeholders are frequently less interested in precise numbers obtained with modeling than in the spatial patterns obtained through spatially explicit modeling. High spatial resolution of urban LES seems to provide for such user needs. That is why urban LES gradually became more accepted among urban stakeholders despite the mentioned barriers and challenges. To become mature, that is to grow out of the academic research domain and to be operationalized (Jakob et al., 2023), urban LES must become receptive to intangible criteria set by the experts from the communities of practice. We schematize the priorities, criteria, and information flow in Fig. 1. The stakeholders' qualitative priorities and criteria undergo “de-fuzzilization”, whereas quantitative model information needs “fuzzilization” to become actionable in communities of practice (Alcamo, 2008). The criteria and priorities could affect the model setup, configuration, parameters, as well as the simulation procedure itself. Simulation scenarios are to be developed iteratively in a co-production process with communities of practice and decision-makers (Kolstad et al., 2019; Masson et al., 2014).

Our choice of urban LES for the LES-enhanced IUS is the PALM modeling system (Esau et al., 2021; Maronga et al., 2020; Resler et al., 2021). Correspondingly, we refer to our IUS modeling chain as the PALM-aided IUS. This study presents two pilot PALM-aided IUS. One IUS demonstrates an integration of PALM simulations into DSS for the port of Bergen, Norway. In this DSS, a generic goal (to sustain a healthy urban atmospheric environment) branches out into an associated objective (to reduce air pollution), indicators (e.g., concentrations of PM2.5 or NOx), and targets (to keep population expose to air pollution below a certain threshold). Another IUS demonstrates the PALM-aided DSS for nature-based urban air quality solutions in the city of Prague, Czech Republic. This IUS analyzes the impact of urban greenery (trees in urban street canyons) and changes in the traffic infrastructure on human thermal comfort and the air quality and ventilation around the Legerova and Sokolská streets. Both pilot IUS wouldn't be possible without the recent model advancements brought by the “Model-based city planning and application in climate change” (MOSAIK) (Fröhlich and Matzarakis, 2020; Maronga et al., 2020, 2019) and the “Turbulent-resolving urban modeling of air quality and thermal comfort” (TURBAN) projects (Resler et al., 2021). Contributions from other PALM development groups, especially from the University of Helsinki (Hellsten et al., 2021), are also acknowledged.

The structure of this manuscript is the following. The PALM-related issues and methods are given in the next Section 2. Section 3 demonstrates the results of two pilot PALM-aided IUS in Bergen and Prague. Section 4 discusses the challenges of model interpretation and communication and introduces the SAS approach realized on an advanced technological platform of a web-based geographical information system (WebGIS). Section 5 outlines conclusions, lessons learned, and prospects of further PALM integration with DSS, IUS, and WebGIS.

2. The urban large-eddy simulation modeling system PALM

Urban LES has changed our understanding of turbulence diffusion, radiative exchange, and atmospheric transport processes in cities. At the beginning, they were simple simulations of a steady-state flow over thermally patchy surfaces (Cai, 1999; Wood, 2000), wall-mounted cubic obstacles (Xie and Castro, 2006), and street canyons (Letzel et al., 2008). Urban LES today are sufficiently developed to enable the fully-fledged interrogation of the urban policy scenarios and emergency response to extreme and dangerous events (Masson et al., 2020b; Mirzaei, 2021). Increased computing capacity enables urban LES to confront the wicked challenges of urban climate change and intricate socio-environmental interactions.

Urban LES is a method that admits many different technological realizations. Our perspective is based on the realization known as

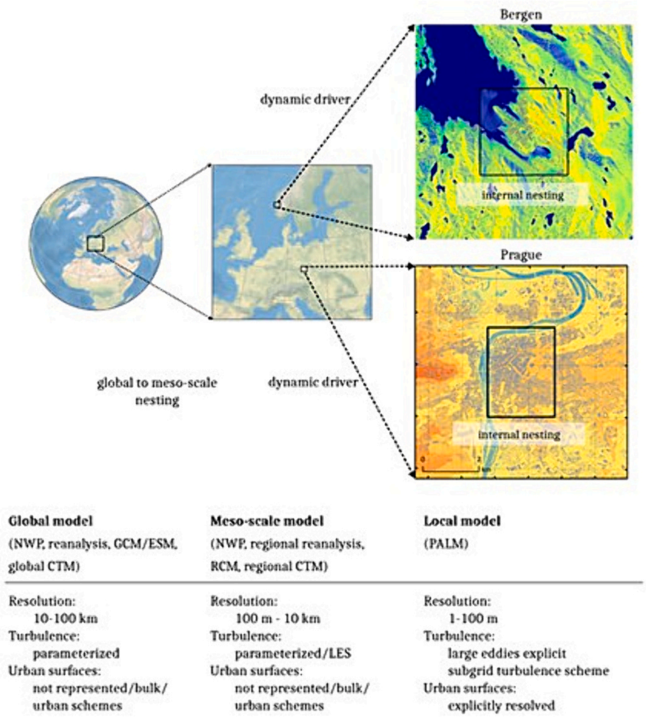

Fig. 2. The PALM-aided IUS downscaling model chain implemented in the TURBAN project for the cities of Bergen and Prague. The chain includes numerical weather prediction (NWP) models of different spatial resolution. On global scales, there are a General Circulation Model (GCM) or an Earth System Model (ESM) and a global Chemistry Transport Model (CTM). On regional scales, there are Regional Climate Models (RCM), a meso-scale meteorological model, and regional CTM. On local scales, we consider the PALM modeling system, which is dynamically coupled to regional meso-scale meteorological and air quality models. Internal nesting in PALM allows for further downscaling (see Fig. 3).

the PALM modeling system, hereafter just PALM (for a brief overview of the PALM model and its configuration see Appendix A). PALM is chosen for two reasons: it is an open-access community model supporting open science principles; and it has a large international developer and user community where many contribute to the code development, debugging, testing, and validation in diverse urban applications. PALM has also participated in several important model intercomparison experiments such as GABLS – the abbreviation for Global Energy and Water Exchanges (GEWEX) Atmospheric Boundary Layer Studies (Beare et al., 2006) – and others (Boutle et al., 2022). These intercomparison experiments constitute the first fundamental transition in the urban LES operationalization - the recognition of common features and persistent traits of the turbulence-resolving modeling approach. European initiatives on zero-emission cities and nature-based solutions now facilitate the second transition that brings PALM to the domain of IUS (Auvinen et al., 2020; Mahura et al., 2024).

Stakeholders are interested in IUS that explores realistic configurations and parameters representing surface thermophysical and geomorphological features. To meet these expectations, urban LES must include not only realistic urban digital elevation and digital surface (topography) models together with general land cover types, but also to characterize thermophysical properties of each grid point in the model domain, and their time dynamics if possible. This is the responsibility of the new static driver in PALM, which provides data for the dynamic core in the model, and works together with the Building Surface Model (BSM) (Maronga et al., 2020; Resler et al., 2017), the Land Surface Model (LSM) (Gehrke et al., 2021), and the Radiative Transfer Model (RTM) and the Plant Canopy Model (PCM) (Krč et al., 2021).

During the project's co-production sessions, stakeholders have demonstrated a keen interest in the forecasting capabilities of models. This is perhaps not surprising as their prioritization of policies and alternative decision options is influenced by their understanding of weather phenomena and expectations about atmospheric pollution trajectories or patterns. To meet the expectations, PALM must be dynamically coupled with meso-scale meteorological models. This is the task for the dynamic driver in PALM. As the PALM domain is too small to simulate any reasonable weather change, a mesoscale model in IUS must take care of weather changes and pass the changes down to PALM as lateral boundary conditions and relaxation forces. The dynamic driver couples PALM with mesoscale models in IUS - the offline mesoscale nesting (MESO) (Kadasch et al., 2021). Furthermore, stakeholders usually focus on some geographical locations about which a decision is currently to be made. More detailed spatially explicit information is therefore required within smaller sub-domains (Masson et al., 2020a). This task is solved with inline nesting (NEST) (Hellsten et al., 2021), which allows for zooming in into subdomains of interest with two-way flow inter- and anterpolation.

Stakeholders are interested in urban comfort and air quality information. Moreover, existing IUS are heavily biased towards urban air quality management (Baklanov et al., 2020). Models for chemical reactions and the atmospheric chemical transport have been

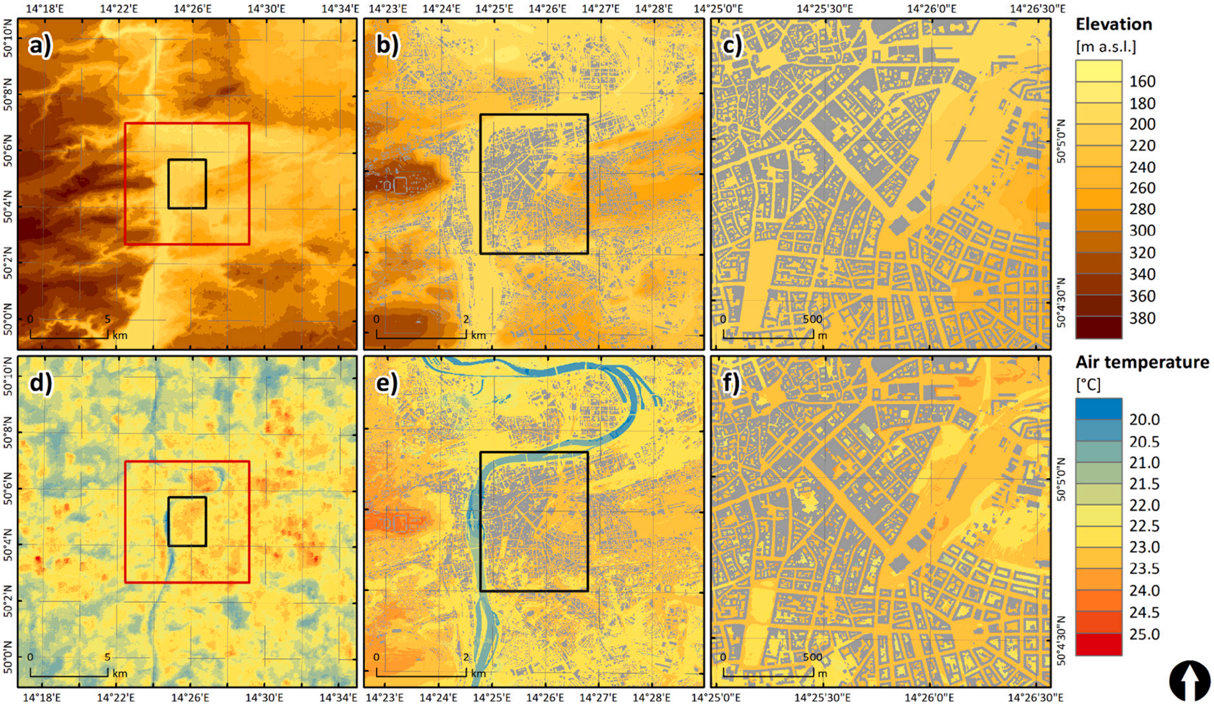

Fig. 3. A city as a multi-scale system: from the city level down to the street canyon. The complexity of the digital elevation model (DEM) in the city of Prague (a–c) and its potential effect on simulated air temperature on the city- (d), local- (e) and street-level (f) scales. For a simulation on the city-level, the urban climate MUKLIMO_3 (the Mikroskaliges Urbanes KLIma Modell) model with a 100 m horizontal resolution was used (Geletič et al., 2021), and local- and micro-scale levels were modeled using the PALM model system with a 10 m and 2 m horizontal resolution. All simulations show hourly-averaged values for 08–09 CEST on 20 August 2023.

integrated in the PALM chemical module (Khan et al., 2021). The module computes the atmospheric pollutant transport, gas phase chemistry, emission input, and dry deposition. The aerosol processes (aerosol nucleation, condensation) are implemented in the Sectional Aerosol module for Large Scale Applications (SALSA) module in PALM. PALM also includes thermal comfort and human biometeorology modules (BIO) (Fröhlich and Matzarakis, 2020; Geletič et al., 2021). Thus, PALM can provide physical, biophysical, and chemical information on meter-scale resolution, allowing for detailed evaluation of the effect of turbulent eddies on meteorology and air quality in street canyons. The major model modifications achieved during the TURBAN project include: (i) the introduction of non-orthogonal (slanted) surfaces; (ii) the multi-model dynamic driver tool PALM-METEO (Advanced modular tool for preparing meteorological inputs to the PALM model; Krč et al., 2024); (iii) a new static driver preparation tool PALM-GeM (Geospatial Data Merging and preprocessing into PALM; Bureš and Resler, 2024) with inbuilt support for three-dimensional surface structure, slanted surfaces, and compatibility with the major European public urban datasets.

We present the recent key developments covered by the TURBAN project in more detail below. For convenience, we illustrate the modeling chain in the PALM-aided IUS in Fig. 2. The chain includes global-scale models driving meso-scale (regional) models. Both the global and regional models are not able to explicitly resolve turbulence and physical processes in cities; they use parameterizations. PALM resolves many key urban features explicitly providing information on desired spatial resolutions. The nesting downscaling in PALM is illustrated in Fig. 3. This jump in resolution and the subsequent localization of information to the street level are presented for the model resolutions of 100 m, 10 m, and 2 m.

2.1. Dynamic driver: PALM coupling to meso-meteorological modeling chains

The dynamic driver in PALM is a pre-processing procedure that interpolates the initial and boundary conditions (IBC) for PALM from meso-meteorological model output. PALM has been modified to read these conditions and set them as constraints at each model time step. Technical details are given in (Kadasch et al., 2021). These conditions could be idealized or obtained from realistic meso-scale models run in the downscaling chain (Fig. 2). The process of IBC preparation within the dynamic driver includes several steps. The required variables from a mesoscale model simulation need to be selected, converted where necessary, and restricted to the PALM simulation domain. Then they must be interpolated to the PALM grid both in horizontal and vertical directions. This includes necessary adjustments due to different terrain representations, i.e., terrain matching and vertical stretching (Radović et al., 2024). In the final step, mass balancing of the boundary fluxes is performed. Apart from the atmospheric state, variables describing surface pressure, radiation, and soil conditions can also be transferred from the mesoscale simulation if available (shortwave and longwave radiative fluxes, soil moisture, soil and air temperatures).

PALM allows it to be driven by real conditions provided as time-evolving three-dimensional fields of the air temperature, wind, etc. Naturally, using observations for this purpose is not sufficient due to their sparse availability in both space and time. Rather a lower-resolution model can be used to provide these IBCs via the offline nesting technique, i.e. providing spatially and temporally variable fields of the meteorological variables taken typically from a mesoscale model simulation.

PALM supports being driven by lower-resolution meteorological models using its *dynamic driver* input file which contains IBC and other time-varying data. It is prepared using a preprocessing utility that transforms and interpolates data from mesoscale model simulations into PALM inputs. Presently, the driver supports the Weather Research and Forecasting (WRF) model, the Icosahedral Nonhydrostatic (ICON) model, and the Aire Limitée Adaptation dynamique Dévelopement InterNational (ALADIN) model as meteorological driving sources. PALM can also use air quality information from the Comprehensive Air Quality Model with Extensions (CAMx), Community Multiscale Air Quality (CMAQ) model, and the Copernicus Atmosphere Monitoring Service. PALM can run with idealized IBC as well. For certain applications (e.g. "what-if" scenarios), idealized driving conditions would be sufficient. However, for the evaluation of model behavior against observations in real urban settings, the driving conditions must also be accurate with respect to weather and observations. In the TURBAN project, we validated PALM against observations performed directly in the streets covered by the modeled domain. We used the observed meteorological conditions to study several episodes of heat waves and air pollution in our cities. In this way, sources of errors can be separated by using a set of "perfect boundary conditions", i.e. assuming IBC correctly represents the inflow.

In addition, turbulence is not resolved in the meso-meteorological model output. It must be generated in PALM at inflow boundaries. This process is managed by a synthetic turbulence generator, which is based on digital filtering of pseudo-random numbers (Xie and Castro, 2008). Turbulence perturbations are forced into inflow velocity components in the parent domain's lateral boundaries at every time step according to prescribed values of the Reynolds stress tensor components and integral length scales. Their values are parameterized in PALM using empirical similarity theory profiles.

2.2. Static driver: PALM coupling to realistic surface boundary conditions

Cities, from the urban LES point of view, are collections of diverse complex and heterogeneous surfaces. These surfaces are described in obstacle resolving models with numerous parameters, most of which are poorly known and hard to get access to (Ching et al., 2018; Masson et al., 2020a). These difficulties prompt simplification. PALM, like other models, utilizes only a limited set of surface parameters in its static driver. The details of the static drivers are given in (Geletič et al., 2022; Heldens et al., 2020; Lin et al., 2024; Resler et al., 2021). Simulations at high spatial resolution (finer than 5 m) for a heterogeneous domain are typically a mixture of ground surfaces, walls, and roof materials. Moreover, the structures in the urban environment often have a full 3D geometry (e.g. bridges, complex interchanges, and overhanging buildings). In this level of detail, geodata are often rare or do not exist yet. One solution is terrain mapping campaigns using estimated surface and material properties, typically described in terms of material category, albedo, and emissivity.

Finally, the most challenging issue in urban environments is urban greenery. Plant canopies are often derived from satellite or aerial images from the leaf area index (LAI). In such a level of detail, more precise data is needed. Each tree could be described by its position, trunk height and diameter, tree height and crown diameter, crown shape, and tree type. The leaf area density (LAD) could be then calculated according to the irradiation/shading profile of the part of the tree crown (distance from the border of the crown). Despite the simplification of plant canopies, a resolved plant canopy as 3D information is provided to analyze the microscale effects of trees. Rarely investigated in detail, the sensitivity of the model results to the settings of these input parameters is an essential part of the overall model performance assessment. Complementing the model validation, one of the outputs of the TURBAN project was an extensive evaluation of the model response to the setting of these parameters (Belda et al., 2021).

2.3. Chemistry driver: PALM coupling to air quality models

An integrated system such as the one developed within the TURBAN project needs to produce reliable information about urban meteorology and air quality. PALM can create fully coupled physical-chemical simulations with its air chemistry module. However, as in previous cases, the model capability is also determined by the quality of the input chemical data: chemistry initial and boundary conditions and local emission input. IBCs are provided through the dynamic driver and emissions are supplied through the *chemistry driver*. PALM implements two major pathways for inputting emissions: (1) a simplified internal emission model and (2) a generic emission input providing fully pre-processed emissions from an external emission model. In the TURBAN project, we used the latter approach because it allowed complex processing of the emission inputs to spatially and temporally detailed emission flows. The emissions coming from various sources need to be adequately preprocessed in the preparatory stages. For this purpose, we used the Flexible Universal processor for Modeling Emissions (FUME), see details in Belda et al. (2024). FUME has been extended with several new features allowing the preparation of fully 3D volume source input files for PALM.

2.4. Internal nesting: PALM multi-scale capability

Large eddy simulations with real conditions are often demanding in terms of domain size. The domain height should always include the full extent of the convective boundary layer due to its intensive vertical mass transport. Horizontally there needs to be a sufficient buffer upwind for the development of realistic turbulent structures. Depending on the required resolution for the area of interest itself, this can easily exceed available computational resources for a single-scale simulation. Considering e.g. an $8 \times 8 \times 3$ km domain with a horizontal and vertical resolution of 2 m, the grid would be composed of 24 billion cells. For this reason, PALM employs 3-D self-nesting. The parent simulation domain may be configured to include any number of finer-resolution horizontally and/or vertically nested child domains, each of which can contain further nested domains recursively as required. All domains share a common timestep which is dynamically adapted based on the shortest requirement among all the domains. In each timestep, the prognostic quantities from the parent domain are interpolated as boundary conditions for its child domain(s) and turbulence is adjusted between domain scales (one-way nesting). In the case of two-way nesting, the quantities from the child domains are also transferred back to the parent domain (interpolation). Following the example above, using two nested domains with the parent domain having a horizontal and vertical resolution of 10 m and the nested 1200 × 1200 × 320 m domain for the area of interest with a resolution of 2 m, the two grids would be composed of only 250 million cells altogether, i.e. two orders of magnitude fewer. Technical details about self-nesting implementation are available in Hellsten et al. (2021).

3. Two pilot PALM-aided IUS

A urban DSS operates in an iterative loop that combines prospective scenarios (often derived from stakeholder's narratives and qualitative expert assessments) and spatially explicit numerical modeling (Gonzales et al., 2013; Houet et al., 2016). IUS organizes the DSS part related to numerical modeling. The essence of this work is setting up simulations with a downscaling model chain where numerical models of different complexity (weather forecast systems, atmospheric chemistry and process-oriented models) and spatial resolution (from global climate to regional meso-meteorological models) are integrated, exchange data, and zoom into details in a coherent seamless manner (Baklanov et al., 2017; Ching et al., 2018; Masson et al., 2020; Esau et al., 2021; Nuterman et al., 2021; Mahura et al., 2024). To set up the simulations, modeling experts select a set of proper and compatible models, collect data for initial and boundary conditions, secure computing resources, and specify the model output parameters. Each of these simulation steps admits alternative choices. They cannot be exhaustively and unambiguously specified in IUS, therefore remaining "fuzzy" (Alcamo, 2008), see Fig. 1. Input data and parameters are frequently incomplete and uncertain so they must be filled in with ad hoc intuitive choices. All that makes IUS highly variable and diverse. As a result, IUS may implement different levels of integration as the experience in four different global cities has revealed (Baklanov et al., 2020). Similarly, the two PALM-aided IUS within the TURBAN project realize distinct setups that link them to different DSS in Bergen and Prague.

3.1. The pilot IUS for Prague: supporting urban planning DSS with PALM

Prague, with a population of over 1,350,000 people, is the capital city of the Czech Republic. The city is slowly, but persistently, sprawling. Prague is a popular and attractive tourist destination. As a result, the city center is often overcrowded and the current transport infrastructure is overloaded by cars, especially during morning and afternoon traffic peaks. With respect to the impact of climate change in Prague, two major vulnerabilities were identified: thermal comfort of dwellers and air quality. At this point, we need to state that any implementation of the modern adaptation or mitigation measure in the built-up city (mainly in districts Prague 1 and Prague 2) is very complicated, because the city center is on the UNESCO's World heritage list. Any reconstruction or reorganization of the building blocks is very difficult and widely discussed.

The first idea of high-fidelity (units of meters) representation of urban-related processes inside the street canyon for the district of Prague-Holešovice was elaborated in a local project UrbanAdapt carried out in 2015–2016 (https://urbanadapt.cz/en). It had two important results: 1) the first detailed analysis of realistic effects of various organization of tree alleys in the street; 2) newly developed building surface model implemented in the large-eddy simulation model PALM (Resler et al., 2017). In the following years, cooperation was extended about new districts, e.g., Prague-Dejvice (Resler et al., 2021), Prague-Bubeneč or Prague 1. The TURBAN project builds on a decade-long cooperation with the city of Prague and districts on their continuing interest in modeling-based solutions for modern urban planning or testing of adaptation and mitigation measures. The experiments described in the following text stemmed from plans conceived at the municipality level. An all-encompassing description of these plans is available in two strategic documents published by the Prague municipality, the Climate Change Adaptation Strategy (Prague City Hall, 2020) and the Prague Climate Plan 2030 (Prague City Hall, 2021). One of the adaptation's targets relevant for our study is the aim to plant 1.5 million trees in Prague by 2030. Urban greenery and the interest in thermal comfort in the city are evidently at the forefront of urban planning in Prague and were thus the primary foundation for the bulk of the experiments in the TURBAN project.

The aim of the PALM-aided IUS in Prague is to resolve complex urban features down to the street level of details, typically on the pedestrian level (so-called a "human-oriented paradigm"). Note that many policy measures in Prague are planned on the city scale, but its realization is typically in the hands of districts. The IUS simulations on the city scale inform on the optimal selection of policy measures to counteract the negative effects of the "urban meteorology island" (Karlický et al., 2020). On the street scale, several 'what-if' scenario simulations were performed for urban greenery settings and changes in the traffic infrastructure and organization (Belda et al., 2021; Geletič et al., 2022) and (Geletič et al., 2023). These scenarios typically cover smaller parts of Prague districts. The selection of scenarios in Belda et al. (2021) currently represents the broadest set of potential adaptation or mitigation measures tested in realistic urban environments. It covers measures including the green, blue or gray infrastructure as well as changing of the various surface properties.

PALM results suggested that stakeholders' attention needs to focus on the potential trade-offs between improving thermal comfort and air quality. Moreover, energy-related processes in the street canyons need to be explained in detail; any generalization could lead

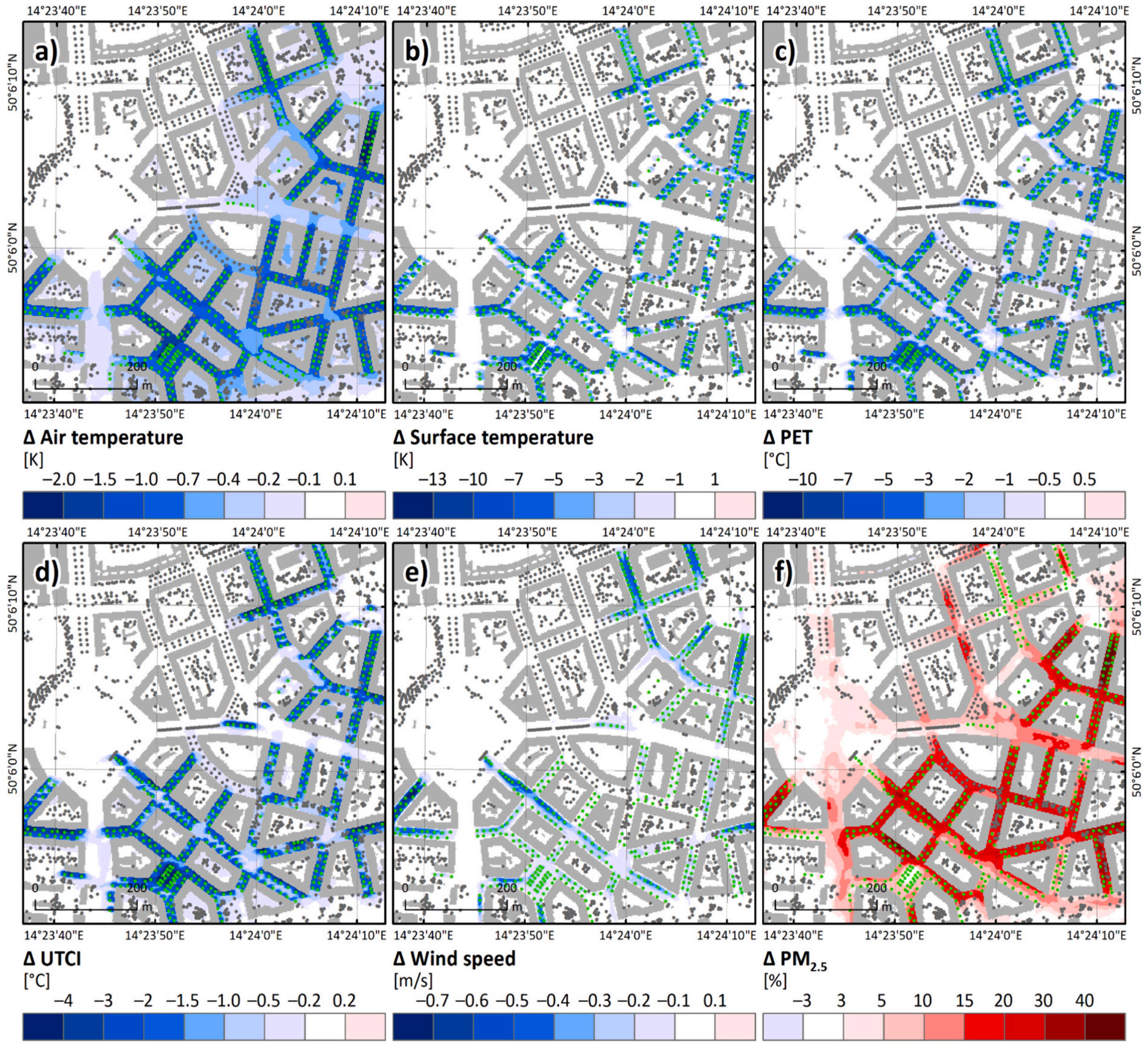

Fig. 4. Example outputs from an IUS based on PALM used for Prague in the TURBAN project. Individual panels show daily averaged effects of newly planted trees (green points) on air temperature at 2 m (a), surface temperature (b), biometeorological indices PET (c) and UTCI (d), wind speed at 10 m (e) and $PM_{2.5}$ concentrations (relative change of concentration C calculated as $(C_{scenario} - C_{base})/C_{base}$ in a typical residential area in Prague. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

to a misleading interpretation of the results. A typical example could be densely planted trees in streets with traffic; trees improve thermal comfort during the day but can contribute to a deterioration of air quality due to decreased ventilation and turbulent mixing in the street canyons. Fig. 4 shows the simulated effect of dense tree planting in the streets of Prague-Dejvice (Geletič et al., 2024). The reader may notice an important improvement in physical and biophysical thermal indicators such as the surface temperature, the Universal Thermal Climate Index (UTCI) introduced by Jendritzky et al. (Jendritzky et al., 2012), and the Physiological Equivalent Temperature (PET) (Höppe, 1999). Thanks to the shading the trees provide, human thermal comfort could be improved up to 4 °C (UTCI) or 10 °C (PET) respectively. We note that the strongest mitigation is located close to tree positions, and hence, it has only a minor effect on the mitigation of its neighborhood. A comparison of daily average values shows a decrease of 2 m air temperature of around 2 °C in the streets where new trees would be planted. However, ventilation in the street canyons is also reduced in this scenario; wind speed decreased by up to 0.7 $m.s^{-1}$. Connected to that, air quality deterioration can be detected in increased (by up to 40%) $PM_{2.5}$ concentrations there. A more detailed description and discussion of this case study are published in Geletič et al. (2022, 2024). This study also reflects special need in close communication with city districts, especially with policymakers; the introduced scenario considered a total of 540 newly planted trees in open public spaces, the so-called "maximum greening alternative" in the popular policy initiatives "Million trees for Prague" or "Planted Prague". After consideration of all local limitations, such as current parking places, engineer networks, phone or optical cables, protected buildings, available space for future growth or soil moisture, only 3 trees could

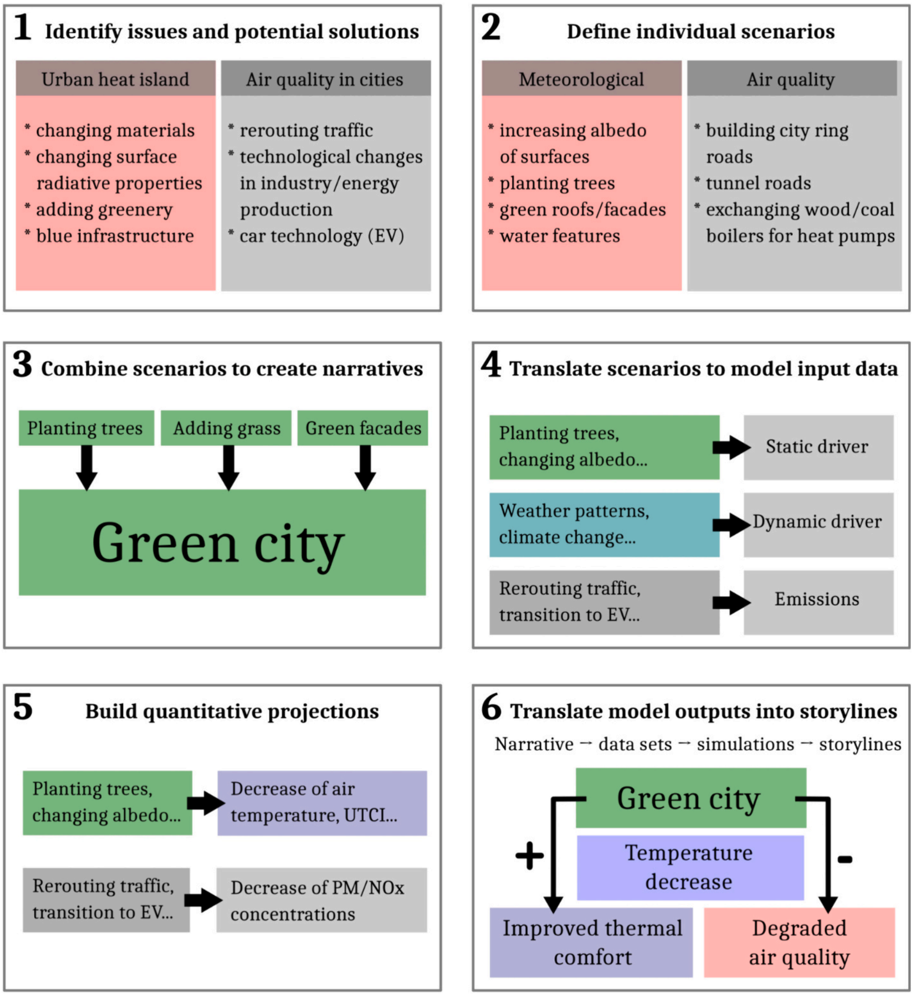

Fig. 5. From narratives to model-informed urban scenario assessment: The methodological synthesis based on Houet et al. (2016) six-step approach illustrating the pilot PALM-aided IUS in Prague.

be really planted.

Previous experiences as well as Prague's environmental complexity led to a specific domain selection within the TURBAN project; it combines both main vulnerabilities: thermal hot-spot in the city center, in the summertime typically overcrowded by tourists, and one of the most important traffic hot spots in Prague, area of Legerova and Sokolská streets. Interestingly, the distance between both hot spots is <2 km. Thermal properties of the city center are well known, but there are - mostly legislative - issues with the implementation of any recommended adaptation or mitigation measure. Air quality is a more complex problem. There are many widely discussed plans for a future 'humanization' of the streets that would transform the current arterial highway into a green boulevard (e.g. by diverting the traffic into tunnels). However, due to other reasons (such as the incompleteness of the two Prague ring roads or the length of all necessary legislative processes), the traffic loads are unlikely to decrease significantly in the nearest future. These aspects make this area an ideal testbed for model experiments. Within the TURBAN project we designed, set up, and ran a targeted measurement campaign. The measurements included reference air quality stations as well as low-cost sensors, a LIDAR instrument, and a microwave radiometer MTP-5 (Bauerová et al., 2024). The collected observations on a very local scale provide for evaluation of PALM at meter-scale resolution. Moreover, it was found that PALM is quite sensitive to the imposed initial and boundary conditions provided by a mesoscale model. The complexity of providing the "perfect boundary conditions" was elaborated in Radović et al. (2024). One important conclusion from these studies is that any street canyon modifications require a modeling analysis of potential indirect effects before the urban planning decisions are made. Fig. 5 shows a six-step methodological approach to transform narratives to numerical models. The approach was proposed in Houet et al. (2016) and contextualized for the greenery decision applications in this study.

3.2. The pilot IUS for Bergen: supporting sectoral DSS with PALM

Bergen, Norway, is a middle-size city (population ca. 275.000) and an attractive tourist destination on the western Norwegian coast

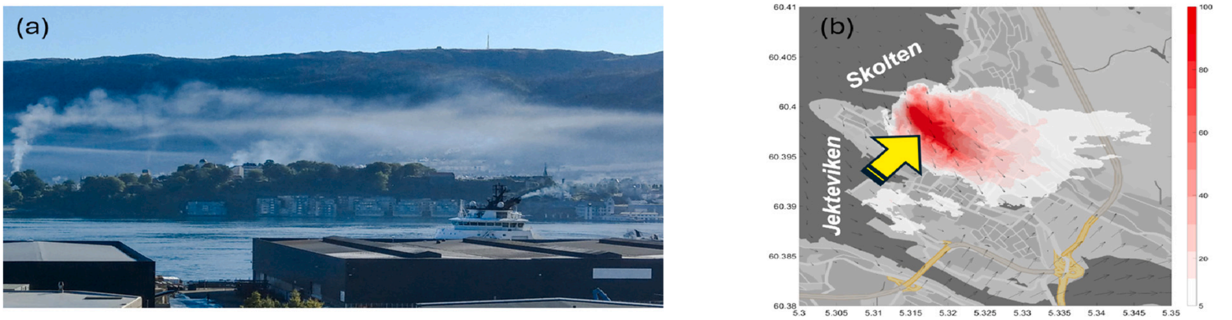

Fig. 6. (a) A visual example of air pollution in the port of Bergen ("Bergens Tidende" newspaper, 23 July 2018). (b) PALM simulations of this air pollution episode (model resolution 15 m, the simulation domain included the whole Bergen municipality). NOx concentrations are shown by red color shades, wind speed and direction by black arrows. The yellow arrow shows the standpoint and direction of the image in (a). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

(Bremer et al., 2020). Its deep-sea inlets (fjords) snaking between steep rocky cliffs and hills (fjell) are picturesque but can trap air pollution from urban traffic (Wolf-Grosse et al., 2017a), households (Wolf et al., 2021), and ships in the harbor. Air pollution from ships may accumulate, becoming highly visible during calm days (Fig. 6a). Smoke plumes from ships and a low-altitude haze layer over Bergen have caused public debates with a good deal of emotions. The debates were hardly supported by any quantitative information. Based on visual evidence, ships docking in the port of Bergen were suspected significant contributors to increased concentrations of aerosol particulate matter (PM) and gaseous nitrogen oxides (NOx) at the pedestrian level of the historical city center and residential districts in the most populated Bergen valley and surrounding coastal areas. McArthur and Osland (McArthur and Osland, 2013) calculated that ships in the Bergen harbor annually emit 664 tons of NOx, 8.7 tons of PM, 40,000 tons of CO2, and 19.4 tons of SO2, whereas cruise ships are responsible for a significant share of the emission. These emissions are 3000 to 4000 times higher than the emissions from passenger cars passing through the city center. Overall externality costs of air pollution from ships are estimated to be 172.2 million Norwegian kroner. Over the last decade, Bergen has also experienced unusually frequent heat (summer) and cold (winter) waves with persistently calm clear-sky weather conditions. It resulted in increased public attention to the air quality and pollution from ships in the harbor. Eventually, the Bergen port management contacted modelers to clarify the issue and to pilot a service that would support their decisions on berth allocations. We have developed and demonstrated the pilot integrated urban services for DSS of the port of Bergen in applied and academic projects. The academic (open science) part of this pilot IUS is presented below as part of the TURBAN project.

Co-production sessions with the Bergen port authorities (Bergen Havn AS; https://www.bergenhavn.no/en) resulted in the following details of the required IUS that shall enhance the functionality of the Bergen port DSS. Communities of practice (the Bergen municipal authorities, the Bergen port authorities) set an objective to minimize the effect of the port emissions on concentrations of pollutants at the pedestrian-level in Bergen. Complex relief and coastline configuration around the port area makes it necessary to minimize the pollutant concentrations in the atmospheric layer between the surface and the tops of the hills at about 500 m above sea level. This objective could be achieved not only through unconditional emission reduction, which would be problematic given the port importance and operation modus but also through spatial reconfiguration of emission sources. Fig. 6b shows that the port has two areas with berths, namely, Skolten and Jekteviken. Ships could be relocated within the harbor between those berth areas. Weather conditions and local wind roses could be used to identify the berths with dominant pollution transport towards unpopulated areas over fjords. Achieving the port DSS target requires a more nuanced service than simple emission reduction. It decouples the emission reduction from the population exposure reduction. Thus, our pilot IUS exemplifies the model-based abatement strategy discussed earlier in the context of population exposure modeling with Urban Air Quality Information and Forecasting Systems (Baklanov et al., 2007).

We simulated atmospheric boundary layer winds, turbulent diffusion, and temperature conditions (atmospheric stability) with PALM. Our simulation approach (agreed with stakeholders) relies on pre-simulated PALM runs. This approach is justified because the air quality in Bergen deteriorates below given thresholds only under persistent anti-cyclonic weather conditions, which are known as atmospheric blocking. An atmospheric blocking manifests itself as a heat wave in summer (Zschenderlein et al., 2019) and a cold wave in winter (Wolf and Esau, 2014). It is worth noting that physical mechanisms favor the co-occurrence of atmospheric blockings in Bergen (Scandinavia) and Prague (Central Europe) according to Spensberger et al. (Spensberger et al., 2020). Atmospheric blocking leads to the development of a distinct local circulation system in the Bergen wind shelter (Jonassen et al., 2012). The local near-surface winds are key to tracing the air pollution pathways on the urban spatial scales but could be resolved only with urban LES as their typical dimensions are <1 km (Wolf-Grosse et al., 2017b). Thus, the PALM pre-simulations were set up for archetypes of the atmospheric blocking in Bergen and ran for up to one day (24 h) at a time. The realistic surface conditions and land cover types have been used. The ship emissions were provided by the port authorities. The city emission inventory was provided by the Bergen municipality, see the list of data sources in (Wolf et al., 2020). An example of the PALM output is given in Fig. 6b.

Our pilot PALM-aided IUS provides information for the port DSS in the form of a single-page report (Fig. 7). The report considers that the operator has a limited time (a few minutes) to decide about the berth (re)-allocation for a calling ship. The information must be

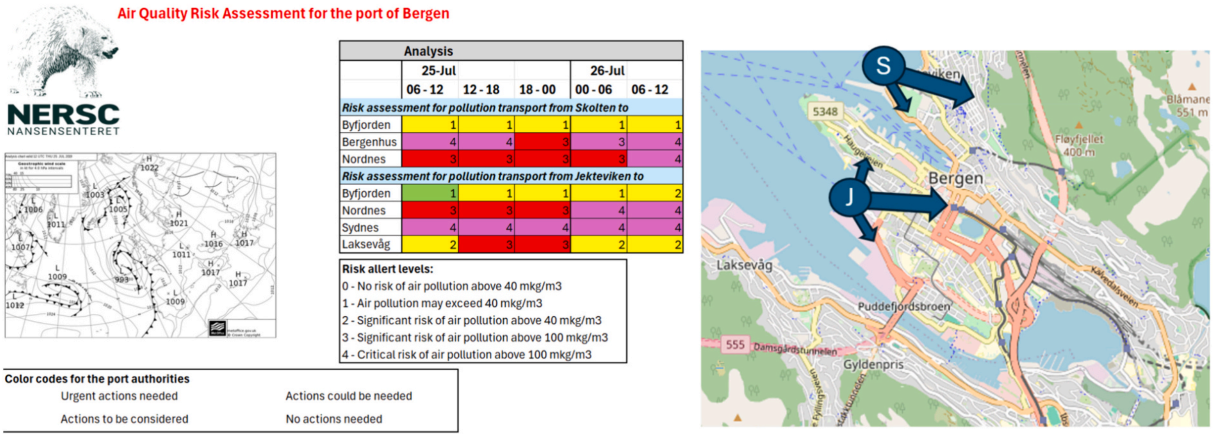

Fig. 7. An example of the PALM-aided IUS service table for in the DSS of the Bergen port authorities (reformatted and translated from Norwegian; this figure is for illustration purposes only).

unambiguous, categorized, and compatible with other types of information serviced to the operator. Disambiguating the IUS information is important for effective decision-making support (Alcamo, 2008; Saaty, 2008). We adopted "color codes" consistent with the approach of the environmental protection authorities (Miljødirectorated; https://luftkvalitet.miljodirektoratet.no/). The green code means "no actions needed"; yellow - "prepare for actions and watch wind changes"; red - "close the berths in vulnerable locations or ask to stop engines"; magenta - "actions necessary, order engine stop or relocate ships". Ship emission control is only one among many factors regulating the port operation. Safety and economic factors are set higher priorities. Nevertheless, there were several episodes when incoming ships were docked with respect to IUS recommendations.

As seen from the physical perspective, our service exploits recurrent local patterns of surface-level winds in a coastal valley (Fernando, 2010; Onwukwe and Jackson, 2020; Wolf-Grosse et al., 2017a; Wu et al., 2021). The cold land - warm water temperature difference drives persistent wintertime breeze with surface-layer winds directed offshore. It generally favors atmospheric pollution transport out of the city but meandering mesoscale winds could create occasional return flows that need to be watched. Such weather conditions could be identified through downscaled meso-meteorological simulations, which are coupled to PALM through the dynamic driver. To distinguish the atmospheric pollution transport from different berths, our IUS summarizes wind roses (relative frequency of wind direction and speed) at given locations in 8 sectors by wind direction. Each port area (Jekteviken and Skolten) is served with an independently produced summary.

4. Storylines and simulations: Communication of PALM results to urban stakeholders

Mature IUS models produce results that are used in decision-making. There is a recognized gap between what modelers understand as useful information and what users recognize as usable (Lemos et al., 2012). Furthermore, modelers frequently assume that information is useful in any form, just because it is numerically accurate and physically consistent. Some IUS developers underappreciate that the information might be incompatible with the DSS context or silent about societally important nuances. As a result, "the knowledge produced remains on the shelf" because stakeholders assign lower priorities to the information they do not comprehend or the information that does not meet their expectations (Lemos et al., 2012). Our own early attempts to apply PALM results for urban decision-making gave several discouraging examples. For instance, Esau et al. (2021) attempted to create a PALM-aided IUS for air quality in city of Apatity (Kola Peninsula, Russia) but recognized that the model (PALM version 4) could not inform the local DSS that prioritizes dust pollution control (Slipenchuk et al., 2019). Wolf et al. (2020) aimed to inform the acute air quality DSS in Bergen with PALM simulations but had to retreat to a posteriori research analysis unable to provide forecasting for the concentrations. After trials and failures, the group in the TURBAN project discovered that a Storylines and Simulation (SAS) approach could bridge model-based IUS and narrative-based DSS. The SAS approach was proposed by Alcamo (2008) and developed and demonstrated in the urban climate context by Houet et al. (2016).

Potentially useful information is used when it is properly communicated or in other words retailed and customized (Lemos et al., 2012). The IUS models produce usable results after rounds of co-production with stakeholders and experts, after data acquisition and model re-configurations. The challenge is that the model output is delivered in the form of numbers, datasets, maps, and tables. It can be comprehended by trained modeling experts but not by intended users. Hence, the results are useful but not usable in such forms (Alcamo, 2008). It is not surprising then that communities of practice face difficulties interpreting the model output, and hence the information from IUS is not fully used (Gonzales et al., 2013). The model output needs interpretation and translation to fit into the conceptual frameworks of stakeholders (Saaty, 2008). Alcamo (2008) described this task as "fuzzilization" of quantitative information. In SAS, first, users' narratives are "defuzzilized" by the specification of the problem and its constraining within a proper parameter space; these tasks are steps 1–3 in the Houet et al. (2016) six-step approach. Then, the selected models simulate the identified scenarios (steps 4–5), finally providing for narrative storylines (step 6), which interpret or "fuzzilize" the information for non-experts. Fig. 5 is

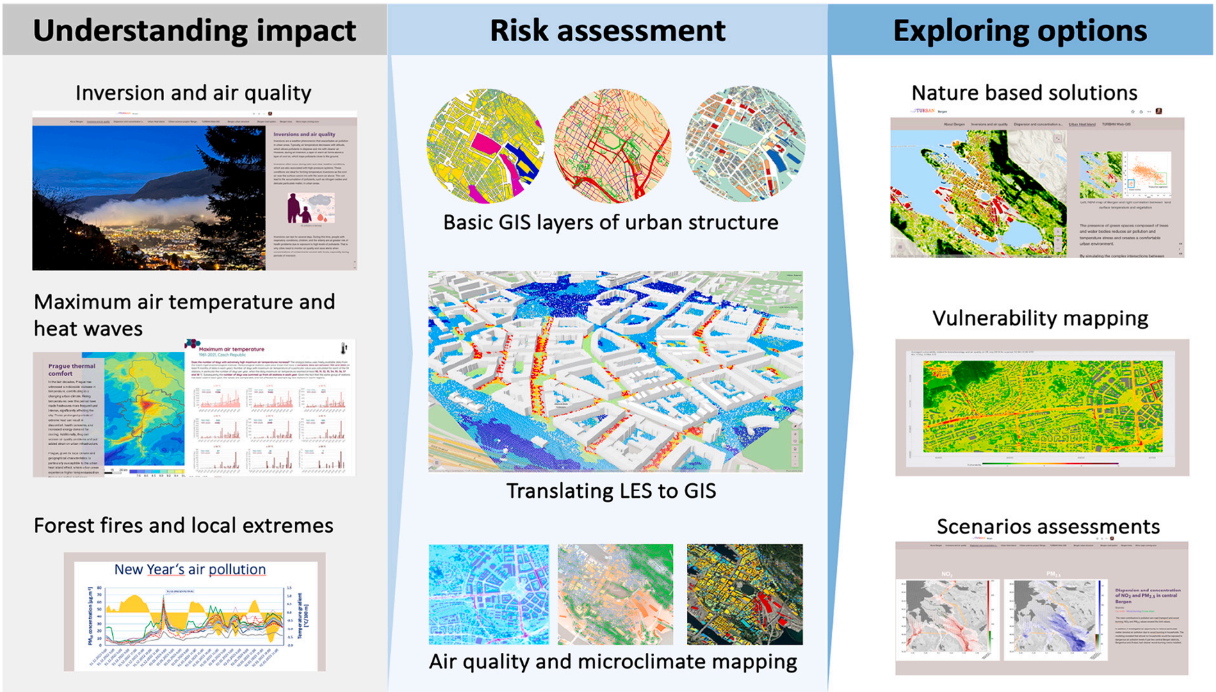

Fig. 8. Visual presentation of the WebGIS functionality developed in the TURBAN project.

inspired by the Houet et al. (2016) scheme but adopted by our PALM-aided IUS. We want to comment that the IUS models could be re-run both for real (observed) and scenario (imagined) cases, also creating ensembles of runs with varying plausible parameters. Irreducible uncertainties in these ensembles of runs could be quantified and, to the degree of our process understanding and data accessibility, constrained. In this sense, the storylines are necessarily pluralistic storylines, which admit flexibility, variability, and uncertainty of model projections, i.e., situations in which the underlying mechanisms, dynamics, and laws governing a system are known only partially (Manski et al., 2021).

4.1. *WebGIS storytelling and simulations*

Recently developed web-based geoinformation systems (WebGIS) have revolutionized science-informed storytelling. Advanced WebGIS applications provide not only a single static scenario report but dynamic, nuanced narratives, inviting us to explore scenarios through flexible visualization of model results. In the TURBAN project, we explore the power and benefits of WebGIS provided by ArcGIS solutions (Miles et al., 2023).

An urban SAS design is challenging as it entails many parameters and multiple interacting factors. In the context of the geographically explicit DSS, geographical visualization (mapping) per se is the most important feature that SAS is expected to provide. Both input information (observations) and IUS results (simulations) are geographically explicit, and therefore best visualized with maps (Heldens et al., 2020). Moreover, maps assisted by computer technologies readily incorporate zooming, pop-up information inserts, on-fly statistical analysis, and other forms of informative augmentation (Lv et al., 2016). Complex visual presentations are needed as much for aesthetics and stakeholders' timesaving as for intuitive exploration of relationships and causal dynamics that influence decisions. In this context, the TURBAN WebGIS (Miles, 2024) resolves the usability bottleneck in the translation of the IUS information to communities of practitioners.

WebGIS operates with geo-referenced information. The static driver in PALM makes the simulations geographically specific and hence distinguishes them from non-referenced process-oriented studies. Geo-referenced information is actionable information and is critical for environmental management (Gharehbaghi and Scott-Young, 2018). Maps and diverse geo-referenced information are integrated within WebGIS in a transparent, accountable, and uniquely identifiable way. For example, many urban LES, including earlier works with PALM (Wolf et al., 2017) suffered from difficulties with geographical coordinate system transformation as they used input matrices in the ASCII format instead of the EPSG-coded maps. Enabling geographical tagging in the underlying database technology was crucial for the identification of spatially resolved objects and processes (Wieczorek and Delmerico, 2009). Thus, on one side, WebGIS leverages spatial connections inherent to IUS.

On the other side, WebGIS is a powerful communication tool. WebGIS content is presented through stories, visualizations, engagement tools, briefings, and surveys to make it easily understandable for all users. Our WebGIS (Fig. 8) framework consists of three main components working together seamlessly. First, the impact analysis component helps users understand the magnitude of impacts on urban quality and potential future risks. Second, the risk assessment component provides a detailed analysis of the likelihood and severity of possible risks associated with the situation. Finally, the options exploration component helps users identify and evaluate various strategies and solutions for managing or mitigating the identified risks. One significant benefit of WebGIS is its ability to assimilate scenarios. The PALM-aided IUS is able to simulate geographically explicit potential trend breaks and tipping points related to changes in the urban physical environment. WebGIS helps attribute those trends and tipping points to societal and land surface changes combining model output with thematic urban layers.

The main problem with traditional qualitative DSS is that they are not fully scientific because the process of expert assessment cannot be reproduced in detail (González et al., 2013; Houet et al., 2016). It frequently leads to obscure and irreproducible decisions. The SAS WebGIS has the potential to technically minimize this problem, making information transparent and documenting each SAS step. Open science and FAIR (Findable, Accessible, Interoperable, Reusable) scientific data management and stewardship principles (Wilkinson et al., 2016) offer several advantages when geographically explicit urban information is communicated to stakeholders. Decisions related to urban climate are enabled through promoting transparency and collaboration, engaging citizens in discussion, data collection and IUS development. Full access to documentation (meta-data) and methodological transparency are open science principles to follow (Munafò et al., 2017; UNESCO, 2021). More than that, WebGIS provides tools for citizen engagement and sharing of citizen data (Chmielewski et al., 2018). This inclusive approach facilitates a better understanding of the complex interactions between urban infrastructure, vegetation, and atmospheric processes, leading to more accurate simulations and predictions of microclimatic conditions. Technically, our WebGIS utilizes the Environmental Systems Research Institute (ESRI) Software as a service (SaaS) cloud platform known as ArcGIS Online, which operates a web map wizard, data storage, and front-end interface for users (Miles et al., 2023). Our solution allows for multi-level mapping of geo-tagged information, quality checks, and user feedback. Fig. 8 schematically shows the used WebGIS technology. WebGIS provides access to a collection of quantitative data and qualitative narratives together with complete documentation on how those data and narratives were obtained and what characteristics they have.

5. Conclusions and future development

There is a growing need to support and enhance urban decision-making with detailed, geographically explicit meteorological information. This kind of information could be provided by integrated urban hydrometeorological services that account for both the needs and the impacts of urban stakeholders on relevant meter-scale resolutions. The IUS modeling chain must be enhanced with an urban turbulence resolving (large-eddy simulation) model to be useful for urban DSS. Up to date, IUS advance was retarded by a lack of: (i) coupling between mesoscale meteorological models and urban LES; (ii) receptivity to realistic surface boundary conditions, radiation transfer, and surface energy balance modules; and (iii) rudimentary scalar and chemistry transfer blocks at turbulence scales. Our overview summarized the code developments, which aim to close the gaps in: (i) the multiscale model coupling - the dynamic driver (Radović et al., 2024); (ii) the model coupling with diverse surface processes - the static driver, radiation and biometeorological blocks (Belda et al., 2021; Geletič et al., 2022); (iii) the inline chemistry transfer and reaction block (Resler et al., 2021).

We consider all these new model features in the IUS model chain context. We conclude that the PALM model system could be used as a developed high-resolution end component of IUS. We acknowledge that PALM technological maturing would not be realized without essential contributions from the PALM group at the Leibniz University in Hannover (Maronga et al., 2020) and the broader model community. Specifically, the group at Helsinki University (Hellsten et al., 2021; Auvinen et al., 2020) equipped the code with an essential option for internal one- and two-way nesting (downscaling). The internal nesting allows for more specific user-oriented IUS without excessive requests for computational resources. Significant potential has model coupling with external air pollution models, such as SALSA presented by the same group (Kurppa et al., 2019).

The mature urban LES is not a model with a multitude of desired options and blocks that provide potentially usable information. The mature model is a component of IUS that is useful and used. Lemos et al. (2012) argued that pre- and post-actions with stakeholders are necessary to make IUS mature. Alcamo (2008) is more specific about those actions. The pre-actions must include “defuzzilization” of DSS narratives, i.e., conversion of stakeholders' scenarios and goals into the properly agreed selection of models, input and output data, and simulation parameters. The post-actions must include “fuzzilization” of IUS results, i.e., conversion of numbers, datasets, maps, and tables into qualitative judgments and actionable information. Gonzalez et al. (2013) and Houet et al. (2016) projected these general frameworks onto urban air quality and climate change agenda. We added two more working examples. For Prague, we demonstrated a pilot IUS for urban greenery planning DSS. For Bergen, we demonstrated a pilot IUS for air quality and pollution exposure control in an urban harbor. We conclude that the PALM-aided IUS is usable and of significant added value when it is actually used in sectoral DSS.

In this study, we recognized that our two pilot IUS lacked something that would procure their wider public acceptance and impact. They lacked storylines. Storylines are essential for knowledge transfer and positions. In the TURBAN project, we tried technologically advanced WebGIS storytelling (Miles et al., 2023). Our WebGIS combines geographical layers with modeling information from the PALM-aimed IUS and societally relevant information. The layers are linked with storylines, which are essentially narratives co-produced with stakeholders. We conclude that WebGIS facilitates co-production with diverse communities of stakeholders, users, and even modelers themselves. Working on WebGIS information, we were able to improve collaboration between Bergen and Prague groups in the project.

In the final words, we reckon that any stand-alone urban LES will be of limited use for stakeholders and citizens. To mature, urban LES must be seamlessly linked to other modeling platforms within IUS (Mahura et al., 2024). But that mostly technological development is not sufficient. Such a LES-enhanced IUS must provide actionable information for a concrete urban DSS. The latter emphasizes the need for a robust methodology of “(de)-fuzzilization” translating between qualitative (expert opinions) and quantitative (model simulations) information in a reproducible (scientific) way. WebGIS seems to be a promising technology facilitating IUS

Table 1
The SWOT analysis for urban LES-enhanced IUS. The analysis is based on the TURBAN project results and Stoll et al. (2020) study.

STRENGTHS	WEAKNESSES
● Simulation of fine-resolution details of atmospheric turbulence, air quality, and urban microclimates ● Reduced sensitivity to parameterizations of unresolved atmospheric dynamics and physics ● Reproduction of previously unobserved, unexplored, or hypothetical urban conditions, including climate change scenarios ● Ability to resolve and trace weather extremes at meter scales, inform about air pollution pathways and microclimate patterns ● Flexibility and versatility of applications that stems from explicit resolution of poorly understood or too complicated processes and phenomena	● Very high computational cost**, which requires access to multiprocessor high-performance computing facilities ● Demand for experienced and knowledgeable personal, which can operate model setup, running, input data collection, and output data interpretation ● Limited documentation on LES models' verification and validation; methodological difficulties related to intercomparison of turbulent processes in complex environments
OPPORTUNITIES	THREATS
● Could be used as an essential environmental component of digital smart cities* ● Promising for broader use in new meteorological applications (e.g., for urban renewable energy) ● Open for capturing and predicting of complex socio-environmental interactions in cities ● Suitable for the design of plausible nature-based solutions (Ysebaert et al., 2021) ● Ongoing improvements in computational power and algorithms may reduce the costs and increase the accessibility of LES	● Lack of experience with LES-enhanced services ● Limited availability of fine-resolution data to set up initial and boundary conditions in LES ● Large uncertainty in simulation results due to atmospheric turbulence; Underdeveloped methodology to deal with simulation uncertainties ● Competition from other modeling methods (e.g., from improved Reynolds-Averaged Navier-Stockes (RANS) models, physics-aware data-driven models, etc.) ● Demand for storage and robust data handling solutions increases rapidly with the resolution refinement of the LES models

[*] Here, we adopt the definition of digital smart cities as cities where digital technologies (serving, e.g., data collection, modeling, information, and communication needs) are integrated with traditional urban functions and management, e.g., (Batty et al., 2012).
[**] The computational cost of the LES-enhanced IUS could be significantly reduced when climatic features of the location are considered, and pre-run simulations are reused.

maturing. This study presented an attempt to reflect on our experience with compilation, evaluation, and to some degree demonstration of the PALM-aided IUS in the context of sectoral urban decision-support systems. We conclude the study with Table 1 that lists the most important strengths, weaknesses, opportunities, and threats (SWOT) related to the urban LES application as the IUS component.

CRediT authorship contribution statement

Igor Esau: Writing – review & editing, Writing – original draft, Visualization, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Michal Belda:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Resources, Methodology, Formal analysis, Conceptualization. **Victoria Miles:** Writing – original draft, Visualization, Methodology, Investigation. **Jan Geletič:** Writing – original draft, Visualization, Software, Resources, Investigation, Formal analysis, Data curation. **Jaroslav Resler:** Writing – review & editing, Writing – original draft, Software, Resources, Project administration, Funding acquisition, Conceptualization. **Pavel Krč:** Software, Investigation, Formal analysis. **Petra Bauerová:** Validation, Formal analysis, Data curation. **Martin Bureš:** Validation, Software, Resources, Investigation, Formal analysis, Data curation. **Kryštof Eben:** Validation, Software, Resources, Formal analysis. **Vladimír Fuka:** Validation, Methodology, Investigation, Formal analysis. **Radek Jareš:** Validation, Resources, Formal analysis, Data curation. **Jan Karel:** Validation, Software, Resources, Formal analysis, Data curation. **Josef Keder:** Validation, Supervision, Resources, Methodology, Data curation. **William Patiño:** Validation, Software, Resources, Formal analysis, Data curation. **Lasse H. Pettersson:** Validation, Supervision, Resources, Methodology. **Jelena Radović:** Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation. **Hynek Řezníček:** Validation, Resources, Data curation. **Adriana Šindelářová:** Validation, Resources, Data curation. **Ondřej Vlček:** Validation, Resources, Formal analysis, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

The study was supported by the following research and networking projects: "URban Sustainability in Action: Multi-disciplinary Approach through Jointly Organized Research schools" – the project of the Norwegian Research Council no. 322317; and the EEA project (Contract No. 2020TO01000219 with TACR) "Turbulent-resolving urban modelling of air quality and thermal comfort (TURBAN)".

Appendix A. Description of the PALM modeling system

The PALM model system (Maronga et al., 2020) is a state-of-the-art micro-scale atmospheric model. Due to a lot of supporting components, the model is able to simulate the flow field, energy transfer, and chemistry within the urban canopy with the complex details in the high spatial and temporal resolution. The model was configured with the LES core and it solves non-hydrostatic, filtered, Boussinesq-approximated, incompressible Navier-Stokes equations. The subgrid stress tensor is modeled by the Deardorff (1980) 1.5-order closure involving Moeng and Wyngaard (1988) and Saiki et al. (2000) modifications. The upwind-biased 5th-order differencing scheme Wicker and Skamarock (2002), and the 3rd-order Runge–Kutta time-stepping scheme Williamson (1980) were used for spatial and temporal discretization, respectively. The solution of the pressure-Poisson equation in the projection step was configured to utilize the multi-grid scheme solver (e.g., Maronga et al., 2020). The simulations were configured with PALM modules developed for studying the urban boundary layer. They include e.g. the land surface model (LSM; Gehrke et al., 2021), the building surface model (BSM; Resler et al., 2017; Maronga et al., 2020), the radiative transfer model and the plant canopy model (RTM and PCM; Krč et al., 2021), internal nesting Hellsten et al. (2021), mesoscale nesting Kadasch et al. (2021), and the chemical transport model (Khan et al., 2021).

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