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Validation of UTCI simulation with PALM-4U on direct measurements in urban environments

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SUMMARY

A micro-meteorological numerical simulation of the urban microclimate on an inner-city area in Copenhagen was conducted using the PALM-4U model. Simulation conditions showed good agreement with full-scale observations, evaluated using the human biometeorology index UTCI. The study explores potential of this modelling approach to inform climate-responsive strategies and support resilient urban design.

Keywords: *PALM-4U, Microclimate, Outdoor thermal comfort, UTCI, Climate Change*

1. INTRODUCTION

The intergovernmental panel on climate change projects scenarios for global warming levels and forecasts that climate-related risks and extreme events in cities will continue to escalate (IPCC, 2023). Dense population and complex infrastructure make cities vulnerable to climate change and the global urbanization trend renders climate adaptation of cities ever more critical. To address these challenges, accurate climate-risk assessment and effective mitigation strategies are gaining importance among urban planners and stakeholders in the built environment. In this context, the German-funded MOSAIK project developed a high-resolution urban climate simulation model PALM-4U (2016–2022) based on state-of-the-art numerical models to support climate-informed city planning (Maronga et al., 2019).

This study is concerned with the potential impact of climate change on daily wind and boundary conditions for urban microclimates. Outdoor thermal comfort is one key dimension of urban livability, with derivative socioeconomic and health-related impacts. Therefore, integrating biometeorological indicators into urban design is essential for supporting climate resilient urban development. This study seeks to evaluate how well micro-meteorological numerical simulations performed with PALM-4U (Maronga et al., 2020) can replicate field measurements conducted in real-life urban settings to estimate human thermal comfort based on Universal Thermal Climate Index (UTCI) (Błażejczyk et al., 2010) and observation of human response behavior. The UTCI uses four key meteorological variables: wind speed, air temperature, water vapor pressure (humidity), and mean radiant temperature (MRT).

2. METHODS

As case study location, Greyfriars Square in the city center of Copenhagen was chosen. The modelled surrounding area of Copenhagen is comparable in morphology to many European cities, and Copenhagen's coastal location allows for examination of both inland and sea-breeze wind conditions. Figure 1 shows the extension of the model domain in the urban context, and the detail level and urban/surface elements included in the simulation for the modelled wind direction South-

South-West. The model topography was based on available geo-spatial data and provided as a static driver created with the preprocessing tool palmpy (Fluck, 2023). One-way self-nesting was used to couple the surrounding city at coarser resolution to high-resolution micro-climate model, with uniform grid sizes of 8 m and 1 m, respectively. This enabled covering an area with lateral extension of roughly 4 km^2 corresponding to neighborhood scale and a vertical height of 0.5 km for the parent domain, and an embedded nested child domain concentrated around Greyfriars Square located in the model center, for detailed local analysis. The simulation employs a 5th-order advection scheme (Wicker and Skamarock, 2002) together with a 3rd-order Runge–Kutta time-integration method (Williamson,1980) with an upper time step limit of 0.5 s. Pressure is solved using a multigrid scheme with appropriate setup for non-cyclic lateral boundary conditions. The model is initialized with a mean wind profile, gradient temperature and humidity profiles based on archived weather data from local weather stations at the date/time of the reference measurements. Simulation runs were performed using parallelization on a high-performance computing cluster.

In-situ measurements at Greyfriars Square were performed in a previous study in the Summer 2018 with a Kestrel Heat Stress Tracker at pedestrian level of 1.5 m, see Figure 2. This data was used as validation basis. Using PALM's Virtual measurement module, time-series of relevant variables were sampled during the simulation in a grid point corresponding to the measurement location.

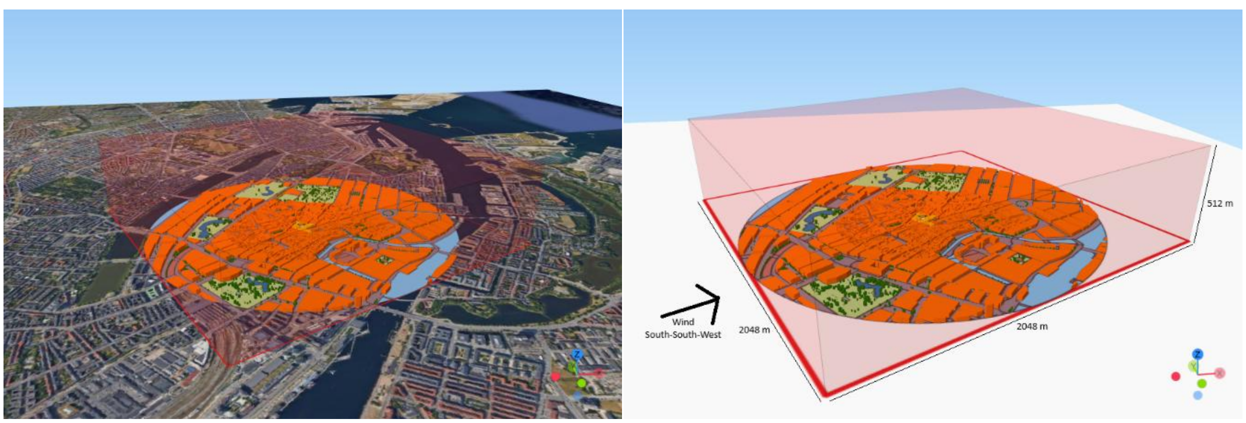

Figure 1: Illustration of urban model domain extensions displayed in its context of the city of Copenhagen, Denmark [Visualization created with QGIS (v3.34.3) using the Qgis2threejs plugin, Basemap: Google Satellite imagery (Imagery © Google)].

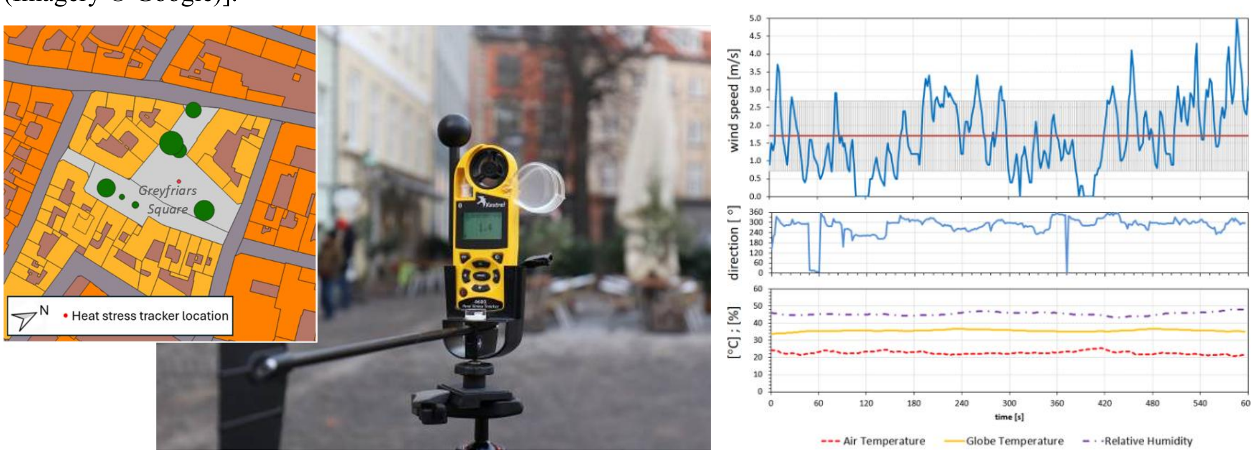

Figure 2, Left – heat stress tracker used to measure the local conditions of the urban microclimate in selected locations in the inner city of Copenhagen including Greyfriars Square as illustrated. Right – recorded data with a sampling frequency of 0.5 Hz over a period of 10 minutes used for comparison with the results from the PALM-4U simulation.

3. RESULTS

The field measurements and observations span over a period of 10 minutes. Amongst the four recorded parameters, wind speed and direction exhibit the largest variability. The comparison of full-scale and simulation results refers to the ergodic similarity of these parameters rather than an exact match of the recorded/simulated time histories. Table 1 lists the mean value and the standard deviation for wind speed, air temperature and relative humidity. The PALM model captures wind speed very accurately at the measurement location with a difference < 1 % from measurements. The differences in variance and standard deviation indicate that the PALM model underestimates wind speed variability. The results show good agreement for means of air temperature and relative humidity. The simulation slightly underestimates air temperature (0.6 °C cooler) but shows similar variability indicating that PALM captures temperature variations well. Humidity variability does not match well with observations.

Table 1: 10-minute statistics of wind speed, air temperature and relative humidity for measurement observations and PALM simulation results at Greyfriars Square. Date: 06-14-2018, Time 16:10-16:20 +02.

	Wind speed [m/s]		Air temperature [°C]		Relative humidity [%]	
	Observations	PALM	Observations	PALM	Observations	PALM
Mean	2.53	2.51	21.99	21.40	47.54	46.98
Variance	0.93	0.67	0.23	0.25	0.34	21.11
Std dev	0.96	0.82	0.48	0.50	0.58	4.59

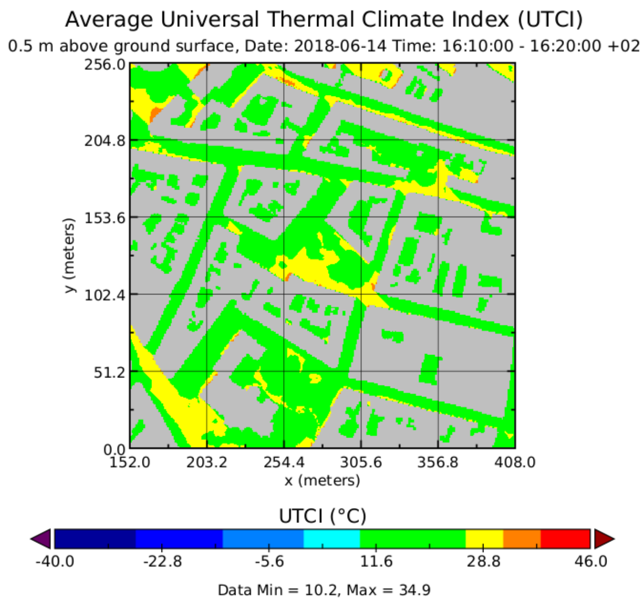

Figure 3, Contour map of spatially distributed Average UTCI from the PALM simulation, based on an average of instantaneous UTCI values measured at time 16:10 +02 and 16:20 +02. The different colours represent formal stress categories of UTCI from cold stress (blue tones) to heat stress (red tones). [Visualized with NASA GISS Panoply].

Figure 3 displays the spatial distribution of the Average UTCI for the 10-minute measurement period, mapping presence of stress categories; no thermal stress (green), moderate heat stress (yellow) and strong heat stress (orange). This is an example of how the multi-variable UTCI metric can be used for identifying micro-climate hotspots.

4. DISCUSSION

Trade-off between computational resources and precision have affected the model and brought about simplifications and the fixed cartesian grid structure in PALM generally limits representation of architectural detailing and curvatures. However, refining the urban model though accurate custom surface properties can be done, but is challenged by the availability and quality of input data. The limited spatial coverage of performed field measurements raise need for additional measurement observations (including diurnal/seasonal changes) to be able to assess how well the PALM model captures spatial and temporal variability of microclimatic conditions. The purpose of model validation is for future model application as a "digital experimental laboratory" for conducting urban-related studies under the impact of future climate scenarios and coupling to mesoscale models, including testing effects of urban adaptation strategies.

5. CONCLUSIONS

The results from re-analyzing the conditions of the urban microclimate on an urban location in the inner city of Copenhagen for a specific day and time show good agreement with the data from full-scale observation. The simulation with PALM-4U was conducted independently of the observational data and iterations focused only on refining the meshing for proper reflection of turbulent flow in the urban boundary- and canopy-layer. The case-based validation indicates a high potential for studying the urban microclimate under future climatic conditions and their impact on human health and comfort. Further studies are planned to apply the experience gained on this case study to other days and other locations to increase the accuracy of re-analysis of reference situations and the reliability of future scenarios and the development or recommendation of remedial measures in urban design.

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