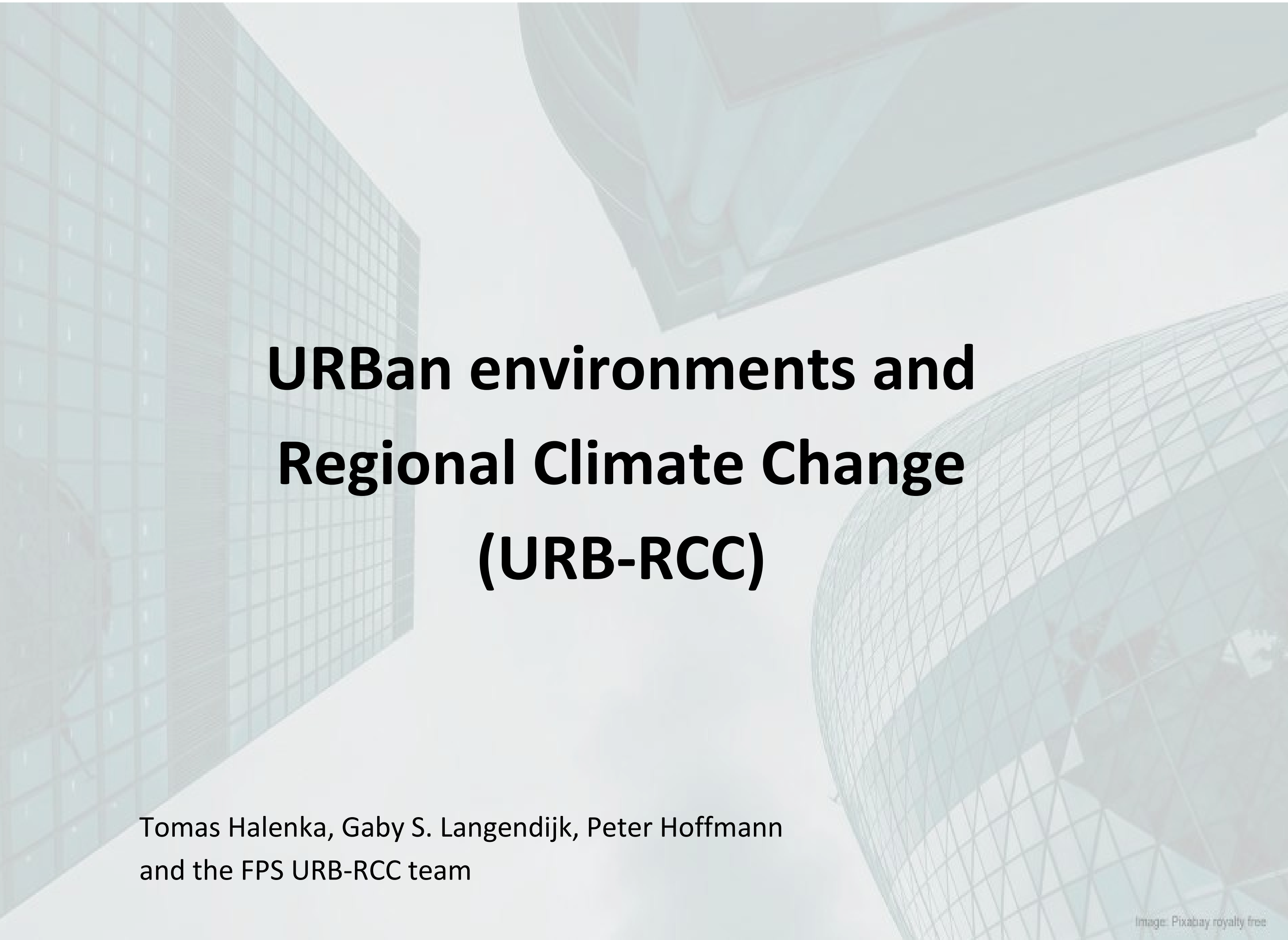
WCRP CORDEX Flagship Pilot Study URB-RCC
Report 2021 - 2025



URBan environments and Regional Climate Change (URB-RCC)

Tomas Halenka, Gaby S. Langendijk, Peter Hoffmann
and the FPS URB-RCC team

1. Background

Cities play a fundamental role on the climate at local to regional scales through modification of heat and moisture fluxes, as well as local convective processes. Vice versa, regional climate change impacts urban areas and is expected to increasingly affect cities and their citizens in the upcoming decades. At the same time, the proportion of the population living in urban areas is rising, and it is expected to reach around 70% of the global population by 2050. This trend is particularly concerning when it comes to extreme events, such as heatwaves, where temperatures are amplified by the urban heat island effect, especially during the night, posing serious risks to human health. Furthermore, with recent advancements in regional climate models that now offer higher spatial resolution down to the city level, accurately representing urban processes is becoming crucial to understanding local and regional climate change. The inclusion of specific urban land-use parameters, reflecting processes that influence energy balance and transport—such as heat, humidity, and momentum fluxes—is essential for correctly simulating urban climate effects. This approach will allow for better assessment of climate change impacts on cities and support decision-makers in developing adaptation and mitigation strategies, while also preparing for climate-related risks like heat waves.

Cities are increasingly becoming one of the most vulnerable environments to climate change. In 2013, the CORDEX community recognized cities as a key scientific challenge. However, significant collaborative efforts in this area were lacking, making enhanced cooperation on these issues highly important for the CORDEX community. In this light, the main goal of FPS URB-RCC is to understand the effect of urban areas on the regional climate, as well as the impact of regional climate change on cities, with the help of coordinated experiments with urbanized regional climate models (RCMs). While the urban climate with all the complex processes has been studied for decades, there is a significant gap to incorporate this knowledge into RCMs. This FPS aims to bridge this gap, leading the way to include urban parameterization schemes as a standard component in RCM simulations, especially at high resolutions.

2. Main objectives

- Investigating the ***interactions of urban environments with local to regional climate change*** based on a coordinated ensemble using urbanized RCMs under a common experiment protocol.

- Intercomparing ***urban parameterization schemes*** in high-resolution RCM simulations and identifying key processes and parameterizations for further use within the CORDEX framework.

- Better understanding the urban environment's vulnerability under climate change and providing the science to ***underpin climate services*** for cities.

3. Project phases

The FPS URB-RCC consists of four main phases (Figure 1). During Phase 1 an overview of urban effects and parameterization schemes incorporated in Regional Climate Models (RCMs) is created. In addition, available simulation outputs are analysed to understand climate change impacts in cities. Furthermore, the simulation protocol for coordinated simulations for Phase 2 is co-developed with the FPS partners and the main city for the coordinated experiment is selected.

Phase 2 focuses on conducting coordinated experiments at a spatial resolution of 2-4 km, including test and evaluation runs. During this phase, the urban processes that need to be incorporated into future RCM simulations are identified.

Selected experiments are part of Phase 3, particularly focusing on coupling RCMs to Chemical Transport Models and incorporating urbanization scenarios in RCMs.

Phase 4 consists of coordinated experiments that incorporate full complex urban effects under future climate scenarios. It includes a comparison and assessment of the added value of urban effects in regional and local climate change modeling. Additionally, this phase evaluates knowledge on urban regional climate and climate change impacts and connects these findings to the development of climate services.

This report will reflect on the above-mentioned phases, highlighting their main outcomes and specifying the contributions to the overall objectives of the FPS URB-RCC activity.

Phase 1:

- Overview of urban effects/parameterization schemes incorporated in RCMs
- Analysis of available simulations outputs to understand climate change impacts in cities
- Co-developing simulation protocols and criteria for city(ies) selection for coordinated experiments

Phase 2:

- Coordinated experiments at 2-4 km spatial resolution (test & evaluation runs)
- Identify urban processes needed to be included in future RCM simulations

Phase 3 *(for selected experiments):*

- Coupling to Chemical Transport Models
- Urbanization scenarios

Phase 4:

- Coordinated experiments with full complex urban effects under future scenarios
- Comparison and added value assessment of urban effects in regional/local CC
- Assessment of knowledge on urban regional climate and CC impacts, and connection to CS development

Figure 1. The four main phases of the FPS URB-RCC project.

4. Partners and associated projects

The partners of the FPS URB-RCC encompass regional climate modelling groups, as well as members of the long-standing urban climate community (Figure 2). The FPS spans across CORDEX domains, with around 30 partners and over 100 individual members, of which approximately two-thirds stems from the European CORDEX community. The advisory board is composed of leading experts in the urban climate change field; Alexander Baklanov, Sue Grimmond, and Robert Bornstein.

The FPS URB-RCC activity is conducted predominantly virtually, with annual FPS meetings online lasting one to two days. In addition to these main meetings, regular online discussions are held on specific subtopics to ensure continuous progress and collaboration. To facilitate in-person engagement, the FPS takes advantage of major international conferences such as the CORDEX International Conference on Regional Climate (ICRC CORDEX), the European Geosciences Union (EGU) General Assemblies, and the International Conference on Urban Climate (ICUC), or EURO-CORDEX General Assemblies, providing opportunities for partners to meet, exchange ideas, and strengthen collaborative efforts.

Figure 2. Main project partners of the FPS URB-RCC activity.

4.1. Associated projects

4.1.1. EU Horizon Europe IMPETUS4CHANGE Project (I4C)

The EU HorizonEurope project I4C (Improving Near-Term Climate Predictions for Societal Transformation - No. 101081555, 2022-2026) focuses on climate prediction at very high resolution, with partial emphasis on urban impacts and climate services development for selected cities. Both the I4C project and FPS URB-RCC entail coordinated RCM simulations for the Paris region and alignment across the protocols and simulations is ensured (Phase 1 and 2 of FPS). A few modelling groups are part of both projects. Furthermore, for Paris, as well as for the I4C so-called "Demonstrator Cities", specific climate services are co-produced with municipalities. The latter could serve as an input to Phase 4 of the FPS project.

4.1.2. EU Horizon Europe FOCI Project

The EU HorizonEurope project FOCI (Non-CO2 Forcers and their Climate, Weather, Air Quality and Health Impacts - No. 101056783, 2022-2026) focuses on chemistry-climate interactions over the km scales, including urban scale, thus, it is supporting especially the FPS activities of Phase 3. Mini-ensemble of coupled chemistry-climate simulations at regional and local scales will be performed and analysed for the assessment of chemistry impacts on land-surface processes and regional to local climate, especially through interactive contribution of aerosols.

4.1.3. MSCA Post-Doc: City-oriented Impacts of Regional Climate for Europe (CIRCE)

- Benjamin le Roy

With support from the Marie Skłodowska-Curie Action program, the EU HorizonEurope CIRCE project (City-oriented Impacts of Regional Climate for Europe - No. 101067769, 2023-2025, https://doi.org/10.3030/101067769) aims to define the best climate model configurations for studying the combined effect of urbanization and climate change on cities. The project uses high-resolution (~3km) regional climate simulations from the past CORDEX FPS on Convection to assess the ability of the new models to simulate the urban climate of several European cities. CIRCE is working in conjunction with the FPS URB-RCC to define the best methodology for model evaluation as well as recommendations concerning (1) the best configuration of regional climate models for simulating cities and (2) guidelines for using the climate data produced based on user needs and the associated uncertainties.

4.1.4. PhD: Deep Learning for urban climate modelling

- Frederico Johannsen

This PhD thesis is titled "Deep learning and physically-based numerical models for very high resolution urban climate modelling", supervised by Pedro Soares and Gaby Langendijk. The main objective of the PhD is to combine data-driven (deep learning) and physically-based numerical models (SURFEX land surface model) to improve urban climate characterization in present and future climate. Leveraging on observational data (gridded and in-situ), the deep learning models have been trained to obtain air temperatures and land surface temperature. Special focus has been given to the models' quality in representing city-specific phenomena (e.g. urban heat island) and temperature extremes (e.g. heatwaves). The city of study is Paris, France, following the FPS URB-RCC guidelines. After testing several predictor setups, the deep learning model, forced with CMIP6 Global Climate Models, has been used to generate future projections of air temperature and land surface temperature for the 21st century under different shared socioeconomic pathways. The DL models developed in this PhD have the potential to contribute to the ensemble of urban climate projections aggregated in the FPS URB-RCC.

4.1.5. Czech Republic OP-JAC Geohazards Project

The project Natural and Anthropogenic Geohazards (No. CZ.02.01.01/00/22_008/0004605) (2024-2028) runs under the "Operational Program Johan Amos Comenius on Excellent Research" by the Czech Republic's Ministry of Education, Youth and Sports. The project covers Earth system risks, their causes, key processes involved, and projected impacts. One part of the project, in WP2, is dealing with urban effects on land-surface-atmosphere interactions, with emphasis on strong impacts of urban heat islands and air-pollutants on populations in cities - specifically aligning with Phase 3 of the FPS URB-RCC activity.

4.1.6. Spanish national PROTECT Project

- Ana Casanueva, Jesús Fernández, Gaby Langendijk

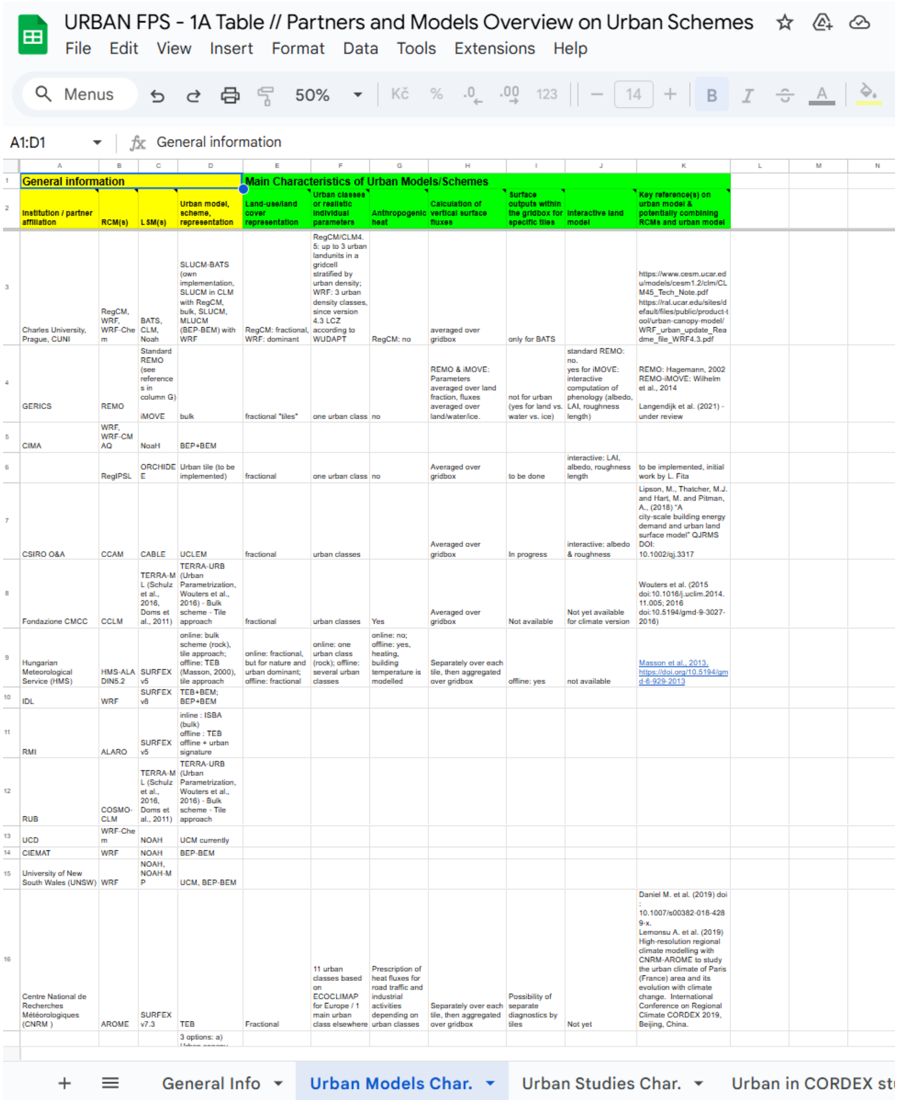
The project "Climate change PROjections of human comfort using dynamical downscaling and deep learning emulation TEChniques" (PROTECT, PID2023-149997OA-I00) runs under the Spanish national research agency since September 2024 and will last 3 years. The main objective of the project is twofold, aiming to use the latest regional climate change simulations available to develop specific climate information for human comfort and to develop innovative regionalization methods suitable to work with multivariate indices. First, the project will exploit different state-of-the-art techniques and regional climate projection datasets, at continental and city scales (including those developed in the FPS URB-RCC during Phase 2 and 4), for the production of high-resolution climate information for end-users. The second objective is strengthening the statistical downscaling methods available to produce high-resolution projections of multidimensional indices, working in the development of new emulators based on novel deep learning methods. A PhD Thesis starting in March 2025 will focus on the development of robust and explainable deep learning downscaling methods for multivariate indices.

5. Main outcomes

5.1 Phase 1

5.1.1. Overview table of urban parameterizations in RCMs

An overview table is created detailing information about the RCMs (Figure 3), including: urban schemes used and/or under development, model specifics, available observations for evaluation (esp. urban), (urban) land surface input data, related publications to models and urban schemes.



	General information				Main Characteristics of Urban Models/Schemes						
2	Institution / partner affiliation	RCM(s)	LSM(s)	Urban model, scheme, representation	Land-use/land cover representation	Urban classes or realistic individual parameters	Anthropogenic heat	Calculation of vertical surface fluxes	Surface outputs within the gridbox for specific tiles	Interactive land model	Key reference(s) on urban model & potentially combining RCMs and urban model
3	Charles University, Prague, CUNI	RegCM, WRF, WRF-Chem	BATS, CLM, Noah	SLUCM-BATS (own implementation, SLUCM in CLM with RegCM, bulk, SLUCM, MLUCM (BEP-BEM) with WRF	RegCM: fractional, WRF: dominant	RegCM/CLM4.5: up to 3 urban landunits in a gridcell stratified by urban density; WRF: 3 urban density classes, since version 4.3 LCZ according to WUDAPT	RegCM: no	averaged over gridbox	only for BATS		https://www.cesm.ucar.edu/models/cesm1.2/clm/CLM45_Tech_Note.pdf https://ral.ucar.edu/sites/default/files/public/product-tool/urban-canopy-model/WRF_urban_update_Readme_file_WRF4.3.pdf
4	GERICS	REMO	Standard REMO (see references in column G) iMOVE	bulk	fractional "tiles"	one urban class	no	REMO & iMOVE: Parameters averaged over land fraction, fluxes averaged over land/water/ice.	not for urban (yes for land vs. water vs. ice)	standard REMO: no. yes for iMOVE: interactive computation of phenology (albedo, LAI, roughness length)	REMO: Hagemann, 2002 REMO-iMOVE: Wilhelm et al., 2014 Langendijk et al. (2021) - under review
5	CIMA	WRF, WRF-CMAQ	NoaH	BEP+BEM							
6		RegIPSL	ORCHIDEE	Urban tile (to be implemented)	fractional	one urban class	no	Averaged over gridbox	to be done	interactive: LAI, albedo, roughness length	to be implemented, initial work by L. Fita
7	CSIRO O&A	CCAM	CABLE	UCLEM	fractional	urban classes		Averaged over gridbox	In progress	interactive: albedo & roughness	Lipson, M., Thatcher, M.J. and Hart, M. and Pitman, A., (2018) "A city-scale building energy demand and urban land surface model" QJRMS DOI: 10.1002/qj.3317
8	Fondazione CMCC	CCLM	TERRA-ML (Schulz et al., 2016, Doms et al., 2011)	TERRA-URB (Urban Parametrization, Wouters et al., 2016) - Bulk scheme - Tile approach	fractional	urban classes	Yes	Averaged over gridbox	Not available	Not yet available for climate version	Wouters et al. (2015 doi:10.1016/j.uclim.2014.11.005; 2016 doi:10.5194/gmd-9-3027-2016)
9	Hungarian Meteorological Service (HMS)	HMS-ALADIN5.2	SURFEX v5	online: bulk scheme (rock), tile approach; offline: TEB (Masson, 2000), tile approach	online: fractional, but for nature and urban dominant; offline: fractional	online: one urban class (rock); offline: several urban classes	online: no; offline: yes, heating, building temperature is modelled	Separately over each tile, then aggregated over gridbox	offline: yes	not available	Masson et al., 2013, https://doi.org/10.5194/gmd-6-929-2013
10	IDL	WRF	SURFEX v8	TEB+BEM; BEP+BEM							
11	RMI	ALARO	SURFEX v5	inline : ISBA (bulk) offline : TEB offline + urban signature							
12	RUB	COSMO-CLM	TERRA-ML (Schulz et al., 2016, Doms et al., 2011)	TERRA-URB (Urban Parametrization, Wouters et al., 2016) - Bulk scheme - Tile approach							
13	UCD	WRF-Chem	NOAH	UCM currently							
14	CIEMAT	WRF	NOAH	BEP-BEM							
15	University of New South Wales (UNSW)	WRF	NOAH, NOAH-MP	UCM, BEP-BEM							
16	Centre National de Recherches Météorologiques (CNRM)	AROME	SURFEX v7.3	TEB	Fractional	11 urban classes based on ECOCLIMAP for Europe / 1 main urban class elsewhere	Prescription of heat fluxes for road traffic and industrial activities depending on urban classes	Separately over each tile, then aggregated over gridbox	Possibility of separate diagnostics by tiles	Not yet	Daniel M. et al. (2019) doi : 10.1007/s00382-018-4289-x. Lemonsu A. et al. (2019) High-resolution regional climate modelling with CNRM-AROME to study the urban climate of Paris (France) area and its evolution with climate change. International Conference on Regional Climate CORDEX 2019, Beijing, China.
				3 options: a)							

Figure 3. Screenshot of the overview table on urban schemes in RCMs, collected in 2021. Please note that this is only one part of one tab of the full table.

5.1.2. Analysis of existing datasets

For the analysis of existing datasets, particularly the global CORDEX-CORE ensemble simulations, the European convection permitting RCM ensemble simulations, and EURO-CORDEX simulations were investigated.

CP RCM Analysis

Leads: Benjamin le Roy, Yohanna Michau, Sophie Bastin

Previous simulations carried out as part of the CORDEX FPS on Convection have given us an initial insight into the differences between RCMs, CPMs and urban parameterizations, and have enabled us to define different approaches for model evaluation. The FPS convection ensemble contains over 20 CPM simulations for the evaluation period (2000-2009), 17 of which have some form of urban representation. A first look at the city of Paris (Figure 4) allows us to see the added value of CPMs compared with some of the RCMs that drive them, as well as the possible limitations that remain even with the increased resolution. For example, some models rely on simpler approaches to representing urban areas, and fail to represent surface heterogeneity within a grid cell (i.e. different types of cover). Some models also present biases that are unrelated to urban parameterization and that need to be taken into account.

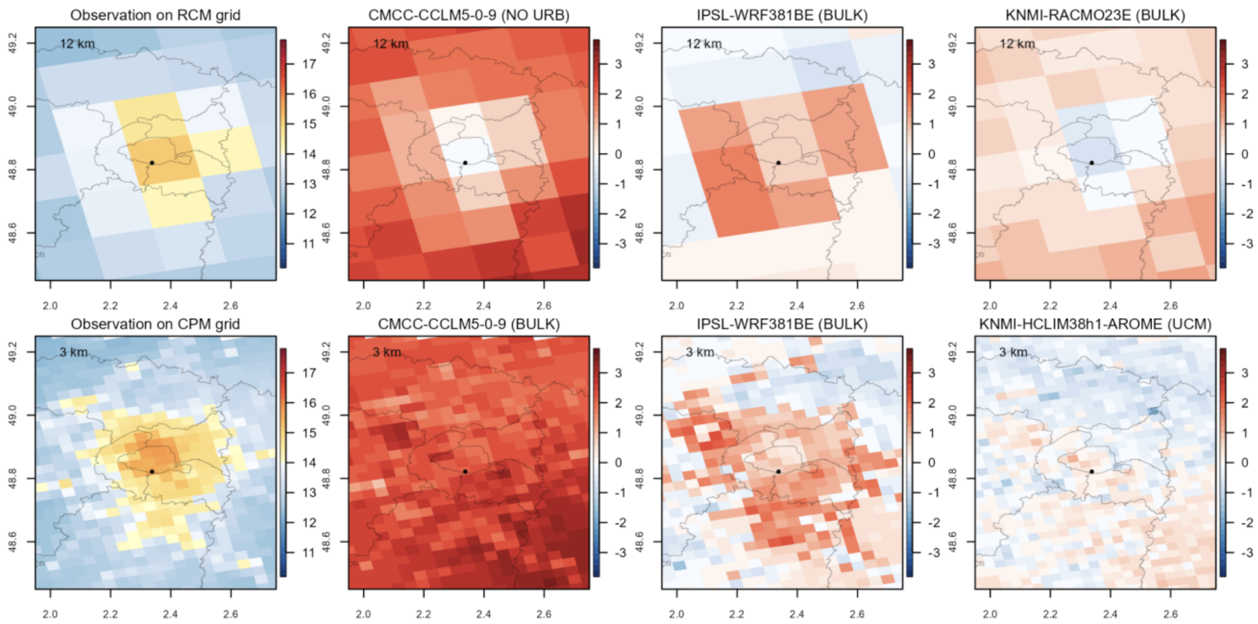


Figure 4. Average daily minimum air temperature (TN 2000-2009 JJA) observed in a 1.25 km dataset (interpolated to the RCM and CPM grids) and corresponding biases for 3 RCMs and their associated CPMs using different urban parametrizations. (Le Roy and Rechid, 2024;. Copernicus Meetings EGU24.)

Beyond the analysis of a single city, the FPS convection ensemble enables us to study the ability of models to represent the urban climate of several cities in different geographical contexts: for example, along the coast or in mountainous areas. This type of multi-city analysis highlights the fact that different models and various urban parameterizations can perform differently depending on the background climate of the simulated city and its specificities. It also enables us to define an evaluation framework adapted to other contexts and limitations, such as the availability of observations. An initial examination of the ensemble shows that CPRCMs using Urban Canopy Models tend to represent nocturnal UHI intensities in continental cities better than those using simpler approaches (Figure 5), but this is not necessarily the case for coastal cities.

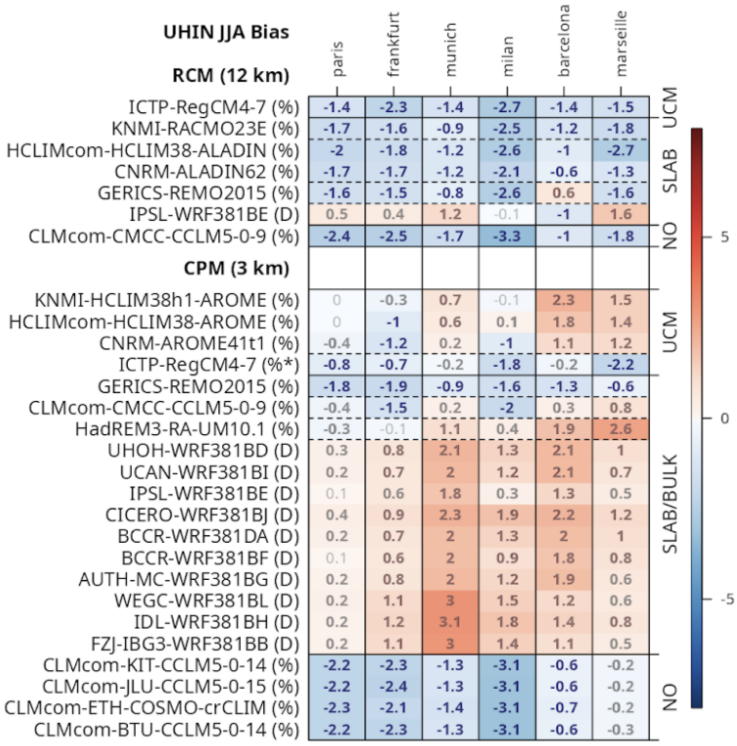


Figure 5. Average nighttime UHI biases (TN 2000-2009 JJA [based on observation]) simulated by different CPMs and some of their driving RCMs. (NO means no urban parametrization; SLAB/BULK refers to more simpler approaches; UCM stands for Urban Canopy Model; % means the model uses a fractional approach to differentiate multiple covers inside a point; D means the model uses a dominant cover approach). (Le Roy et al., in preparation)

Thanks to their added values, CPRCMs appear to be a promising tool for impact studies, in particular for studying and quantifying urban climate evolution in response to global warming. In Michau et al. (preprint), the FPS Convection ensemble (smaller than that used in Le Roy et al., in preparation, with 7 simulations using different modeling chains and different levels of sophistication for urban climate simulations) was used to study the future urban climate of Paris. As shown in figure 6, analysis of CPRCM results over the HIST period showed that CPRCMs with urban surface parameterization were capable of representing UHIs (daytime and nighttime), including their typical seasonal variations. However, the comparison of CPRCMs revealed no difference in performance between CPRCMs based on a simple slab approach and those incorporating an urban canopy model to represent the urban area. Based on the RCP8.5 GHG emission scenario, the study highlighted that most CPRCMs, despite the different parameterizations of the urban surface, project a decrease in the UHI effect during the day in JJA, similar to the results obtained by Hamdi et al. (2015) for Brussels, Belgium.

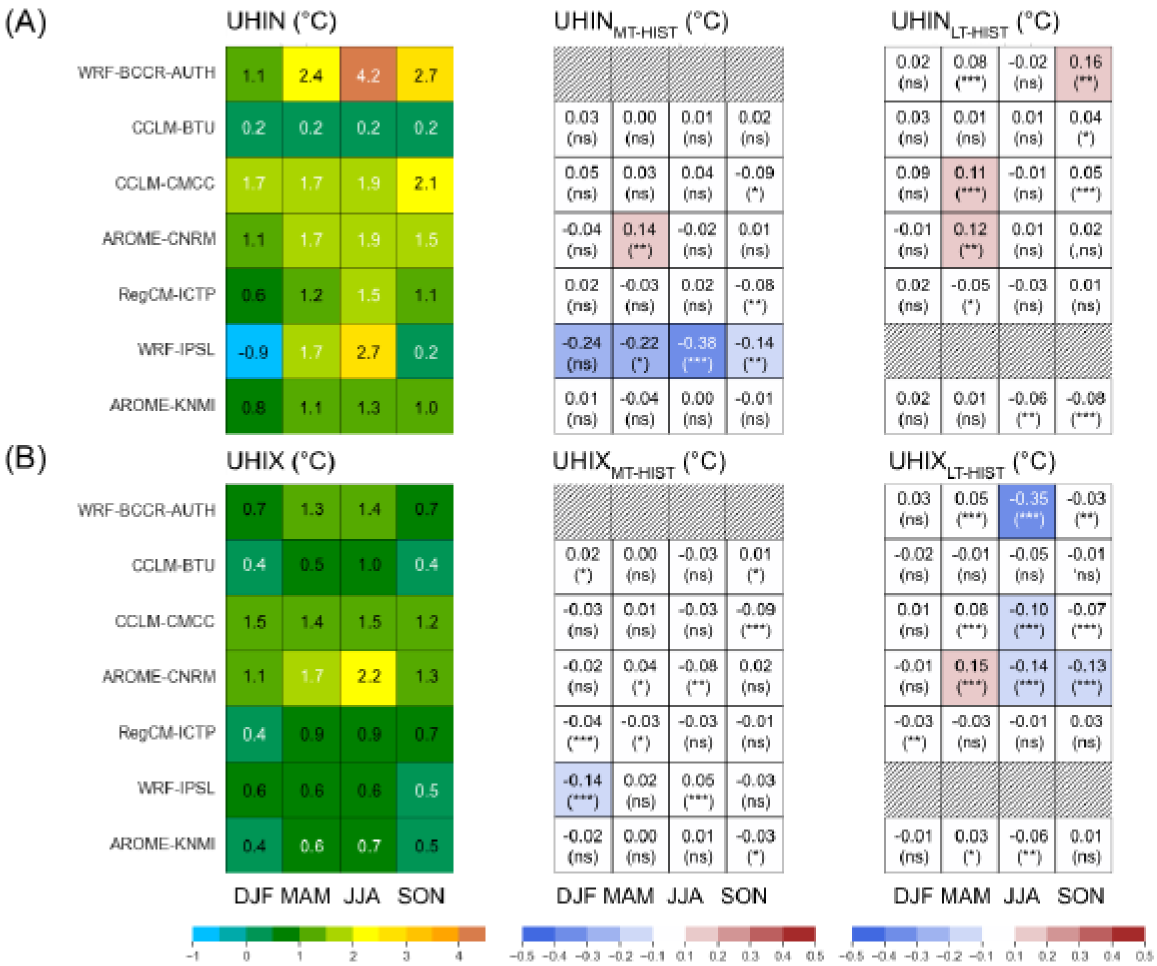


*Figure 6. (A) Nocturnal (top) and diurnal (bottom) median daily UHIs (in °C) for each CPRCM in the different seasons. (B) Variation in median daily UHIs (in °C) for each CPRCM between midterm and historical periods (left), as well as between longterm and historical periods (right) in the different seasons. Differences between distributions were assessed using the Mann-Whitney non-parametric test adapted for independent samples with hypotheses H0 (medians are equal) and H1 (medians are different). Symbols refer to the following significance thresholds: ***: 1e-4 <= p-value <= 1e-3, **: 1e-3 <= p-value <= 1e-2, *: 1e-2 <= p-value <= 0.05, ns (not significant): 0.05 <= p-value <= 1 (Michau et al., under review)*

Related publications:

- Pre-print: Projected Evolution of the Urban Climate and Heatwaves using an Ensemble of Convection-Permitting Regional Climate Models. Michau, Y., Lemonsu, A., Lucas-Picher, P., Bastin, S., Caillaud, C., de Vries, H., ... & Coppola, E. https://doi.org/10.21203/rs.3.rs-5309528/v1
- Paper in preparation: Le Roy, B. et al. How do convection permitting climate models improve the representation of Urban Heat Islands compared with standard regional climate models? Climate Dynamics.
- Michau, Y., Lemonsu, A., Lucas-Picher, P., Schneider, M., & Caillaud, C. (2024). On the future evolution of heatwaves in French cities and associated rural areas: Insights from a convection-permitting model. *Urban Climate*, *55*, 101920.

CORDEX-CORE can detect the urban imprint of large cities

Leads: Gaby Langendijk, Jesus Fernandez, Matthias Demuzere, Javier Diez-Sierra

This analysis of the CORDEX-CORE dataset focuses on the representation of global mega-cities and their associated urban heat island (UHI) effects in CORDEX-CORE regional climate model simulations. CORDEX-CORE provides climate data at a spatial resolution of 25 km, offering insights into urban climate dynamics on a regional scale. CORDEX-CORE encompasses two RCMs, REMO and RegCM, of which REMO contains a simple “bulk” scheme to represent urban areas and RegCM a single layer urban canopy model. It is crucial to note that RegCM used an urban fraction (UF) cut-off threshold value of >40% for all domains, except EUR where no UF cut-off threshold was used, and for NAM and EAS where no urban land-use was used.

Results indicate that impervious surface areas are significantly underestimated in the land-use datasets used by the REMO and RegCM models, with this underestimation being geographically imbalanced (Figure 7). While urban land-use representation is relatively accurate for Europe and America, both models fail to adequately capture urban areas across Asia and Africa, particularly in the case of RegCM when urban fraction (UF) is below 40%.

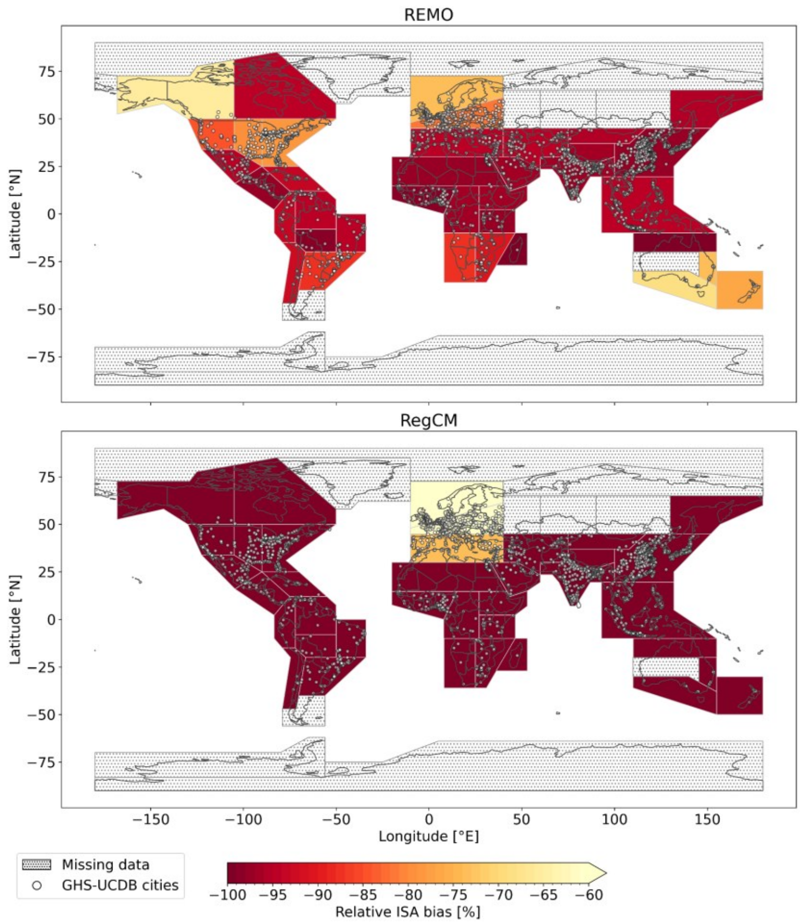


Figure 7. Average relative Impervious Surface Area (ISA) bias (%) per IPCC AR6 reference domain, for REMO (top panel) and RegCM (bottom panel). Cities are indicated by white markers. Please note that for EUR the 0.11º spatial resolution was used. (by Matthias Demuzere).

UHI effects are detectable for larger cities at a finer spatial resolution of 0.22º for the evaluations simulations of the CORDEX-CORE dataset (Figure 8). The REMO model tends to underestimate nighttime UHI due to its reliance on a simple bulk scheme. In contrast, the RegCM model provides a more accurate representation of UHI, particularly at night, owing to its use of the Community Land Model (CLM) with a simplified urban canopy parameterization. Many cities are not visible in RegCM due to 40% cut-off for urban fraction.

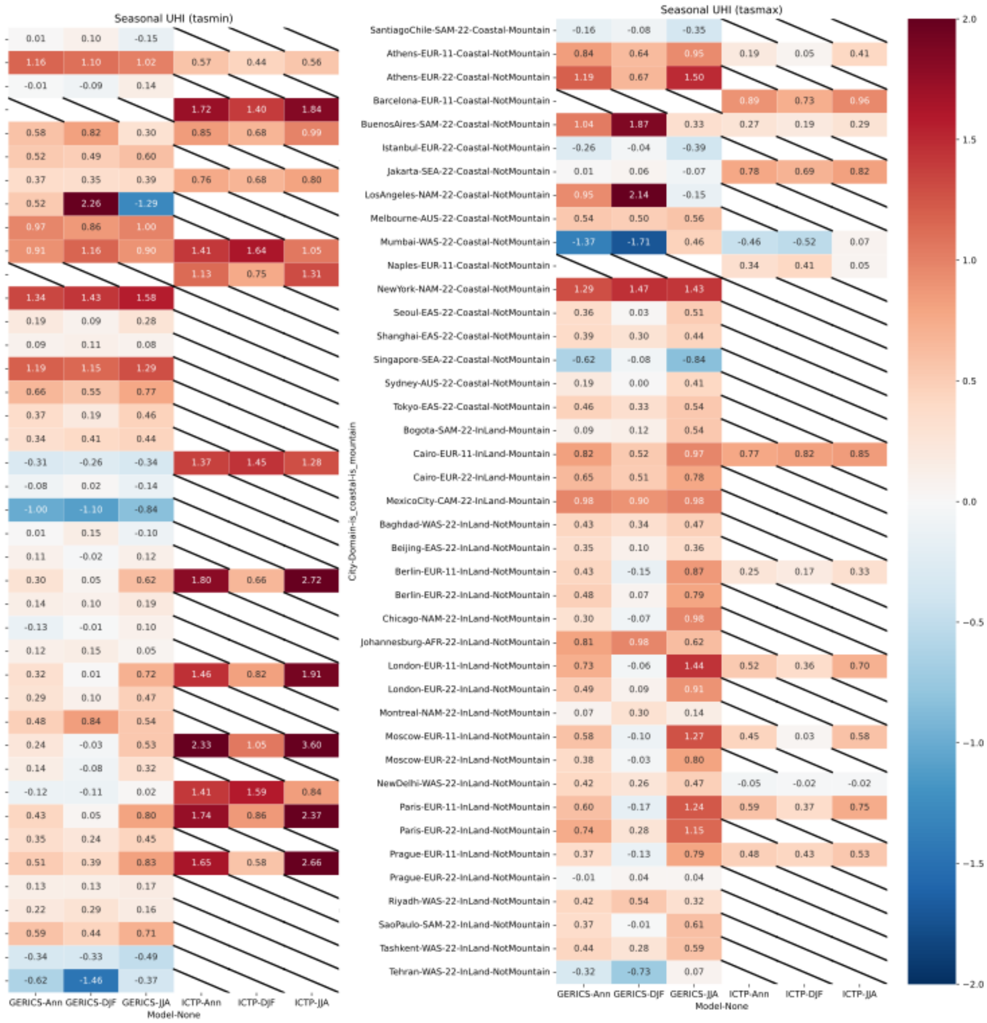


Figure 8. Heat map showing seasonal urban heat island for minimum temperature (tasmin) and maximum temperature (tasmax) for cities across the globe for the evaluation period of the CORDEX-CORE dataset. Left columns: REMO (GERICS), right columns: RegCM (ICTP). (by Jesus Fernandez and Javier Diez-Sierra).

To enhance the accuracy of regional climate models in representing urban environments, it is essential to improve urbanization schemes not only in terms of physical processes and parameterizations but also by incorporating more precise urban land-use datasets. There is an opportunity to enable urban representation in future CORDEX-CORE Phase II experiments and within EURO-CORDEX simulations, which would significantly improve the modeling of urban climate impacts on a regional scale.

Related publication:

Representation of global mega-cities and their urban heat island in CORDEX-CORE regional climate model simulations. Langendijk, G. S., Fernandez, J., Diez-Sierra, J., Quintana, Y., Demuzere, M., Fita, L. Hoffmann, P., Rechid, D., Halenka, T., Nogherotto, R., Zazulie, N., Coppola, E., Hamdi, R., Kwok Chun, S., et al. [In final phase of preparation]

A novel method for delimiting urban and rural areas for megacities

Leads: Javier Diez-Sierra, Jesus Fernandez

A database is created of urban and rural masks for CORDEX-CORE and EURO-CORDEX, covering the cities selected within the CORDEX-CORE FPS URB-RCC study. This database was generated through a novel method using the urban fraction (UF) static data, and a Python-based workflow for delimiting urban and rural surrounding areas, along with additional functionalities for analyzing and visualizing the UHI effect. These new methods are specifically designed for applications in climate change models. The goal of this work is to establish a collaborative framework for evaluating urban climate change using a consistent methodology to delimit urban and rural areas.

Related publication:

A dataset delimiting urban and rural areas for megacities worldwide to assess urban climate change across CORDEX experiments. Diez-Sierra, J., Fernandez, J., Quintana, Y., Langendijk, G.S., Milovac, J., Gutiérrez, J.M., et al. [In final phase of preparation]

Other FPS related publications using existing datasets:

EURO-CORDEX:

Assessing Climate Change Hazards in Urban and Rural Areas for European Cities Using EURO-CORDEX ensemble. Zazulie, N., Nogherotto, R., Coppola, E. et al.
[In preparation (tentative title)]

CCAM global 50km simulations with urban parameterization:

Effects of urban areas on the diurnal cycle of temperature and precipitation in a global climate simulation. 2024. Katzfey, J., Schlünzen, K.H. & Hoffmann, P. Quarterly Journal of the Royal Meteorological Society, 150(765), 4885–4914. https://doi.org/10.1002/qj.4847

5.1.3. Preparation coordinated STAGE-0 simulations

A first set of coordinated test-simulations, so-called STAGE-0, were prepared during Phase 1 of the FPS activity. This section elaborates the key associated decisions and products, such as protocols and variable lists.

Paris selected as "CORE" city for coordinated experiments

Paris was selected as the "CORE" city for the coordinated experiment within the FPS URB-RCC. An extensive selection procedure was developed, with co-developed selection criteria and a survey among the FPS partners to select the coordinated "CORE" city. A careful selection procedure is critical to safeguard a solid number of teams within the FPS for the coordinated ensemble simulations.

Additionally to Paris, the different groups intend to simulate their "local" city/cities across different continents. We have developed the concept of the Global Satellite Cities, which enable some groups not having resources to participate in the coordinated experiment for the selected city, to contribute with their local simulations of their city of interest, following a similar set-up/protocol.

Joint protocol for coordinated STAGE-0 test simulations developed

A joint protocol was developed for the first set of coordinated simulations, so-called STAGE-0. These coordinated simulations include the double-nested downscaling of 2 short events for the Paris region: a severe convective event and a heat-wave. Both extremes occurred in 2020 and are simulated within a period of 4-5 months using ERA5.1 reanalysis data (Table 1). The months in between the extremes are used as a "benign" benchmarking period. The domains for STAGE-0 are specified in Figure 9.

Run Name	Description	Forcing	Domain	Resolution	Time period
1. Test URBRCC precip-heat	Reanalysis test run for heat wave and heavy precipitation event in same year (2020)	ERA5.1	EURO-CORDEX or parent domain	0.11°	April - August 2020
		0.11° LBC	Paris region	2-4 km	May - August 2020

Table 1. Overview of STAGE-0 simulations.

The main aim of the STAGE-0 coordinated simulations is to test the RCMs and urban schemes, as well as model and domain set-up using short-term simulations for the Paris region. The test simulations cover two extreme events in 2020, which allows for a coordinated analysis of these extreme events. In addition, these test simulations prepare the ground for the coordinated evaluation simulations (STAGE 1).

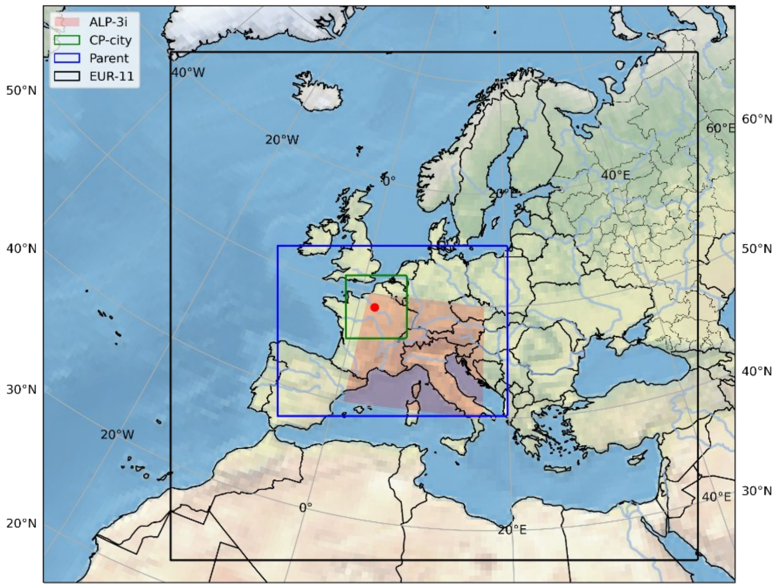


Figure 9. Approximated minimum domain locations and size. Green = CP-city domain. Blue = 0.11° "Parent" domain. Black = EUR-11 standard domain.

An output variable list developed for urban specific needs

In adjunction to the STAGE-0 protocol an output variable list was developed, tailored to urban specific needs. The variable list was based on the CORDEX CMIP6 output variable, while adding variables for urban specific needs (Figure 10). One of the key variables added was the static urban fraction data (sfturf), of key interest when analysing cities. The variable list was closely aligned with the I4C project.

z0	m	i	Surface Roughness Length	surface_roughness_length
sfturf	%		Percentage of the Grid Cell Occupied by City	urban_area_fraction
taspav	K	i	Near-surface temperature pavements	pavement_temperature
tasroof	K	i	Near-surface temperature roof	roof_temperature
tasgree	K	i	Near-surface temperature green spaces	greenspaces_temperature
tasblue	K	i	Near-surface temperature blue spaces	bluespaces_temperature
anthroheat	W/m2		Anthropogenic heat flux	anthropogenic_heatflux
tsskin	K	i	Skin temperature	skin_temperature
tspav	K	i	Surface temperature pavements	pavement_surface_temperature
tsroof	K	i	Surface temperature roof	roof_surface_temperature
tsgree	K	i	Surface temperature green spaces	greenspaces_surface_temperature
tsblue	K	i	Surface temperature blue spaces	bluespaces_surface_temperature
tascan	K	i	Near-surface temperature within canyon	temperature_canyon
hurscan	%	i	Near-Surface Relative Humidity within canyon	relative_humidity_canyon
husscan	1	i	Near-Surface Specific Humidity within canyon	specific_humidity_canyon
sfcWindcan	m s-1	i	Near-Surface Wind Speed within canyon	wind_speed_canyon

Figure 10. Urban specific variables in FPS output variable list.

Joint analysis protocol developed to analyse STAGE-0 simulations

A joint analysis protocol was created to analyse the STAGE-0 simulations. The analysis protocol specifies the analysis domain, available observations, data access and storage, CMORization process, naming conventions, dealing with authorship and joint analyses, etc.

Data storage and exchange via DKRZ

The model output from the STAGE-0 experiment, and in the future from the STAGE-1 experiment, is shared via a server at the German Climate Computing Center (DKRZ). This setup facilitates quick data exchange and promotes collaborative analysis. Additionally, URB-RCC has applied for computing time, which is currently being used to process the files and conduct basic analyses.

5.1.4. Further activities

A FPS overview paper was published in the international Urban Climate journal

Langendijk, G. S., Halenka, T., Hoffmann, P., Adinolfi, M., Campino, A. A., Asselin, O., ... & Yuan, J. (2024). Towards better understanding the urban environment and its interactions with regional climate change-The WCRP CORDEX Flagship Pilot Study URB-RCC. Urban Climate, 58, 102165. https://doi.org/10.1016/j.uclim.2024.102165

In-person side-event during ICRC-CORDEX

During the CORDEX International Conference on Regional Climate (ICRC-CORDEX) in 2023 a FPS side-event was held (Figure 11), where partners could meet in-person and discuss progress and develop the next steps of the activity.

Figure 11. Participants of the FPS URB-RCC side-event during ICRC-CORDEX 2023.

5.2 Phase 2

5.2.1 STAGE-0 coordinated simulations completed

The STAGE-0 simulations have been completed, as shown in Figure 12, involving 18 institutions and 9 regional climate models. A total of 41 simulations were conducted, with 39 currently shared, and 2 completed (status Feb. 2025). Sensitivity runs included 29 simulations using WRF, 3 with CNRM-AROME, 2 with CCLM, and 2 with RegCM. The STAGE-0 simulations have been shared via DKRZ.

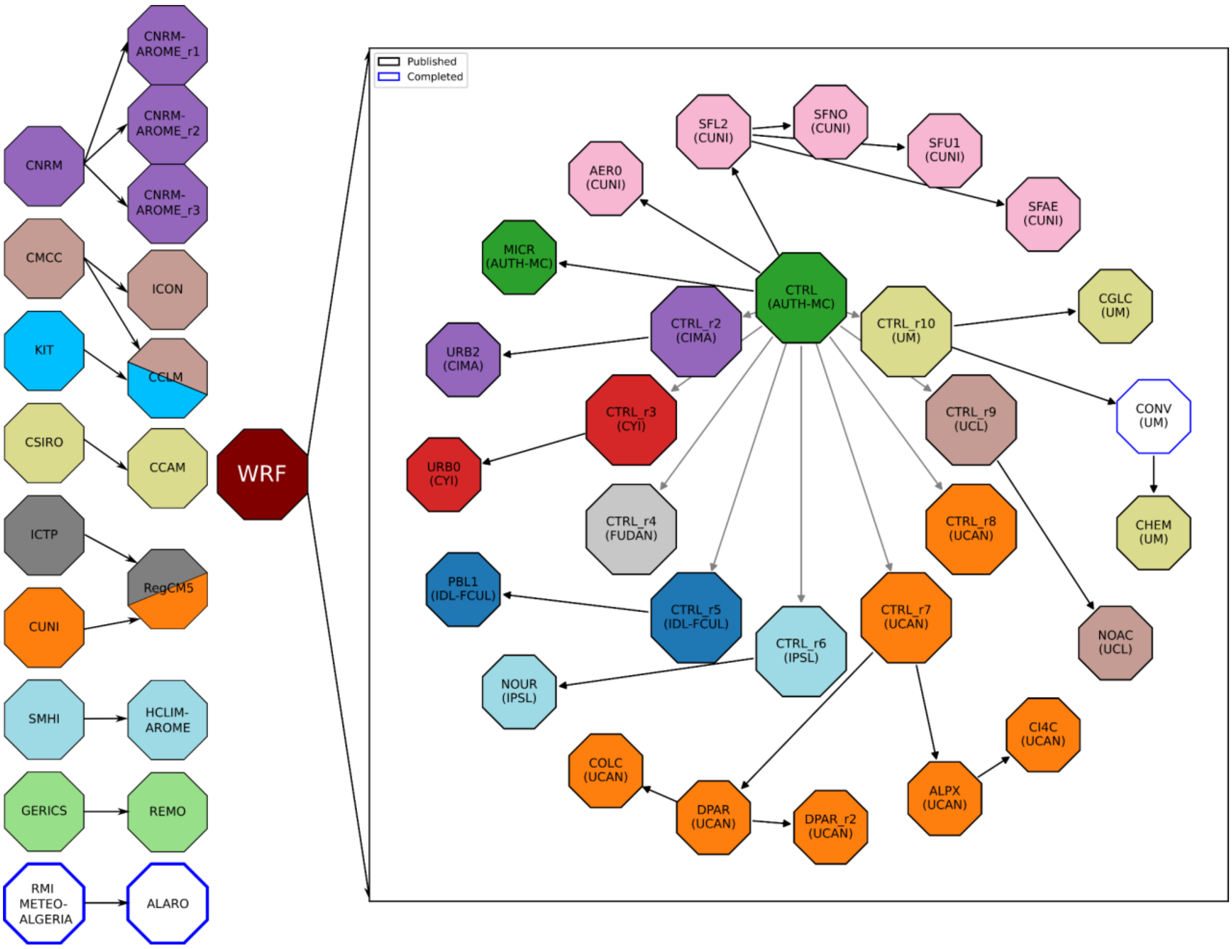


Figure 12. Overview of conducted STAGE-0 simulations, status Feb. 2025. (by Josipa Milovac).

5.2.2 On-going analyses STAGE-0 output data *[preliminary results]*

Various analyses of STAGE-0 simulations output data are currently on-going. This section highlights here are five on-going analyses, some with (very) preliminary results.

UHI and overall analysis

Leads: Tomas Halenka and Michal Belda (Charles University, Czech Republic)

The simulations were analyzed for Paris, focusing on two episodes: a heat wave in August 2020 and an intensive precipitation event in May 2020. The first analysis compares the model simulations with observations at meteorological stations in and around Paris. For the heat wave event, the representation of the urban heat island intensity was calculated as the difference between the urban stations and rural ones in hourly steps. The averages over the full summer season (June-September 2020, see Figure 13) and during the studied heat wave on 7-13 August 2020 (Figure 14) show quite consistent behaviour of the models, mostly with an underestimation of the intensity during night-time and overestimation during afternoon. The underestimation during night-time is higher than overestimation in the afternoon, when for both cases two different patterns can be seen, depending on different models and their setting.

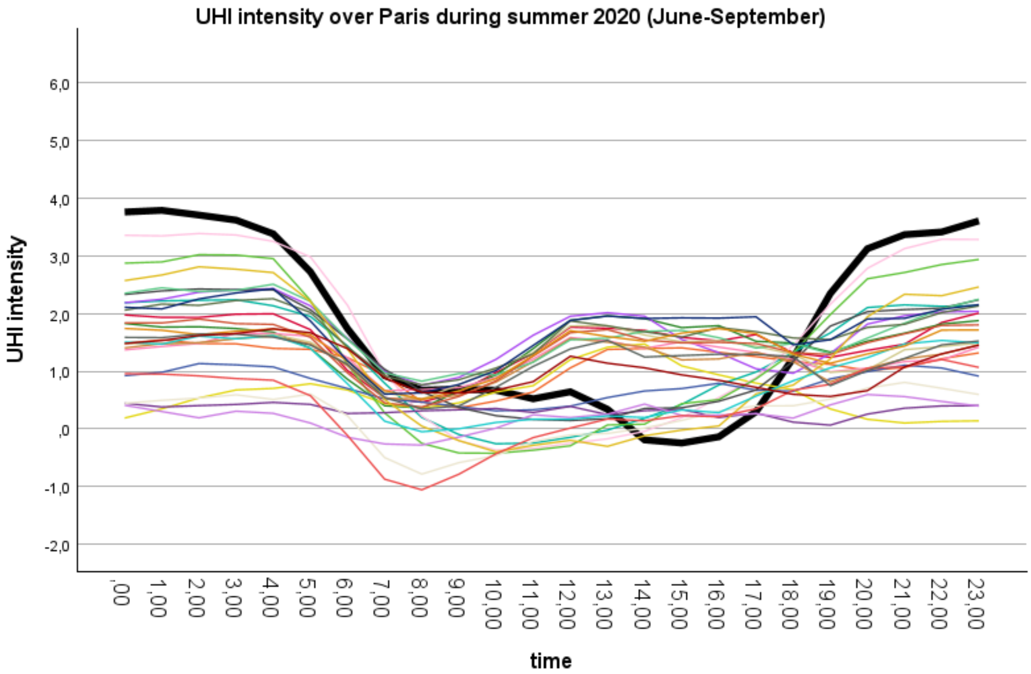


Figure 13. Daily cycle of UHI intensity at the gridbox of urban station Lariboisiere vs. gridbox of rural station Meaux-Esbly, over June-September. Bold back line showing the observations for the stations.

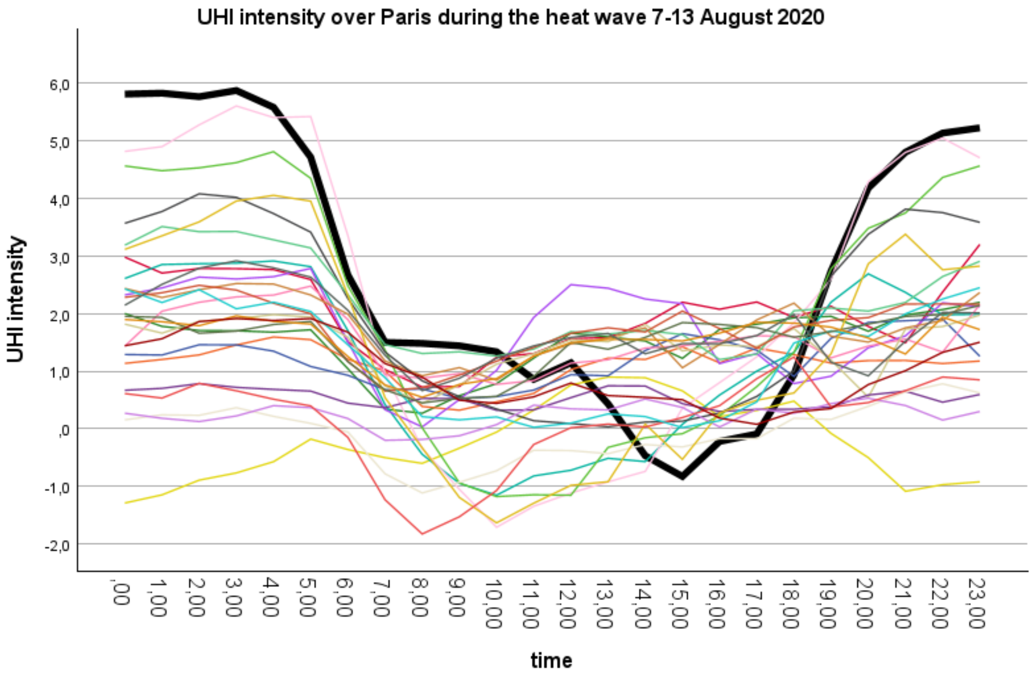


Figure 14. Daily cycle of UHI intensity at the gridbox of urban station Lariboisiere vs. gridbox of rural station Meaux-Esbly, over heat wave 7-13 August. Bold back line showing the observations for the stations.

Land-surface characteristics

Lead: Kwok P. Chun (Sun) (University of the West of England)

Different urban land use effects on boundary layers are revealed in the km-scale convection-permitting model outputs, which previous regional models at a 0.11° scale could not represent. Comparing observations of 53 stations from urban, cropland, and forest areas in the Paris region, the quality of multiple FPS URB-RCC model output ensembles from 18 institutes is evaluated based on temperature. Consistent with station differences between urban, cropland, and forest areas, the temperature is generally higher in urban locations. The performance of model simulations could be land use dependent. For the ensemble simulations, urban locations perform better than forest locations. Moreover, the relationship between boundary layer depth and 2-meter temperatures is explored. Most models show that forests have a higher correlation between boundary layer depth and temperature than urban areas (Figure 15). Based on the decomposition of the correlation of boundary layer time series, sensible and latent heats explain substantial amounts of variance as variables. Results from the analysis help to produce hypotheses for regional climate-sensitive land use management based on energy fluxes.

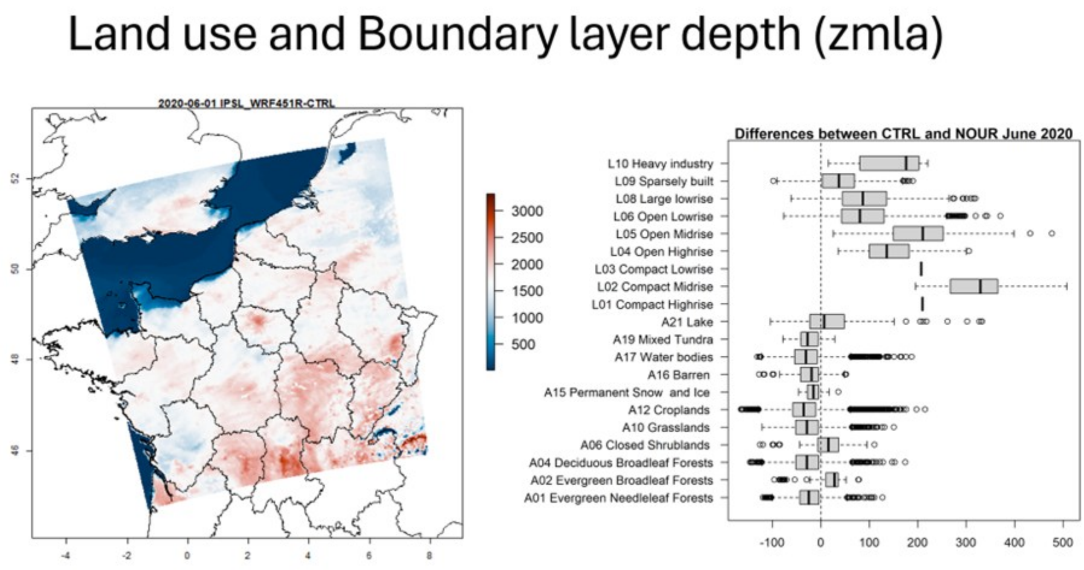


Figure 15. Boundary layer and land use relationships. The boxplots show that urban land use types have deeper boundary layers than forests and croplands in a WRF simulation ensemble by IPSL.

Heat stress and biometeorology

Lead: Ana Casanueva (University of Cantabria, Spain)

Heatwaves are among the most detrimental climate-related natural hazards, being associated with considerable effects on the population, who mostly live in urbanized areas. Although temperature is their main driver, other variables such as relative humidity can enhance the negative effects on the human body. For instance, under high temperature and high humidity, the ability of the human body to regulate its core temperature is largely reduced.

In this work, we evaluate the STAGE-0 simulations, developed on a 3-km resolution grid, for the Paris heatwave considering multivariate heat stress indices, with a special focus on the intervariable relationship between temperature and humidity. By considering the full STAGE-0 ensemble we are able to assess the sensitivity to the use of different models and urban representations. Further, specific analysis of the WRF sub-ensemble allows us to examine the effect of changing initial conditions, land-cover data and urban parameters included in the urban schemes.

As an example, the maps in Figure 16 show mean values over 7-13 August 2020 for daily maximum temperature, daily mean relative humidity and two heat stress indices derived from the former variables (wet bulb temperature -WBT- and wet bulb globe temperature on the shade -WBGT), for the WRF sub-ensemble control simulations (i.e. WRF CTRL runs in Figure 12). These results reveal the high (low) temperatures (relative humidity) over Paris during the heatwave. The combined effect of temperature and humidity leads to a wide-spread pattern for the stress indices, mainly due to their different dependencies on temperature and humidity. The temporal evolution over the heatwave (right panels) for the WRF-CTRL simulations (orange shading, with multi-model mean in bold) shows that heat stress indices reach the highest values towards the end of the heatwave, under more humid conditions and still high temperatures. This effect is even more evident for other WRF simulations with different urban configurations (purple shading, namely NOUR, NOAC, DPAR in Fig. 3), with higher humidity, thus higher heat stress especially at the end of the heatwave.

A comprehensive analysis of the full ensemble, including the evaluation with existing observations, will help to improve the model representation and overall understanding of heat stress in urban areas.

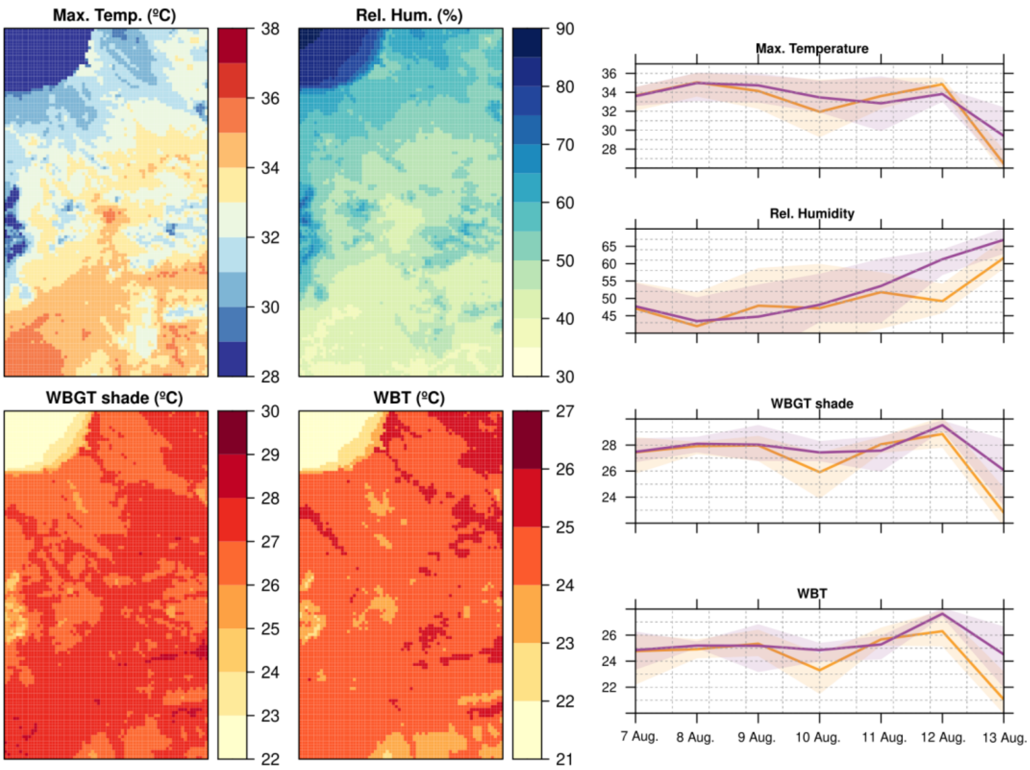


Figure 16. (Left panel) Daily maximum temperature, daily mean relative humidity and derived heat stress indices (WBGT: wet bulb globe temperature, WBT: wet bulb temperature) averaged over 7-13 August 2020 for the sub-ensemble of WRF-CTRL STAGE-0 simulations (see Figure 12). (Right) Temporal evolution over the heatwave for the grid box over Paris considering WRF-CTRL runs (orange shading, the multi-model mean is depicted in bold) and other WRF simulations with changing urban representations (purple shading, NOUR, NOAC, DPAR; see Figure 12).

Precipitation analysis

Leads: Andrés Simon-Moral (CSIC, Spain), Natália Machado Crespo (Charles University, Czech Republic)

Two analyses have been developed focusing on precipitation: the potential impact of i) the representation of urbanization and ii) the horizontal resolution.

The potential impact on precipitation of improving the representation of urbanization in climate simulations is studied by comparing every simulation with the simulations not considering the city, or using a simple parameterization to represent its impact. Two simulations with exactly the same configuration, except for the urban representation are compared first, showing an apparent increase of precipitation in the city of Paris, when the urban area is considered. However, a preliminary analysis of the entire set of simulations shows differences of the same order, opening the question to internal variability as a possible explanation. This result contrasts with event based simulations, where urban influence on precipitation has been largely proven. The urban influence within climate simulations will be further explored and contrasted against the internal variability explanation. The analysis will be extended to different resolutions and precipitation precursors, such as wind and moisture convergence.

In total 23 (12 km) and 29 (3 km) simulations were considered for the preliminary analysis regarding the horizontal resolution. The results were compared to EOBS data and showed that basically all models were able to capture the precipitation over the city of Paris in May 2020. The PARIS-3 simulations showed some improvement in representing the average precipitation over the city, as well as the minimum and maximum values observed inside the domain of the city. Nevertheless, five days before the event, both resolutions overestimated a short precipitation event (by 200%), although capturing the timing.

WRF sensitivity simulations, differences, and land-atmosphere feedbacks

Lead: Josipa Milovac (Instituto de Fisica de Cantabria (IFCA), CSIC-Universidad de Cantabria, Spain)

An extensive WRF activity during the STAGE-0 experiment produced a large coordinated sub-ensemble of 28 sensitivity simulations at CP-3 km resolution over the Paris domain. In this study, we use the WRF sub-ensemble to examine how WRF model settings influence land-atmosphere feedback, with a focus on urban representation. We assess sensitivity to available urban parameterizations in WRF, land-cover data (e.g., different datasets, LCZ inclusion/exclusion, urban grids), coupling with PBL and surface schemes, microphysics options, aerosol inputs, and domain size. The ensemble also enables us to quantify internal variability and distinguish it from true model sensitivity, as 10 identical WRF configurations were run on different machines and with slight variations in initial conditions.

5.2.3. Associated modelling studies

Deep learning models for Paris

Frederico Johannsen (University of Lisbon)

Frederico's PhD entitled "Deep learning and physically-based numerical models for very high resolution urban climate modelling" aims at combining data-driven and physically-based numerical models to improve urban climate modelling. Data-driven models, leveraging on observational datasets during their training phase, are cost-effective and generate high-quality projections. In this work, the models generate air temperature and land surface temperature projections. By focusing on the city of Paris, France, this work has the potential to contribute to the ensemble of urban climate projections defined by the FPS URB-RCC. The overall performance is evaluated in the historical period (Johannsen et al., 2024), including the representation of the urban heat island and heatwaves by the models. Substantial improvements in LST, T2m and UHI downscaling with DL (using a small number of predictors) were reported in comparison to ERA5 for present climate. For example, the best-performing DL models presented nighttime UHI and daytime SUHI biases (RMSE) below 0.80 ◦C and 0.50 ◦C (2.8 ◦C and 2.3 ◦C), respectively.

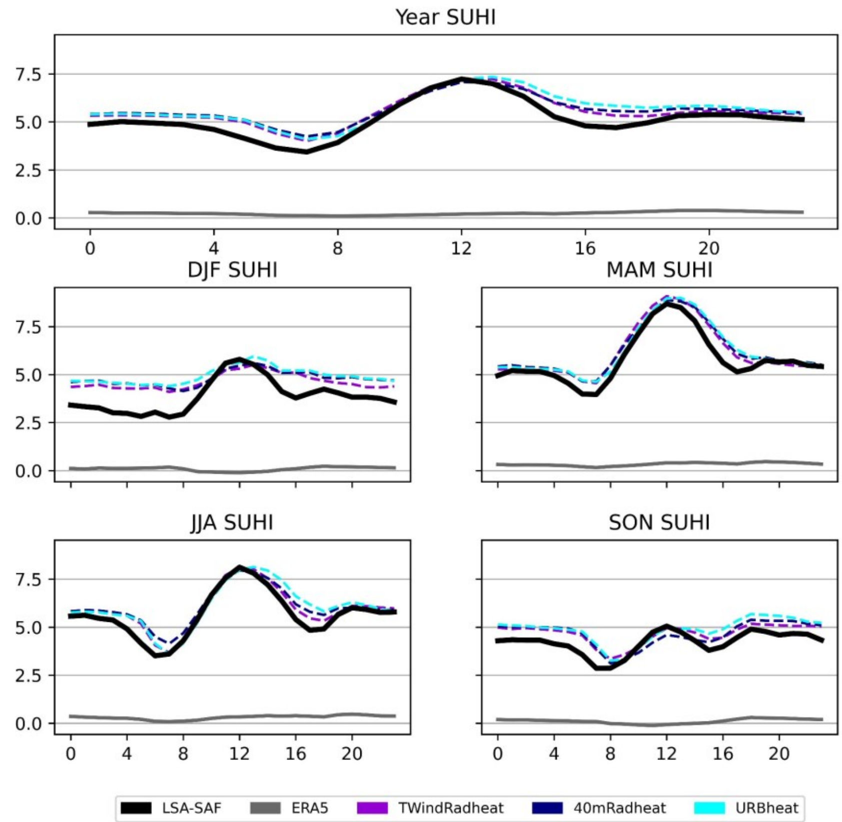


Figure 17. Average Surface Urban Heat Island (SUHI) diurnal cycle computed over the 2013–2022 period for LSA-SAF (black), ERA5 (grey), and three DL experiments (TWindRadheat, 40mRadheat, URBheat): a) whole year; b) DJF; c) MAM; d) JJA; e) SON.

Subsequently, the models are forced with CMIP6 Global Climate Model (GCM) data to generate a multi-model future projections for the 21st century under four shared socioeconomic pathways scenarios (submitted paper under revision). DL models effectively downscale CMIP6 GCM data, replicating the UHI effect learned from the observations, which was absent in the original GCM simulations, while following the overall GCM trends. 21st century projections suggest stable nighttime air UHI intensity (~2.2°C) and surface UHI intensity (~5°C). Heatwave frequency increases from ~1.5 events per year in 2015-2040 to ~2.5 events per year in 2071-2100 under the most severe scenario (SSP5-8.5), though DL underestimates heatwave increases relative to the GCMs.

In the last part of the PhD, the objective is to combine the SURFEX land surface model with a deep learning model to create an enhanced product that provides higher-quality urban climate projections of air and land surface temperature.

Paper published:

Johannsen, F., Soares, P. M., & Langendijk, G. S. (2024). On the Deep learning approach for improving the representation of urban climate: the Paris urban heat island and temperature extremes. Urban Climate, 56, 102039. https://doi.org/10.1016/j.uclim.2024.102039

2nd paper under review / pre-print:

Johannsen, F., Soares, P. M., & Langendijk, G. S. Future Projections of Temperature Extremes and Urban Heat Island in Paris Using Deep Learning. Available at SSRN 5080130. http://dx.doi.org/10.2139/ssrn.5080130

Machine learning models for Madrid

Angelina Bushenkova (University of Lisbon)

Angelina's Master Thesis, entitled " Towards an improved representation of the urban climate: An Application of Artificial Intelligence," aimed to explore the advantage of applying a Machine Learning (ML) method – Extreme Gradient Boosting (XGBoost) – for better describing Madrid's urban climate. More specifically, the study was focused on the ability of XGBoost to reproduce present climate, including the 2-meter air temperature, surface temperature variables and the urban heat island (UHI) and surface urban heat island (SUHI) effects, and be used to generate future projections of the urban climate

The method evaluation was conducted at multiple temporal scales, including monthly and daily scales for ground temperature predictions and an hourly scale to represent the spatial structure of land surface temperature w.r.t. remote sensing data. Firstly, for the present climate, XGBoost was trained with a set of ERA5 predictors (0.25°), ground stations, and Land Surface Temperature (LST) observations. Secondly, a number of sensitivity cases were performed to assess the results dependency to predictors and their resolution. Thirdly, the learned relationships between the set of predictors and predictands, was applied to a set of ESGCM predictors, providing historical (1985-2014) and future (2015-2040, 2041-2070 and 2071-2100) climate projections for the 21st century under four emission scenarios (SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5).

Overall, the results showed that XGBoost outperformed both ERA5 and ESGCM (Figure 18). For present climate, the XGBoost model provided a more accurate representation of Tmax, Tmin, LST, and more importantly, the UHI (-0.5°C and +3°C for Tmax and Tmin), and the SUHI (+1°C and +2°C for Tmax and Tmin) effects. For future climate, the XGBoost significantly corrected the ESGCM UHI misrepresentation but seemed to underestimate Madrid's expected local warming (3.5°C anomaly).

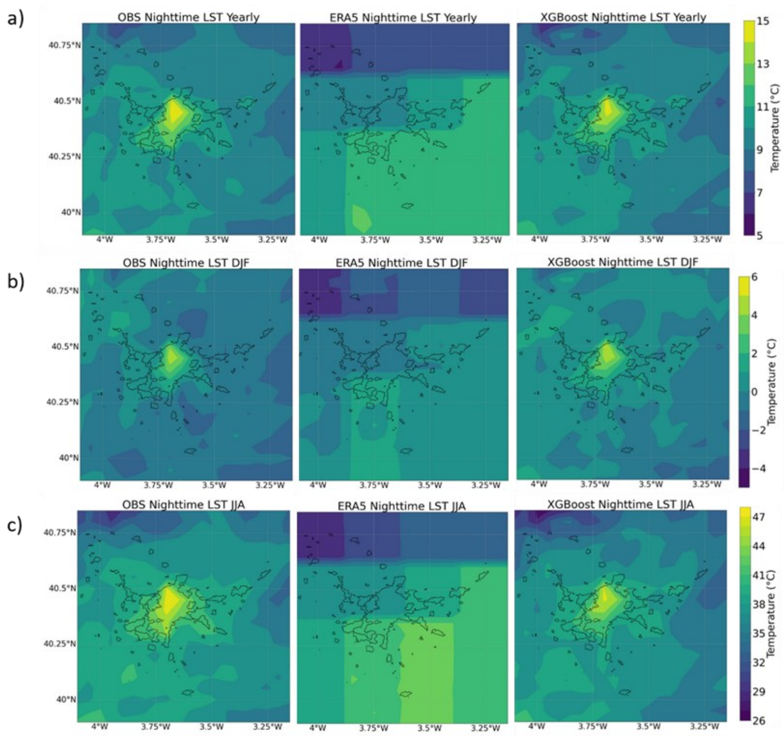


Figure 18: Maps of observed (left), ERA5 (middle) and XGBoost (right) mean nighttime (00:00 to 07:00 UTC) LST averaged over the (a) Yearly, (b) winter (DJF) and (c) summer (JJA) scales for the 2017-2022 period.

Paper published:

Bushenkova, A., Soares, P. M. M., Johannsen, F., & Lima, D. C. A. (2024). Towards an Improved Representation of the Urban Heat Island Effect: A Multi-Scale Application of XGBoost for Madrid. Urban Climate, 55, 101982. https://doi.org/10.2139/SSRN.4729233

Impact of urban areas on specific humidity over Central Europe

Based on 10 years CUNI WRF model simulations for Central Europe, a sensitivity analysis was performed with many different settings of the model parameterization, especially in terms of specific humidity. Specific humidity can be considered as a bit overlooked climate characteristic, despite being the most sensitive to the model parameterization settings, with strong connection to cloudiness and precipitation. Large cities in the region like Berlin, Budapest, Munich, Prague, Vienna and Warsaw, were selected for the study.

Paper under review / pre-print:

Long-term impact of urban areas on meteorological conditions over Central Europe. Submitted to Annals of the New York Academy of Sciences. Villalba-Pradas, A., Karlický, J. Huszár, P., Žák, M., Halenka, T. Under Review.

5.2.4 STAGE-1 protocol completed

The STAGE-1 simulations focus on ERA5-driven, 10-year simulations using a one-way double nesting approach at a spatial resolution of 3 km for the selected coordinated "CORE" city, the Paris region (Table 2). Many of the participating groups conduct simulations for this location for the period 2000-2009 (alignment with FPS CP and the I4C project). Additionally, several cities are selected as part of the Global Satellite Cities (GSC) approach across CORDEX domains (Figure 19). The simulations for the GSC follow the same simulation protocol, forming mini-ensembles to provide comparative insights for cities globally, with different geographic characteristics and across climate zones.

Table 2. Overview of STAGE-1 coordinated simulations, including the evaluation runs for the Paris region and for the global satellite cities.

1. Evaluation runs for Paris region

Run Name	Description	Forcing	Domain	Resolution	Time period
1. URBRCC_EVAL	Evaluation runs for Paris region	ERA5.1	EUR12 or parent domain	0.11°	2000-2009 (minimum)
		0.11° LBC	Paris region	2-4 km	2000-2009

2. Evaluation runs for satellite cities

Run Name	Description	Forcing	Domain	Resolution	Time period
2. URBRCC_EVAL_SAT	Evaluation runs for satellite cities	ERA5.1	CORDEX or parent domain *Region dependent*	0.22° or 0.11° *Region dependent*	10 years (minimum)
		0.22°/0.11° LBC	Satellite city region	2-4 km	10 years

The primary objectives of the STAGE-1 simulations are twofold. First, they aim to simulate the CORE city of Paris over a longer-term climate timescale, enabling more robust model comparisons, facilitating the standardization of urban schemes within CORDEX simulations, and improving process understanding. Second, they seek to enhance understanding of cities and regional climate variations across the globe by analyzing different urban characteristics—such as coastal influences—through the creation of mini-ensembles for key megacities worldwide.

The STAGE-1 protocol has been co-developed with the FPS partners. The coordinated STAGE-1 simulations have recently started and aim to be completed by October 2025.

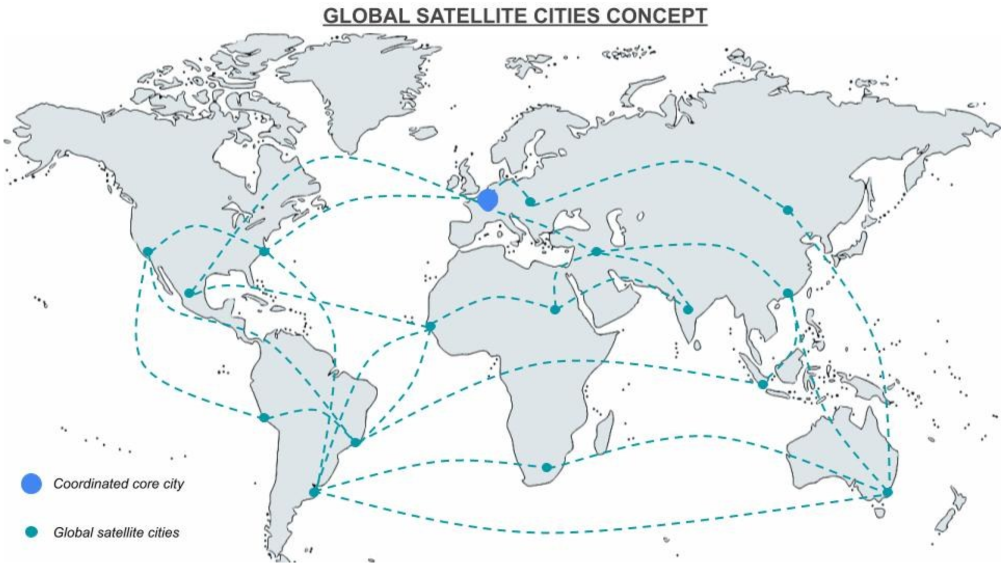


Figure 19. Illustration of FPS URB-RCC "Global Satellite Cities Concept". This figure serves as an illustration, and does not depict the final set of selected cities (Langendijk et al., 2024).

5.3. Phase 3

Phase 3 activities center around selected experiments for chemistry and including urbanization scenarios. This Phase is still on-going and would certainly benefit from an extension of the FPS activity. Here we describe some first efforts and potential next steps.

5.3.1. Selected experiments with chemistry coupling

One of the sensitivity runs (experimental ID is CHEM in Figure 12) within the STAGE-0 experiment with WRF includes the WRF-Chem setup, which was conducted by University of Murcia. In this setting WRF is fully coupled to an atmospheric chemistry model. Certain tweaks of the WRF-CTRL model setting had to be made in order for WRF-Chem to run smoothly. The produced output is shared and included in the analyses of STAGE-0 simulations, to investigate the effects of online coupling of atmospheric chemistry on the model output in urban environments.

At CUNI the simulations with coupled RCM/CTM are under preparation and testing, in connection to activities within EU Horizon Europe project FOCI, where the chemistry climate interactions are one of the main tasks of the project. We are trying to keep the connection to standard CORDEX protocols, however, e.g. full EuroCORDEX domain in 0.11 resolution with full chemistry is too demanding, thus lower resolution was adopted. We are working with interim domain which is expected to be close to parent domain for our Stage-0 and Stage-1 simulations and in addition to high resolution nested domain for City of Prague (CP), simulation with the same configuration of meteorology with chemistry is planned for Paris as well. Two models will be used, WRF-Chem, as well as RegCM with internal chemistry module, with urban parameterizations. Further, these activities will be developed and analysed in terms of risks of extreme compound events in the cities (UHI and air pollution).

5.3.2. Selected experiments with urbanization scenarios

Currently, no urbanization scenario has been selected nor implemented in FPS URB-RCC simulations. For this topic, we could utilize the results from the FPS LUCAS, which developed a land use change dataset (LUCAS LUC; Hoffmann et al., 2023). This dataset includes urban land cover changes based on RCP/SSP scenarios provided by the LUH2 dataset. However, the dataset's current resolution is 0.1° and it only includes a generic urban class. In close collaboration with the LUCAS community (many of them partners within FPS URB-RCC), we will explore whether this dataset can be adapted to meet the needs of the FPS URB-RCC experiments.

5.4. Phase 4

5.4.1 Initial preparations ongoing for future projection simulations (STAGE-2)

Ongoing discussions and preparations are underway for STAGE-2 simulations, which will extend the analysis of the Paris region and global satellite cities to future time periods. These simulations aim to build on the insights gained from STAGE-0 and STAGE-1, further refining urban climate modeling at high resolutions. For the STAGE-2 protocol alignment with the I4C project is envisioned, particularly regarding the Global Warming Levels (GWL). The successful completion of STAGE-2 simulations would require an extension of the FPS activity.

5.4.2 Preliminary assessment of added value of urban schemes in RCMs

It is too early to draw detailed conclusions about the added value of urban schemes in RCMs. Nevertheless some first overarching lessons learned can be distilled, based on the analysis of the existing datasets and the STAGE-0 preliminary results.

Key findings show that RCMs capture urban climate imprints, and higher-resolution RCM simulations lead to improved accuracy in capturing urban climate features, based on the analysis of the CORDEX-CORE, EURO-CORDEX, and CP RCM existing datasets. More advanced urban schemes outperform simple bulk parameterizations, especially in representing the nighttime urban heat island effect. Nevertheless, the quality of urban land-surface input data is as essential as that of urban parameterisations. While advanced urban land-use datasets are available, RCMs lack incorporation of such datasets and RCMs globally underestimate urban land use, especially in Africa and Asia (CORDEX-CORE). Sensitivity experiments of the STAGE-0 simulations confirm the added value of more detailed urban land-use data, such as Local Climate Zones (LCZs). Furthermore, different methods are being developed to extract urban areas and their surroundings from RCM data, but this remains challenging, especially across spatial resolutions. A comparison among the different methods across resolutions would be useful.

5.4.3 Climate services aspects

The climate services aspects need further development and for a more fulfilling completion of this task an extension of the FPS activity would be beneficial. Nevertheless, a few on-going efforts can be highlighted with respect to climate services.

Definition of new output variables for urban areas

In the course of preparing the protocol for the STAGE 0 simulation protocol, a variable list with new urban-specific output variables was prepared (Section 5.1.3). In particular, the in-canyon variables are of great importance to climate services as they represent the meteorological conditions in which the urban population lives. The variables are defined in a consistent way and the FPS URB-RCC is currently trying to add these variables to the CF standard name table. The FPS is thus laying the groundwork for the provision of these important variables (e.g. via ESGF) from upcoming RCM simulations within CORDEX.

Urban layer in Copernicus Interactive Climate Atlas

Leads: Javier Diez-Sierra and Jesus Fernandez (CSIC)

The Copernicus Interactive Climate Atlas (https://atlas.climate.copernicus.eu, C3S Atlas in short) evolves from the frozen IPCC Atlas (Gutiérrez et al., 2021; https://interactive-atlas.ipcc.ch/) to potentially address the needs of the IPCC's seventh assessment cycle. A key novelty in the upcoming IPCC cycle is the inclusion of a Special Report on Climate Change and Cities and therefore the inclusion of an urban climate analysis layer is envisioned for the C3S Atlas, aligned with the FPS-URB-RCC initiative. The urban layer analyzes the urban effects through spatial maps and seasonal anomalies between urban areas and their surroundings for several climatic impact-drivers (CIDs). REMO and RegCM models are used for CORDEX-CORE and EURO-CORDEX, covering different scenarios (RCP4.5, RCP8.5) and Global Warming Levels (e.g., 1.5, 2, 3, and 4 ºC). This analysis is envisioned to be included in the next release of the C3S Atlas (spring 2025) and will provide a global perspective based on existing worldwide regional projections focused on urban aspects.

Connection to I4C project

The full ensemble of FPS URB-RCC simulations can complement the development and co-creation of climate services within the I4C project, particularly for the activities of the I4C Demonstrator and Pilot Cities involved. In Phase 2, our FPS can benefit from the additional simulations provided by the I4C project, while in Phase 4, the complete ensemble will enable us to offer more accurate information on uncertainties and the distribution of extreme events, particularly in assessing climate indices. These indices, which are extensively provided through the I4C project, will be crucial for building climate services and supporting decision-making in the participating I4C Demonstrator and Pilot Cities. This effort will also contribute to relevant activities under the DestinE initiative.

6. Connection to urban climate community

From the outset of the project, there has been a strong connection with the urban climate community, particularly through the International Association of Urban Climate (IAUC). Continued efforts focus on bridging the regional climate modeling (RCM) and urban climate communities to ensure that long-standing urban climate knowledge is adequately integrated into RCM development. This collaboration also facilitates the exchange of insights on climate change and regional urban climate interactions within the urban climate community. Several key activities can be highlighted in this context:

- A contribution to the IAUC Newsletter (Volume 80, 2021) by the FPS URB-RCC initiative, describing its main goals and envisioned activities (https://urban-climate.org/wp-content/uploads/2023/02/IAUC080.pdf).
- Joint analyses and publications, including the CORDEX-CORE analysis, and the overview publication for the FPS (Langendijk et al., 2024).
- Urban climate community members contributed to the STAGE-0 simulations.
- Discussions on land-use data and conducted associated sensitivity experiments, particularly related to incorporating Local Climate Zones (LCZs) into RCMs.
- Organization and participation in major urban climate sessions at EGU conferences in 2023, 2024, and 2025, with Gaby Langendijk as a co-convener, together with member(s) of the urban climate community.
- Participation in ICUC11 in Sydney (August 28 – September 1, 2023, Sydney), attended by FPS coordinator Tomas Halenka and others. Contributions included:
    - Poster No. 721: *"Urban Environments and Regional Climate Change – CORDEX Flagship Pilot Study URB-RCC"*
    - Oral presentation No. 450: *"Heat in cities across the globe: what can the CORDEX-CORE regional climate model ensemble tell?"*
- Future participation in ICUC12 (July 7–11, 2025), featuring the PM6 session: *"Mesoscale Modelling and Climate Change – Interactions between Urban and Regional Climate Processes."* Conveners: Peter Hoffmann, Gaby Langendijk, Tomas Halenka, Mathew Lipson, and Quang-Van Doan (Session PM6).

7. Conclusions

During the last years the FPS URB-RCC community made substantial progress advancing coordinated RCM experiments to improve simulations for urban areas, and understanding what existing RCM datasets can already tell about cities in the context of regional climate change.

Currently, the consortium finished >35 simulations for the coordinated STAGE-0 test experiments for the Paris region, covering a 5 month period including heat and precipitation extremes on the km-scale spatial resolution. The STAGE-0 simulations are being analyzed, and around 5 papers are being prepared on different topics such as urban-rural temperature differences, land-use settings for cities, precipitation, and biometeorology indicators for heat. Currently, the next phase of coordinated simulations is underway (STAGE-1), entailing a 10-year evaluation period for the Paris region, as well as other cities globally following the Global Satellite Cities concept. The first discussions are ongoing for the STAGE-2 simulations, aiming at future projections.

In addition, we are completing the analyses of existing datasets, including the global CORDEX-CORE EXP-I simulations and the European CP-simulations of the FPS Convection. These analyses give insights into the capabilities and limitations of the RCMs to simulate urban areas and to provide data and information about climate change for cities. Currently, a number of papers are prepared on these topics in the frame of the FPS URB-RCC.

Furthermore, we have been actively building a strong community bridging between the CORDEX community and urban climate community, through platforms like CORDEX, the International Association of Urban Climate, the International Conference on Urban Climate, and through co-convening EGU sessions on urban climate change.

8. Specific objectives not yet been achieved

Despite significant progress, the FPS URB-RCC activity has not yet achieved all its objectives. An extension would be highly beneficial to allow for the full completion of the FPS, ensuring that all planned simulations, analyses, and scientific contributions are thoroughly carried out.

The project is still in the middle of conducting the **STAGE-1 coordinated evaluation simulations**, which are essential for establishing a strong baseline for high-resolution urban climate modeling. Additionally, the planned **STAGE-2 simulations**, which will assess future climate scenarios for Paris and global satellite cities, have yet to be carried out. These simulations are critical for understanding projected urban climate changes and their implications.

Further work is also needed to incorporate **urbanization scenarios** and assess **air quality impacts**. In addition, a broader analysis, particularly moving beyond the urban heat island effect, of key climate variables, such as **precipitation patterns, surface fluxes, humidity, heat stress, and other urban-relevant processes**, remains incomplete. These aspects are essential for gaining a comprehensive understanding of urban climate dynamics and its interactions with regional climate change.

Moreover, the extension is necessary to finalize the evaluation of **urban schemes across different models**, allowing the project to draw **key conclusions and formulate recommendations for the CORDEX community**. Strengthening the connection to **climate services** is also a crucial goal, ensuring that the findings can be effectively applied in urban planning, policy-making, and climate adaptation strategies. Extending the project will provide the necessary time to achieve these objectives, ensuring a more complete and impactful contribution to the regional climate and urban climate communities.

In addition, extending the timeline will also allow us to align more effectively with the **IPCC's schedule of the Special Report on Cities and Climate Change** (expected release in 2027) and the overall AR7 IPCC report cycle, as well as the timeline of the **EU Horizon I4C project** for which a number of partners align their simulations with the FPS project. Moreover, we could further develop the cooperation with WCRP DigitalTwin activity, which is just starting.

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FPS URB-RCC related publications

Published

- Langendijk, G. S., Halenka, T., Hoffmann, P., Adinolfi, M., Campino, A. A., Asselin, O., ... & Yuan, J. (2024). Towards better understanding the urban environment and its interactions with regional climate change-The WCRP CORDEX Flagship Pilot Study URB-RCC. Urban Climate, 58, 102165. https://doi.org/10.1016/j.uclim.2024.102165
- Michau, Y., Lemonsu, A., Lucas-Picher, P., Schneider, M., & Caillaud, C. (2024). On the future evolution of heatwaves in French cities and associated rural areas: Insights from a convection-permitting model. Urban Climate, 55, 101920.
- Johannsen, F., Soares, P. M., & Langendijk, G. S. (2024). On the Deep learning approach for improving the representation of urban climate: the Paris urban heat island and temperature extremes. Urban Climate, 56, 102039. https://doi.org/10.1016/j.uclim.2024.102039
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- Katzfey, J., Schlünzen, K. H., & Hoffmann, P. (2024). Effects of urban areas on the diurnal cycle of temperature and precipitation in a global climate simulation. Quarterly Journal of the Royal Meteorological Society, 150(765), 4885-4914. https://doi.org/10.1002/qj.4847

Under review / pre-print:

- Michau, Y., Lemonsu, A., Lucas-Picher, P., Bastin, S., Caillaud, C., de Vries, H., ... & Coppola, E. (2024). Projected Evolution of the Urban Climate and Heatwaves using an Ensemble of Convection-Permitting Regional Climate Models. https://doi.org/10.21203/rs.3.rs-5309528/v1
- Johannsen, F., Soares, P. M., & Langendijk, G. S. Future Projections of Temperature Extremes and Urban Heat Island in Paris Using Deep Learning. Available at SSRN 5080130. http://dx.doi.org/10.2139/ssrn.5080130
- Villalba-Pradas, A., Karlický, J. Huszár, P., Žák, M., Halenka, T. Long-term impact of urban areas on meteorological conditions over Central Europe.

Papers in preparation:

- Diez-Sierra, J., Fernandez, J., Quintana, Y., Langendijk, G.S., Milovac, J., Gutiérrez, J.M., et al. A dataset delimiting urban and rural areas for megacities worldwide to assess urban climate change across CORDEX experiments.
- Langendijk, G. S., Fernandez, J., Diez-Sierra, J., Quintana, Y., Demuzere, M., Fita, L. Hoffmann, P., Rechid, D., Halenka, T., Nogherotto, R., Zazulie, N., Coppola, E., Hamdi, R., Kwok Chun, S., et al. Representation of global mega-cities and their urban heat island in CORDEX-CORE regional climate model simulations.

- Le Roy, B. et al. How do convection permitting climate models improve the representation of Urban Heat Islands compared with standard regional climate models?
- Zazulie, N., Nogherotto, R., Coppola, E. et al. Assessing Climate Change Hazards in Urban and Rural Areas for European Cities Using EURO-CORDEX ensemble *(tentative title).*

Selected conference contributions

- Milovac, J., Simon-Moral, A., Chun, K.P.., Fernández, J., Langendijk, G.S. and the FPS-URB-RCC community: CORDEX activity on URBan environments and Regional Climate Change (FPS-URB-RCC), oral presentation at XIII Congreso de la AEC - Cambio climático y sociedad: De la ciencia básica a los servicios climáticos, 22-24 Jan 2025, San Lorenzo de El Escorial (Madrid), Spain
- Le Roy, B., & Rechid, D. (2024). What can high-resolution regional climate simulations tell us about the future urban climate of European cities? (No. EMS2024-880). Copernicus Meetings EMS.
- Le Roy, B., & Rechid, D. (2024). Added values and uncertainties of convection permitting regional climate model simulations for urban impact studies over Europe (No. EGU24-11048). Copernicus Meetings EGU24.
- Johannsen, F., Soares, P. M., & Langendijk, G. S. (2024). Using Deep Learning to simulate the urban heat island over Paris (No. EGU24-996). Copernicus Meetings.
- Halenka, T., Belda, M., Crespo, N., Langendijk, G., & Hoffmann, P. (2024). CORDEX Flagship Pilot Study URB-RCC–Case Studies on Urban Environment Implementation (No. EGU24-20302). Copernicus Meetings.
- FPS Side-Event at ICRC CORDEX, Trieste (Italy), 27 Sept. 2023, Meetings. Tomas Halenka, Peter Hoffmann, Gaby Langendijk
- Urban science session, ICRC-CORDEX, Trieste (Italy), 29 Sept. 2023: Session D6: High resolution urban climate modeling and regional climate change – progress and challenges for CORDEX (online and Trieste) – ICRC-CORDEX2023 Tomas Halenka, Gaby Langendijk
- Presentation about the FPS was held during the hybrid WMO-GURME annual meeting, held at WMO, 23-24 Nov. 2023. Gaby Langendijk
- Presentation on the FPS at EMS 2023, 3-8/9. 2023, Bratislava, EMS2023-616 UP2.1 solicited „CORDEX Flagship Pilot Study URB-RCC: Urban Environments and Regional Climate Change“ Tomas Halenka
- Poster on the FPS at WCRP Open Science Conference, Kigali, 23.-27/10, 2023 “Urban Environments and Regional Climate Change - CORDEX Flagship Pilot Study URB-RCC” Tomas Halenka
- Invited lecture at conference Chemical Weather and Chemical Climate 2023, Shanghai, 16.-20/10, 2023 Urban in Changing Climate Tomas Halenka
- Contributions at ICUC 2023, 28/8-1/9, 2023, Sydney:

    - No. 721 „Urban Environments and Regional Climate Change - CORDEX Flagship Pilot Study URB-RCC“ (poster), Tomas Halenka, Gaby Langendijk
    - No. 450 „Heat in cities across the globe: what can the CORDEX-CORE regional climate model ensemble tell?“ (oral) Tomas Halenka, Gaby Langendijk

- T. Halenka convenor and chair of session JM01a - Recent Advances in Regional Climate Modelling (IAMAS, IACS) at IUGG 2023, 11-20/7, 2023, Berlin, presentation IUGG23- 4732: „Urban environments and regional climate change - CORDEX flagship pilot study URB-RCC” Tomas Halenka
- Halenka, T., & Langendijk, G. (2022, May). CORDEX Flagship Pilot Study on Urbanization-URBan environments and Regional Climate Change (URB-RCC). In EGU General Assembly Conference Abstracts (pp. EGU22-11040).
- Halenka, T., & Langendijk, G. (2021). URBan environments and Regional Climate Change (URB-RCC)–new CORDEX FPS on Urbanization (No. EMS2021-478). Copernicus Meetings.
- Halenka, T., & Langendijk, G. (2021, December). New CORDEX FPS on Urbanization-URBan environments and Regional Climate Change (URB-RCC). In AGU Fall Meeting Abstracts (Vol. 2021, pp. GC33C-06).