

Towards better understanding the urban environment and its interactions with regional climate change - The WCRP CORDEX Flagship Pilot Study URB-RCC

Gaby S. Langendijk^{c,a,*}, Tomas Halenka^b, Peter Hoffmann^c, Marianna Adinolfi^d, Aitor Aldama Campino^e, Olivier Asselin^f, Sophie Bastin^g, Benjamin Bechtel^h, Michal Belda^b, Angelina Bushenkovaⁱ, Angelo Campanale^d, Kwok Pan Chun^j, Katiana Constantinidou^k, Erika Coppola^l, Matthias Demuzere^m, Quang-Van Doanⁿ, Jason Evans^o, Hendrik Feldmann^p, Jesus Fernandez^t, Lluís Fita^q, Panos Hadjinicolaou^k, Rafiq Hamdi^r, Marie Hundhausen^p, David Grawe^s, Frederico Johannsenⁱ, Josipa Milovac^t, Eleni Katragkou^u, Nour El Islam Kerroumi^v, Sven Kotlarski^w, Benjamin Le Roy^c, Aude Lemonsu^x, Christopher Lennard^y, Mathew Lipson^z, Shailendra Mandal^{aa}, Luís E. Muñoz Pabón^q, Vassileios Pavlidis^u, Joni-Pekka Pietikäinen^c, Mario Raffa^d, Eloisa Raluy-López^{ab}, Diana Rechid^c, Rui Ito^{ac}, Jan-Peter Schulz^{ad}, Pedro M.M. Soaresⁱ, Yuya Takane^{ae}, Claas Teichmann^c, Marcus Thatcher^{af}, Sara Top^{ag}, Bert Van Schaeybroeck^r, Fuxing Wang^e, Jiacan Yuan^{ah}

^a Climate Adaptation and Disaster Risk Department, Deltares, PO Box 177, 2600, MH, Delft, the Netherlands

^b Department of Atmospheric Physics, Faculty of Mathematics and Physics, Charles University, V Holešovičkách 2, 180 00 Prague 8, Czech Republic

^c Climate Service Center Germany (GERICS), Helmholtz-Zentrum Hereon, Fischertwiete 1, 20095 Hamburg, Germany

^d Regional Models and Geo-Hydrological Impacts (REMHI) Division, CMCC Foundation - Euro-Mediterranean Center on Climate Change, via Thomas Alva Edison s.n.c., 81100 Caserta (CE), Italy

^e Swedish Meteorological and Hydrological Institute, Folkborgsvägen 17, 60176 Norrköping, Sweden

^f Ouranos, 550 rue Sherbrooke Ouest, H3A 1B9 Montréal, Canada

* Corresponding author.

E-mail addresses: langendijk.gs@gmail.com (G.S. Langendijk), tomas.halenka@mff.cuni.cz (T. Halenka), peter.hoffmann@hereon.de (P. Hoffmann), marianna.adinolfi@cmcc.it (M. Adinolfi), aitor.aldamacampino@smhi.se (A. Aldama Campino), asselin.olivier@ouranos.ca (O. Asselin), sophie.bastin@latmos.ipsl.fr (S. Bastin), benjamin.bechteler@rub.de (B. Bechtel), michal.belda@mff.cuni.cz (M. Belda), avbushenkova@ciencias.ulisboa.pt (A. Bushenkova), angelo.campanale@cmcc.it (A. Campanale), kwok.chun@uwe.ac.uk (K.P. Chun), k.constantinidou@cyi.ac.cy (K. Constantinidou), coppola@ictp.it (E. Coppola), Matthias@b-kode.be (M. Demuzere), doan.van.gb@u.tsukuba.ac.jp (Q.-V. Doan), jason.evans@unsw.edu.au (J. Evans), hendrik.feldmann@kit.edu (H. Feldmann), jesus.fernandez@unican.es (J. Fernandez), lluis.fita@cima.fcen.uba.ar (L. Fita), p.hadjinicolaou@cyi.ac.cy (P. Hadjinicolaou), Rafiq.hamdi@meteo.be (R. Hamdi), marie.hundhausen@kit.edu (M. Hundhausen), david.grawe@uni-hamburg.de (D. Grawe), jfjohannsen@ciencias.ulisboa.pt (F. Johannsen), josipa.milovac@unican.es (J. Milovac), katragkou@geo.auth.gr (E. Katragkou), sven.kotlarski@meteoswiss.ch (S. Kotlarski), benjamin.le-roy@hereon.de (B. Le Roy), aude.lemonsu@meteo.fr (A. Lemonsu), lennard@csag.uct.ac.za (C. Lennard), mathew.lipson@bom.gov.au (M. Lipson), shailendra@fulbrightmail.org (S. Mandal), luís.munoz.pabon@cima.fcen.uba.ar (L.E. Muñoz Pabón), vaspavli@physics.auth.gr (V. Pavlidis), joni-pekka.pietikaenen@hereon.de (J.-P. Pietikäinen), mario.raffa@cmcc.it (M. Raffa), eloisa.raluy@um.es (E. Raluy-López), diana.rechid@hereon.de (D. Rechid), rui.ito@jamstec.go.jp (R. Ito), jan-peter.schulz@dwd.de (J.-P. Schulz), pmssoares@ciencias.ulisboa.pt (P.M.M. Soares), takane.yuya@aist.go.jp (Y. Takane), claas.teichmann@hereon.de (C. Teichmann), marcus.thatcher@csiro.au (M. Thatcher), sara.top@ugent.be (S. Top), fuxing.wang@smhi.se (F. Wang), jcyuan@fudan.edu.cn (J. Yuan).

<https://doi.org/10.1016/j.uclim.2024.102165>

Received 26 March 2024; Accepted 7 October 2024

Available online 6 November 2024

2212-0955/© 2024 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

- ^g LATMOS/IPSL, UVSQ-Univ. Paris Saclay, Sorbonne Université, CNRS, CNES, Guyancourt, France
- ^h Bochum Urban Climate Lab, Ruhr University Bochum, Bochum, Germany
- ⁱ Instituto Dom Luiz (IDL), Faculdade de Ciências da Universidade de Lisboa, Campo Grande, Lisbon, Portugal
- ^j School of Architecture and Environment, University of the West of England, Stoke Gifford, Bristol BS16 1YN, UK
- ^k Climate and Atmosphere Research Center (CARE-C), The Cyprus Institute, Nicosia, Cyprus
- ^l The Abdus Salam International Centre for Theoretical Physics (ICTP), Trieste, Italy
- ^m B-Kode VOG, Ghent, Belgium
- ⁿ Center for Computational Sciences, University of Tsukuba, Tsukuba, Japan
- ^o Climate Change Research Centre, University of New South Wales, Australia
- ^p Institute for Meteorology and Climate Research (IMKTRO), Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany
- ^q Universidad de Buenos Aires (UBA), Centro de Investigaciones del Mar y la Atmósfera (CIMA), IRL 3351 IFAECI, UBA-CONICET-CNRS-IRD, C. A. Buenos Aires, Argentina
- ^r Royal Meteorological Institute of Belgium, Brussels, Belgium
- ^s University of Hamburg, CEN Urban Climate Lab Meteorologisches Institut, Bundesstr. 55, 20146 Hamburg, Germany
- ^t Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain
- ^u Aristotle University of Thessaloniki, School of Geology, Department of Meteorology and Climatology, Thessaloniki, Greece
- ^v Office National de la Météorologie, Dar el Beida, Algeria
- ^w Federal Office of Meteorology and Climatology MeteoSwiss, Zurich-Airport, Switzerland
- ^x CNRM, Université de Toulouse, Météo-France, CNRS, Toulouse, France
- ^y University of Cape Town, South Africa
- ^z Bureau of Meteorology, Australia
- ^{aa} Department of Architecture and Planning, National Institute of Technology Patna, Ashok Rajpath, Patna 800005, India
- ^{ab} Physics of the Earth, Regional Campus of International Excellence (CEIR) Campus Mare Nostrum, University of Murcia, Murcia, Spain
- ^{ac} Japan Agency for Marine-Earth Science and Technology (JAMSTEC), 3173-25 Showa-machi, Kanazawa-ku, Yokohama 236-0001, Japan
- ^{ad} German Meteorological Service (DWD), Frankfurter Straße 135, 63067 Offenbach am Main, Germany
- ^{ae} Environmental Management Research Institute, National Institute of Advanced Industrial Sciences and Technology (AIST), Tsukuba, Japan
- ^{af} Commonwealth Scientific and Industrial Research Organisation (CSIRO), Australia
- ^{ag} Ghent University, Ghent, Belgium
- ^{ah} Department of Atmospheric and Oceanic Sciences & Institute of Atmospheric Sciences & Shanghai Key Laboratory of Ocean-land-atmosphere Boundary Dynamics and Climate Change, Fudan University, Shanghai, China

ARTICLE INFO

Keywords:

Urban areas
Regional climate models
Coordinated experiment
URB-RCC
Kilometer scale modelling

ABSTRACT

High-quality climate information tailored to cities' needs assists decision makers to prepare for and adapt to climate change impacts, as well as to support the targeted transition towards climate resilient cities. During the last decades, two main modelling approaches emerged to understand and analyse the urban climate and to generate information. Firstly, meso- and microscale urban climate models commonly resolve the street to city scale climate (1 m to 1 km) through simulating short "weather" type episodes, possibly under climate change conditions. Secondly, regional climate models (RCMs) are currently approaching the kilometer scale grid resolutions (1–4 km) and becoming increasingly relevant to understand the interactions of cities with the regional climate on timescales from decades up to a century. Therefore, the WCRP CORDEX Flagship Pilot Study "URBAN environments and Regional Climate Change (FPS URB-RCC)" brings together the urban climate modelling community and the RCM community and focuses on understanding the interactions between urban areas and regional climate change, with the help of coordinated experiments with an RCM ensemble having refined urban representations. This paper presents the FPS URB-RCC, its main aims, as well as the initial steps taken. The FPS URB-RCC advances urban climate projections and information to support evidence-based climate action towards climate resilient cities.

1. Introduction

Urban areas are where the largest share of the global population lives (UN-HABITAT, 2022) and where most humans directly experience the impacts of climate change. Due to high population, plenteous socio-economic activity, and infrastructure density, cities are especially prone to well-known climate impacts such as heat waves, drought, heavy precipitation events, sea level rise, storm surges, and flash floods (Baklanov et al., 2018; Rosenzweig et al., 2018). Besides these well-known climate impacts, residents of urban areas may experience increased heat stress, enhanced pollen allergies, affected quality of life, and reduced work productivity due to the effects of climate change, that will undermine socioeconomic development and increase socioeconomic inequalities (Casanueva et al., 2020; Doan et al., 2016; Duchêne et al., 2022a; Heal and Park, 2016; Langendijk et al., 2022; Reckien et al., 2017). The wide variety of climate change related extremes and their impacts are projected to intensify and/or distributionally shift during the course of this century, further straining cities and its populations. Cities are economies of scale and have a great potential to mitigate climate change (Eisenack and Roggero, 2022; Hsu et al., 2020). Nevertheless, cities are currently responsible for about 70 % of global greenhouse gas emissions. The related air pollution profoundly affects the urban environment and its populations (Baklanov et al., 2010; Huszár et al., 2020; Sokhi et al., 2022).

There have been substantial scientific strides to understand the urban climate, as well as to understand the urban climate under

longer-term climate change (Doan et al., 2022; Doan and Kusaka, 2018; Gu et al., 2023; Hamdi et al., 2020; Huszár et al., 2014; Masson et al., 2020; Nogueira et al., 2020; Nogueira and Soares, 2019; Stewart, 2019; Takane et al., 2019, 2020). Particularly, a large share of the scientific efforts investigated urban overheating, including the well-known urban heat island effect (UHI; Schlünzen et al., 2023). Literature shows cities are commonly warmer than their surroundings, especially at nighttime (Argüeso et al., 2014; Arnfield, 2003; Nogueira et al., 2022). Nevertheless, uncertainties remain for many urban areas around the world about the effect of climate change on the UHI during the course of this century (Deilami et al., 2018; Kim and Brown, 2021). The effect of urban areas on precipitation is widely investigated with some studies showing an amplification of precipitation over and downwind of urban areas (Doan et al., 2022; Liu and Niyogi, 2019), but others finding contesting results depending on the city studied and the methodology used, making it challenging to draw general conclusions (Lalonde et al., 2023; Yue et al., 2021). Only limited research exists that investigates the effects of cities on precipitation under future climate change (Hamdi et al., 2020). Recently, the urban dryness island effect (UDI) regained increased attention. Literature indicates that cities often have lower humidity levels than their surroundings, especially for midlatitude in-land areas (Langendijk et al., 2019, 2021; Zhao et al., 2021). The urban wind island (UWI) is also investigated, finding both decreased and increased wind speeds in and around urban areas (Baidar et al., 2020; Droste et al., 2018; Yang et al., 2020).

Urban areas are major emission sources of different pollutants or atmospheric constituents. In addition to traditional greenhouse gases connected to human activities and life support, like energy production, heating and cooling of buildings, and transportation, other pollutants (both gaseous and aerosols) are emitted and subsequently produced via chemical transformation and interactions in the urban environment. Recently, studies can be found which are evaluating the interaction of air pollution and climate change, providing an analysis of long-term development of pollutants in full two-way interaction between meteorology and air quality under climate change conditions (Baklanov et al., 2010, 2018; Huszár et al., 2016a; Huszár et al., 2016b). An extensive literature review by Sokhi et al. (2022) shows that the connection between urban areas, air quality and climate change is still underexplored and needs further investigation.

The aforementioned urban-specific meteorological conditions can have direct impacts on the urban population. Increased heat stress and a loss of work productivity are found under high temperatures in cities (Duchêne et al., 2022b; Heal and Park, 2016). Heat stress is causing an increase in mortality and morbidity related to respiratory, cardiovascular, and renal diseases (Dang et al., 2018; Kovats and Hajat, 2008). This reduces human well-being and increases healthcare costs (Wondmagegn et al., 2019). Flash floods and other impacts due to heavy precipitation, such as land-slides, continue to devastate cities across the globe (Andreadis et al., 2022; Laino and Iglesias, 2023; Rentschler et al., 2023; Rosenzweig et al., 2018). Urban green–blue infrastructure can provide important benefits to urban residents (Demuzere et al., 2014), but may also affect mosquito abundance, with associated negative nuisance and infection transmission impacts affecting public health (Kache et al., 2022; Lindberg et al., 2024). Sea level rise combined with land subsidence is expected to put 330–350 million urban inhabitants at risk by 2050 (Nicholls et al., 2021). Lower humidity levels, combined with increased CO₂ levels in urban areas, enhance pollen allergies of urban dwellers (Langendijk et al., 2022; Ziska et al., 2003). It is apparent that the impacts of climate change on the urban population are pressing and manifold. There are large differences in urban climate and climate change impacts across the world, as well as within cities.

In order to prepare for, and adapt to climate change impacts, high-quality climate information tailored to cities is critical for urban decision-makers to ensure the long-term resilience of urban areas (Baklanov et al., 2018).

2. The urban climate and regional climate models

The local-scale urban climate, with all its complex processes, has been studied for decades predominantly through meso- and microscale urban climate models (Hamdi et al., 2020; Jänicke et al., 2021; Lipson et al., 2024; Masson et al., 2020). These models commonly operate from the street scale up to the city scale, with high spatial resolutions of 1 km up to 1 m, and are only able to simulate relatively short timescales from hours up to several months. Urban climate models are particularly suitable to investigate short meteorological episodes, e.g. a heat wave or a heavy-precipitation event, as well as the effect of adaptation measures, such as green spaces in a street, district, or entire city. These urban climate models are also capable of investigating climate change, for instance through adding a specific temperature increase to the urban climate model simulation, e.g. using the pseudo global warming approach (Doan and Kusaka, 2018; Gu et al., 2023; Schär et al., 1996), or through using boundary conditions from global or regional climate models (RCMs), or by using statistical (Hoffmann et al., 2012), statistical-dynamical downscaling methods (Duchêne et al., 2020; Hoffmann et al., 2018; Le Roy et al., 2021), or AI methods (Bushenkova et al., 2024; Johannsen et al., 2024). Nevertheless, due to limitations in domain size, urban climate models are commonly unable to simulate the full dynamical interactions between the regional surroundings and the city, as well as the interactions of climate change and the urban areas in a physically consistent manner on climatological timescales from years to decades (Hamdi et al., 2020; Masson et al., 2020) (Table 1).

RCMs are a promising tool to simulate the interactions of cities and the regional climate on longer timescales up to decades or even a century. Recently, RCM developments have moved towards increasing grid resolutions down to kilometer scales (1–4 km, so-called convection permitting resolution), and therewith the city scale (Brecht et al., 2020; Coppola et al., 2020; Garbero et al., 2021; Hundhausen et al., 2023; Prein et al., 2015; Schär et al., 2020). At this resolution, models resolve smaller scale processes and features of the Earth's surface. In particular, a larger proportion of model grid boxes are categorised as “urban” with higher urban fractions, and can also represent the heterogeneity of the urban area (Grimmond et al., 2010; Langendijk et al., 2021). Proper parameterization of urban processes is starting to play an increasingly important role to understand local-to-regional interactions (Daniel et al., 2019; Hamdi et al., 2014), particularly under climate change (Katzfey et al., 2020; Trusilova et al., 2013). The inclusion of individual urban processes affecting energy balance and mass transport (i.e. radiation, heat, humidity, momentum fluxes), via special urban land-use parameterization of distinct local processes, becomes critical to simulate the urban effects adequately and to capture interactions

Table 1

Typical characteristics of urban climate models and regional climate models in the context of simulating urban climate (change).

Modelling approach	Considered spatial scales	Grid resolutions	Simulation timescales	Typical simulations and applications
Urban climate models	Street/building to city scale climate	~1 m to 1 km (<i>Convective permitting- down to large eddy resolving grid resolution</i>)	Minutes to day (s) to month(s)	Short-term simulations of relevant weather events or episodes (heat waves, heavy precipitation, etc.), possibly under climate change through defined level(s) of global warming
Regional climate models	City scale and interactions with local-to-regional climate change	~1 km to 4 km (<i>Convection permitting grid resolution</i>) (RCMs can go up to > 10kms)	Decade(s) to century	Urban-rural contrasts under climate change (e.g., urban heat island), trends, and interactions between cities and regional climate change

within the regional climate (Kusaka et al., 2001; Martilli et al., 2002). Traditionally, at best, RCMs represent cities as a “rock” surface, the so-called bulk approach, usually characterised by a modified albedo, higher roughness length, and no water storage (Langendijk et al., 2019; Schwingshackl et al., 2023). Some RCMs started to incorporate a more sophisticated urban scheme. Most commonly, RCMs implement an urban scheme as part of the land-surface scheme by means of coupling to an urban canopy model, such as a single-layer urban canopy model (e.g. TEB, CLMu, SLUCM) or a multi-layer urban canopy model (e.g. BEP) (Hamdi and Masson, 2008; Kusaka et al., 2001; Lipson et al., 2024; Martilli et al., 2002; Masson et al., 2002, 2020; Oleson and Feddema, 2020; Schlünzen et al., 2023) (Table 1). In connection to incorporating a sophisticated urban scheme, the land-surface input data shall adequately represent urban land use, including size, location and heterogeneity (Fan et al., 2022; Hertwig et al., 2021). Recently, it has become possible to incorporate high-resolution urban land-surface input data, such as the Local Climate Zone database, in the RCMs to improve the representation of urban heterogeneity on urban climate modelling (Apreda et al., 2023; Bechtel et al., 2019; Brousse et al., 2016; Demuzere et al., 2022; Wang et al., 2023). Even though an increasing number of RCMs have implemented a more sophisticated urban parameterization, for standard RCM simulations (e.g. CORDEX: Jacob et al., 2020) the urban scheme is often not activated (Hamdi et al., 2020).

The extension of RCMs towards the inclusion of air quality is usually performed via coupling of RCMs (atmosphere and land/sea interactions) with so-called Chemistry Transport Models (CTM), which can be done either off-line or on-line (Grell and Baklanov, 2011). Off-line coupling can provide information on air quality under specific conditions, but potential feedbacks to the atmospheric processes are either ignored or provided as external forcing, while on-line coupling considers changes in air quality directly, e.g., for radiative processes or microphysics. To simulate a more realistic behaviour of the system, the latter method is required in RCM development, especially in connection with urbanisation effects, where chemistry including aerosols can play an important role and affect, e.g., the regional to local radiation balance (Baklanov et al., 2010; Sokhi et al., 2022).

The aforementioned model developments towards the incorporation of sophisticated urban schemes in RCMs and including air quality, enable improved assessments of climate change impacts in cities, inform adaptation and mitigation options for urban decision makers, and ultimately assist the adequate preparation for climate related risks (e.g. heat waves, smog conditions, etc.) (Masson et al., 2020). The incorporation of urban schemes in RCMs could also contribute to the development of regional Earth system models (RESMs) and underpin the progress towards urban digital twins (Giorgi and Gao, 2018).

3. Research outlook: the flagship pilot study URB-RCC

There remains a significant gap to incorporate the knowledge relevant at regional scale from the urban climate modelling community into RCMs in order to downscale climate change projections up to the urban environment, and to simulate urban interactions with the regional climate on climatological timescales. In order to facilitate and coordinate this development, the Flagship Pilot Study (FPS) “*URBan environments and Regional Climate Change* (FPS URB-RCC)” was launched on 1 May 2021 under the umbrella of the Coordinated Regional Climate Downscaling Experiment (CORDEX) of the World Climate Research Programme (WCRP).

The main goal of the 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 an urbanised RCM ensemble.

A coordinated intercomparison between the different RCMs, and particularly their urban schemes, will be conducted. This allows for an improved understanding of the models behaviour, as well as the confidence and uncertainties that arise within and between the different RCMs and their urban representations. As a first stage, four- to five-month coordinated simulations are conducted on the kilometer-scale resolution. These are feasible for both the urban modelling and RCM communities and cover two extreme weather events, a heatwave episode and a heavy precipitation event, along with a sufficient number of daily cycles with more normal conditions. Thereafter, longer term reanalysis-driven (ERA-5; Hersbach et al., 2020) simulations of minimum ten years will be performed to understand the models’ behaviour on longer (climatological) timescales. This RCM intercomparison will support the assessment of options and improvements for the urban parameterization schemes in high-resolution RCM simulations for further use in CORDEX. The long-term goal is to support the development and provide guidelines to include efficient, as well as adequate urban representation in RCMs for the standard CORDEX simulations.

In addition, the FPS URB-RCC will improve the understanding of urban climate change impacts, across local-to-regional scales. Firstly, existing CORDEX and convection-permitting model datasets will be analysed for European cities, as well as for cities across the

globe. In the second half of the activity, coordinated urbanised RCM simulations on climatological timescales are envisioned using climate change projections, in coordination with standard CORDEX protocol simulations (e.g. Katragkou et al., 2024) to highlight the impact of advanced urban parameterizations on official regional climate products (e.g. Copernicus C3s) widely used by the research and impact communities. This will allow analysing the interactions between urban areas and climate change conditions. Herewith, the FPS URB-RCC enhances the understanding of the urban environment's vulnerability under climate change and provides the urban climate change science to underpin climate services for cities.

In recent years, a large number of global land cover datasets that delineate urban land have been released, due to improvements in high-resolution satellite remote sensing and computational advancements. These datasets are crucial for understanding climate risks in our increasingly urbanising world. (Chakraborty, 2024) analysed a large number of high-resolution urban land cover datasets that all confirm a rapidly urbanising world, with global urban land that nearly tripled between 1985 and 2015. However, there are substantial discrepancies in urban land area estimates among them, influenced by scale, differing urban definitions, and methodologies. This, in combination with the fact that many model systems rely on “older” global datasets as the lower boundary conditions for the atmosphere in coupled model simulations, makes it worthwhile to investigate the role of the urban surface and land cover data, and provide guidelines and opportunities for future developments.

Similarly, urbanisation scenarios will also be investigated by individual groups, depending on their research interests. Furthermore, the groups are encouraged to use simulations coupled with CTM where available to assess the effects and contribution of air quality on the urban environment and on the urban plume, particularly for changes in temperature and moisture under climate change. In addition, a sub-group of FPS partners is centred around statistical and AI-based downscaling techniques to complement the dynamically downscaled simulations.

The selected “core” city for the coordinated experiments is Paris, in France. This city was carefully picked in close consultation with the FPS partners and based on a set of co-developed criteria. Paris has high-quality openly available observational datasets which are critical for the evaluation of the RCMs. Furthermore, Paris is a large city situated in-land and is surrounded by relatively flat terrain. Thus, there is a strong urban-rural contrast which aids to detect the typical urban effects, such as the UHI. These geographic characteristics make Paris a suitable city to investigate with RCMs. In addition to the core city of Paris, the individual partners are encouraged to simulate their local or a nearby city, following the ‘Global Satellite Cities Concept’ (Fig. 1). The ‘Global Satellite Cities Concept’ aims at including cities across the globe, and comparing cities across different climate zones, as well as cities with different geographic conditions (in-land, coastal, mountains). The simulations for the local cities shall follow the FPS URB-RCC protocols, to enable appropriate comparisons (Fig. 1).

Currently the FPS URB-RCC encompasses approximately 30 partners, across the globe, mainly coming from the CORDEX community, as well as the International Association for Urban Climate (IAUC). The FPS remains open to interested groups and new partners. The FPS URB-RCC aims to create synergies with ongoing national and international projects. For instance, the EU Horizon Europe projects FOCL, focusing on chemistry coupling to RCMs, and Impetus4Change (I4C), wherein the activities around urbanised convection permitting simulations for European cities are especially relevant for URB-RCC. The research community gathered around

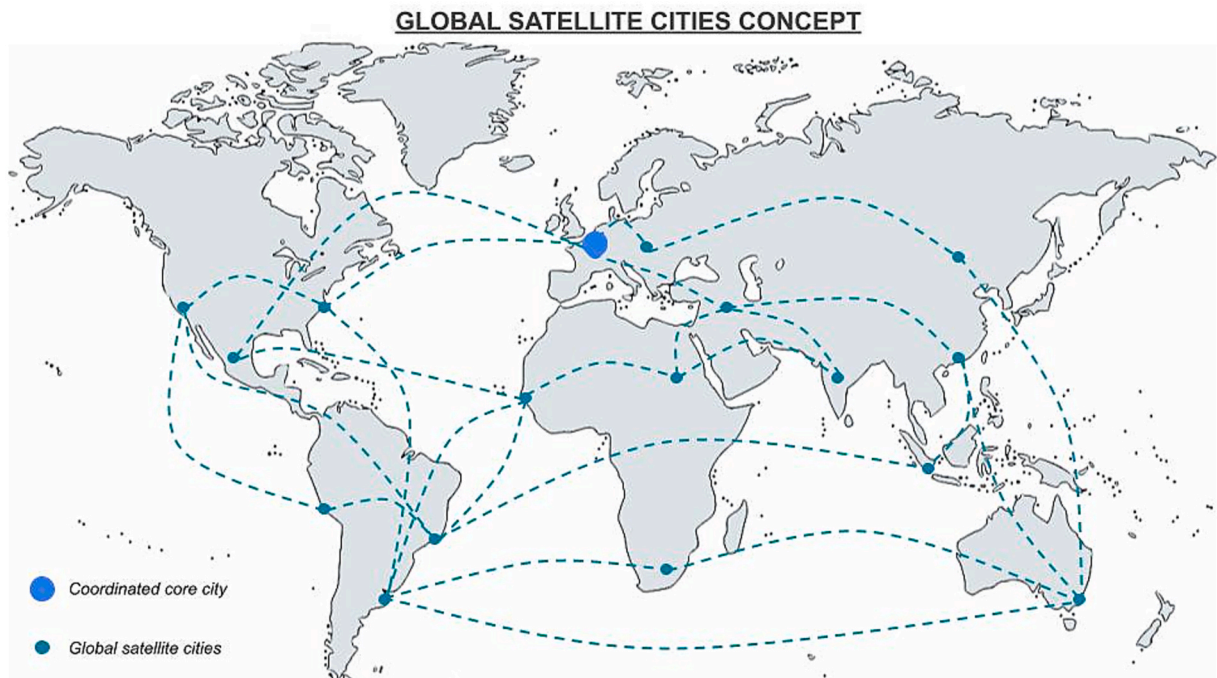


Fig. 1. Illustration of FPS URB-RCC “Global Satellite Cities Concept”. This figure serves as an illustration, the final satellite cities are to be selected.

the FPS initiative is already sharing knowledge about a large variety of topics as a result of the studies done for Paris as well as for their ‘satellite’ cities, ranging from the technological aspects of best model practices, model configuration, data and analysis sharing. This exchange is already fostering the research capabilities and competence of the FPS members. For example, there is a WRF model specific group involving more than 20 different institutions worldwide.

The FPS URB-RCC aims to make scientific strides towards intercomparing urban representations in RCM simulations and investigating the urban climate and its interactions with regional climate change. Sustainable urban futures derive significant advantages from climate change projections and information that span from the city-scale to regional climate change modelling. The resulting downscaled information of the FPS URB-RCC can assist cities in preparing for and adapting to climate change impacts, directly informing their urban planning processes. Simultaneously, it supports the transition towards climate-resilient urban environments. Decision makers at both multinational and local levels gain valuable insights from this regional climate model knowledge at the urban scale, empowering them to make informed adaptations and contribute to building the resilient cities of tomorrow.

CRedit authorship contribution statement

Gaby S. Langendijk: Conceptualization, Writing – original draft, Writing – review & editing. **Tomas Halenka:** Conceptualization, Writing – original draft, Writing – review & editing. **Peter Hoffmann:** Writing – original draft, Writing – review & editing. **Marianna Adinolfi:** Writing – review & editing. **Aitor Aldama Campino:** Writing – review & editing. **Olivier Asselin:** Writing – review & editing. **Sophie Bastin:** Writing – review & editing. **Benjamin Bechtel:** Writing – review & editing. **Michal Belda:** Writing – review & editing. **Angelina Bushenkova:** Writing – review & editing. **Angelo Campanale:** Writing – review & editing. **Kwok Pan Chun:** Writing – review & editing. **Katiana Constantinidou:** Writing – review & editing. **Erika Coppola:** Writing – review & editing. **Matthias Demuzere:** Writing – review & editing. **Quang-Van Doan:** Writing – review & editing. **Jason Evans:** Writing – review & editing. **Hendrik Feldmann:** Writing – review & editing. **Jesus Fernandez:** Writing – review & editing. **Lluís Fita:** Writing – review & editing. **Panos Hadjinicolaou:** Writing – review & editing. **Rafiq Hamdi:** Writing – review & editing. **Marie Hundhausen:** Writing – review & editing. **David Grawe:** Writing – review & editing. **Frederico Johannsen:** Writing – review & editing. **Josipa Milovac:** Writing – review & editing. **Eleni Katragkou:** Writing – review & editing. **Nour El Islam Kerroumi:** Writing – review & editing. **Sven Kotlarski:** Writing – review & editing. **Benjamin Le Roy:** Writing – review & editing. **Aude Lemonsu:** Writing – review & editing. **Christopher Lennard:** Writing – review & editing. **Mathew Lipson:** Writing – review & editing. **Shailendra Mandal:** Writing – review & editing. **Luis E. Muñoz Pabón:** Writing – review & editing. **Vassileios Pavlidis:** Writing – review & editing. **Joni-Pekka Pietikäinen:** Writing – review & editing. **Mario Raffa:** Writing – review & editing. **Eloisa Raluy-López:** Writing – review & editing. **Diana Rechid:** Writing – review & editing. **Rui Ito:** Writing – review & editing. **Jan-Peter Schulz:** Writing – review & editing. **Pedro M.M. Soares:** Writing – review & editing. **Yuya Takane:** Writing – review & editing. **Claas Teichmann:** Writing – review & editing. **Marcus Thatcher:** Writing – review & editing. **Sara Top:** Writing – review & editing. **Bert Van Schaeybroeck:** Writing – review & editing. **Fuxing Wang:** Writing – review & editing. **Jiacan Yuan:** Writing – review & editing.

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

No data was used for the research described in the article.

Acknowledgement

We wish to thank the partners of the WCRP CORDEX FPS URB-RCC for their engagement and contributions to the initiative. We would like to thank the World Climate Research Programme (WCRP) and the COordinated Regional climate Downscaling EXperiment (CORDEX) for their endorsement and support to the Flagship Pilot Study URB-RCC. G.S. Langendijk conducted a large share of this work at the Climate Service Center Germany (GERICS), Helmholtz-Zentrum Hereon, Germany. We especially wish to thank Hereon for kindly covering the open access fee of this publication.

In addition, we thank the Charles University Program COOPERATIO-ENVI, of which T. Halenka is part. Furthermore, there are connections between the CORDEX FPS URB-RCC and EU Horizon Europe projects IMPETUS4CHANGE (101081555) and FOCI (101056783). P. Hoffmann would like to thank the German Federal Ministry of Education and Research (BMBF) for the BMBF Junior Research Group (CoSynHealth, 01LN2204A) funding support and the project management support from the German Aerospace Center (DLR). Luis E. Muñoz Pabón is funded by the CONICET with a PhD grant. Kwok P. Chun is funded by the Vice Chancellor's Accelerator Programme from the University of the West of England. J.F. and J.M. acknowledge support from project CORDyS (PID2020-116595RB-I00), funded by MICIU/AEI/10.13039/501100011033. M. Demuzere acknowledges support from the EU Horizon Europea CARMINE project and the ENLIGHT project, project funded by the German Research Foundation (DFG) under grant no. 437467569. IPSL and CIMA thank the CNRS/INSU/LEFE program for financial support and GENCI for granted access to HPC resources of TGCC under the allocation A0150106877. S. Top is funded by the Fund for Scientific Research of the Flemish regional government (FWO), fellowship 1270723 N.

References

- Andreadis, K.M., Wing, O.E.J., Colven, E., Gleason, C.J., Bates, P.D., Brown, C.M., 2022. Urbanizing the floodplain: global changes of imperviousness in flood-prone areas. *Environ. Res. Lett.* 17 (10), 104024. <https://doi.org/10.1088/1748-9326/ac9197>.
- Appreda, C., Schulz, J.-P., Reder, A., Mercogliano, P., 2023. Survey of land cover datasets for updating the imperviousness field in urban parameterisation scheme TERRA_URB for climate and weather applications. *Urban Clim.* 49, 101535. <https://doi.org/10.1016/j.uclim.2023.101535>.
- Argüeso, D., Evans, J.P., Fita, L., Bormann, K.J., 2014. Temperature response to future urbanization and climate change. *Clim. Dyn.* 42 (7–8), 2183–2199. <https://doi.org/10.1007/s00382-013-1789-6>.
- Arnfield, A.J., 2003. Two decades of urban climate research: a review of turbulence, exchanges of energy and water, and the urban heat island. *Int. J. Climatol.* 23 (1), 1–26. <https://doi.org/10.1002/joc.859>.
- Baidar, S., Bonin, T., Choukulkar, A., Brewer, A., Hardesty, M., 2020. Observation of the urban Wind Island effect. *EPJ. Web. Conf.* 237, 06009. <https://doi.org/10.1051/epjconf/202023706009>.
- Baklanov, A., Lawrence, M., Pandis, S., Mahura, A., Finardi, S., Moussiopoulos, N., Beekmann, M., Laj, P., Gomes, L., Jaffrezou, J.-L., Borbon, A., Coll, I., Gros, V., Sciare, J., Kukkonen, J., Galmarini, S., Giorgi, F., Grimmond, S., Esau, I., Rossow, W.B., 2010. MEGAPOLI: concept of multi-scale modelling of megacity impact on air quality and climate. *Adv. Sci. Res.* 4 (1), 115–120. <https://doi.org/10.5194/asr-4-115-2010>.
- Baklanov, A., Grimmond, C.S.B., Carlson, D., Terblanche, D., Tang, X., Bouchet, V., Lee, B., Langendijk, G., Kolli, R.K., Hovsepyan, A., 2018. From urban meteorology, climate and environment research to integrated city services. *Urban Clim.* 23, 330–341. <https://doi.org/10.1016/j.uclim.2017.05.004>.
- Bechtel, B., Alexander, P.J., Beck, C., Böhner, J., Brousse, O., Ching, J., Demuzere, M., Fonte, C., Gál, T., Hidalgo, J., Hoffmann, P., Middel, A., Mills, G., Ren, C., See, L., Sismanidis, P., Verdonck, M.-L., Xu, G., Xu, Y., 2019. Generating WUDAPT level 0 data – current status of production and evaluation. *Urban Clim.* 27, 24–45. <https://doi.org/10.1016/j.uclim.2018.10.001>.
- Brecht, B.M., Schädler, G., Schipper, J.W., 2020. UCI climatology and its future change in Germany – an RCM ensemble approach. *Meteorol. Z.* 29 (2), 97–116. <https://doi.org/10.1127/metz/2020/1010>.
- Brousse, O., Martilli, A., Foley, M., Mills, G., Bechtel, B., 2016. WUDAPT, an efficient land use producing data tool for mesoscale models? Integration of urban LCZ in WRF over Madrid. *Urban Clim.* 17, 116–134. <https://doi.org/10.1016/j.uclim.2016.04.001>.
- 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. <https://ssrn.com/abstract=4729233>.
- Casanueva, A., Kotlarski, S., Fischer, A.M., Flouris, A.D., Kjellstrom, T., Lemke, B., Nybo, L., Schwierz, C., Liniger, M.A., 2020. Escalating environmental summer heat exposure—a future threat for the European workforce. *Reg. Environ. Chang.* 20 (2), 40. <https://doi.org/10.1007/s10113-020-01625-6>.
- Chakraborty, T.C.V. Z. S.D. M.Z. W.G. J.Z. L.Q. Y., 2024. Large disagreements in estimates of urban land across scales and their implications. *Nat. Commun.* <https://doi.org/10.1021/2023/rs.3.rs-3958909/v1> (preprint).
- Coppola, E., Sobolowski, S., Pichelli, E., Raffaele, F., Ahrens, B., Anders, I., Ban, N., Bastin, S., Belda, M., Belusic, D., Caldas-Alvarez, A., Cardoso, R.M., Davolio, S., Dobler, A., Fernandez, J., Fita, L., Fumiere, Q., Giorgi, F., Goergen, K., Warrach-Sagi, K., 2020. A first-of-its-kind multi-model convection permitting ensemble for investigating convective phenomena over Europe and the Mediterranean. *Clim. Dyn.* 55 (1–2), 3–34. <https://doi.org/10.1007/s00382-018-4521-8>.
- Dang, T.N., Van, D.Q., Kusaka, H., Seposo, X.T., Honda, Y., 2018. Green space and deaths attributable to the urban Heat Island effect in Ho Chi Minh City. *Am. J. Public Health* 108 (S2), S137–S143. <https://doi.org/10.2105/AJPH.2017.304123>.
- Daniel, M., Lemosu, A., Déqué, M., Somot, S., Alias, A., Masson, V., 2019. Benefits of explicit urban parameterization in regional climate modeling to study climate and city interactions. *Clim. Dyn.* 52 (5–6), 2745–2764. <https://doi.org/10.1007/s00382-018-4289-x>.
- Deilami, K., Kamruzzaman, Md., Liu, Y., 2018. Urban heat island effect: a systematic review of spatio-temporal factors, data, methods, and mitigation measures. *Int. J. Appl. Earth Obs. Geoinf.* 67, 30–42. <https://doi.org/10.1016/j.jag.2017.12.009>.
- Demuzere, M., Orru, K., Heinrich, O., Olazabal, E., Geneletti, D., Orru, H., Bhavé, A.G., Mittal, N., Feliu, E., Faehnle, M., 2014. Mitigating and adapting to climate change: multi-functional and multi-scale assessment of green urban infrastructure. *J. Environ. Manag.* 146, 107–115. <https://doi.org/10.1016/j.jenvman.2014.07.025>.
- Demuzere, M., Kittner, J., Martilli, A., Mills, G., Moede, C., Stewart, I.D., van Vliet, J., Bechtel, B., 2022. A global map of local climate zones to support earth system modelling and urban-scale environmental science. *Earth Syst. Sci. Data* 14 (8), 3835–3873. <https://doi.org/10.5194/essd-14-3835-2022>.
- Doan, V.Q., Kusaka, H., 2018. Projections of urban climate in the 2050s in a fast-growing city in Southeast Asia: the greater Ho Chi Minh City metropolitan area, Vietnam. *Int. J. Climatol.* 38 (11), 4155–4171. <https://doi.org/10.1002/joc.5559>.
- Doan, Q.-V., Kusaka, H., Ho, Q.-B., 2016. Impact of future urbanization on temperature and thermal comfort index in a developing tropical city: Ho Chi Minh City. *Urban Clim.* 17, 20–31. <https://doi.org/10.1016/j.uclim.2016.04.003>.
- Doan, Q., Chen, F., Kusaka, H., Dipankar, A., Khan, A., Hamdi, R., Roth, M., Niyogi, D., 2022. Increased risk of extreme precipitation over an urban agglomeration with future global warming. *Earth's Future* 10 (6). <https://doi.org/10.1029/2021EF002563>.
- Droste, A.M., Steeneveld, G.J., Holtslag, A.A.M., 2018. Introducing the urban wind island effect. *Environ. Res. Lett.* 13 (9), 094007. <https://doi.org/10.1088/1748-9326/aad8ef>.
- Duchêne, F., Van Schaeybroeck, B., Caluwaerts, S., De Troch, R., Hamdi, R., Termonia, P., 2020. A Statistical–Dynamical Methodology to Downscale Regional Climate Projections to Urban Scale. *J. Appl. Meteorol. Climatol.* 59 (6), 1109–1123. <https://doi.org/10.1175/JAMC-D-19-0104.1>.
- Duchêne, F., Hamdi, R., Van Schaeybroeck, B., Caluwaerts, S., De Troch, R., de Cruz, L., Termonia, P., 2022a. Downscaling ensemble climate projections to urban scale: Brussels's future climate at 1.5 °C, 2 °C, and 3 °C global warming. *Urban Clim.* 46, 101319. <https://doi.org/10.1016/j.uclim.2022.101319>.
- Duchêne, F., Hamdi, R., Van Schaeybroeck, B., Caluwaerts, S., De Troch, R., de Cruz, L., Termonia, P., 2022b. Downscaling ensemble climate projections to urban scale: Brussels's future climate at 1.5 °C, 2 °C, and 3 °C global warming. *Urban Clim.* 46, 101319. <https://doi.org/10.1016/j.uclim.2022.101319>.
- Eisenack, K., Roggero, M., 2022. Many roads to Paris: explaining urban climate action in 885 European cities. *Glob. Environ. Chang.* 72, 102439. <https://doi.org/10.1016/j.gloenvcha.2021.102439>.
- Fan, P.Y., Chun, K.P., Mijic, A., Mah, D.N.-Y., He, Q., Choi, B., Lam, C.K.C., Yetemen, O., 2022. Spatially-heterogeneous impacts of surface characteristics on urban thermal environment, a case of the Guangdong-Hong Kong-Macau Greater Bay Area. *Urban Clim.* 41, 101034. <https://doi.org/10.1016/j.uclim.2021.101034>.
- Garbero, V., Milelli, M., Buccignani, E., Mercogliano, P., Varentsov, M., Rozinkina, I., Rivin, G., Blinov, D., Wouters, H., Schulz, J.-P., Schättler, U., Bassani, F., Demuzere, M., Repola, F., 2021. Evaluating the urban canopy scheme TERRA_URB in the COSMO model for selected European cities. *Atmosphere* 12 (2), 237. <https://doi.org/10.3390/atmos12020237>.
- Giorgi, F., Gao, X.-J., 2018. Regional earth system modeling: review and future directions. *Atmospher. Ocean. Sci. Lett.* 11 (2), 189–197. <https://doi.org/10.1080/16742834.2018.1452520>.
- Grell, G., Baklanov, A., 2011. Integrated modeling for forecasting weather and air quality: a call for fully coupled approaches. *Atmos. Environ.* 45 (38), 6845–6851. <https://doi.org/10.1016/j.atmosenv.2011.01.017>.
- Grimmond, C.S.B., Blackett, M., Best, M.J., Barlow, J., Baik, J.-J., Belcher, S.E., Bohnstengel, S.I., Calmet, I., Chen, F., Dandou, A., Fortuniak, K., Gouvea, M.L., Hamdi, R., Hendry, M., Kawai, T., Kawamoto, Y., Kondo, H., Krayenhoff, E.S., Lee, S.-H., Zhang, N., 2010. The international urban energy balance models comparison project: first results from phase 1. *J. Appl. Meteorol. Climatol.* 49 (6), 1268–1292. <https://doi.org/10.1175/2010JAMC2354.1>.
- Gu, Y., Kusaka, H., Doan, Q.-V., 2023. An advection fog event response to future climate forcing in the 2030s–2080s: a case study for Shanghai. *Front. Earth Sci.* 17 (2), 527–546. <https://doi.org/10.1007/s11707-022-1002-5>.
- Hamdi, R., Masson, V., 2008. Inclusion of a drag approach in the town energy balance (TEB) scheme: offline 1D evaluation in a street canyon. *J. Appl. Meteorol. Climatol.* 47 (10), 2627–2644. <https://doi.org/10.1175/2008JAMC1865.1>.
- Hamdi, R., Van de Vyver, H., De Troch, R., Termonia, P., 2014. Assessment of three dynamical urban climate downscaling methods: Brussels's future urban heat island under an <sc>A1B</sc> emission scenario. *Int. J. Climatol.* 34 (4), 978–999. <https://doi.org/10.1002/joc.3734>.

- Hamdi, R., Kusaka, H., Doan, Q.-V., Cai, P., He, H., Luo, G., Kuang, W., Caluwaerts, S., Duchêne, F., Van Schaeybroeck, B., Termonia, P., 2020. The state-of-the-art of urban climate change modeling and observations. *Earth Syst. Environ.* 4 (4), 631–646. <https://doi.org/10.1007/s41748-020-00193-3>.
- Heal, G., Park, J., 2016. Reflections—temperature stress and the direct impact of climate change: a review of an emerging literature. *Rev. Environ. Econ. Policy* 10 (2), 347–362. <https://doi.org/10.1093/reep/rew007>.
- Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., Nicolas, J., Peubey, C., Radu, R., Schepers, D., Simmons, A., Soci, C., Abdalla, S., Abellan, X., Balsamo, G., Bechtold, P., Biavati, G., Bidlot, J., Bonavita, M., Thépaut, J., 2020. The ERA5 global reanalysis. *Q. J. R. Meteorol. Soc.* 146 (730), 1999–2049. <https://doi.org/10.1002/qj.3803>.
- Hertwig, D., Ng, M., Grimmond, S., Vidale, P.L., McGuire, P.C., 2021. High-resolution global climate simulations: representation of cities. *Int. J. Climatol.* 41 (5), 3266–3285. <https://doi.org/10.1002/joc.7018>.
- Hoffmann, P., Krueger, O., Schlünzen, K.H., 2012. A statistical model for the urban heat island and its application to a climate change scenario. *Int. J. Climatol.* 32 (8), 1238–1248. <https://doi.org/10.1002/joc.2348>.
- Hoffmann, P., Schoetter, R., Schlünzen, K.H., 2018. Statistical-dynamical downscaling of the urban heat island in Hamburg. *Meteorol. Z.* <https://doi.org/10.1127/metz/2016/0773>.
- Hsu, A., Tan, J., Ng, Y.M., Toh, W., Vanda, R., Goyal, N., 2020. Performance determinants show European cities are delivering on climate mitigation. *Nat. Clim. Chang.* 10 (11), 1015–1022. <https://doi.org/10.1038/s41558-020-0879-9>.
- Hundhausen, M., Feldmann, H., Laube, N., Pinto, J.G., 2023. Future heat extremes and impacts in a convection-permitting climate ensemble over Germany. *Nat. Hazards Earth Syst. Sci.* 23 (8), 2873–2893. <https://doi.org/10.5194/nhess-23-2873-2023>.
- Huszar, P., Halenka, T., Belda, M., Zak, M., Sindelarova, K., Miksovsky, J., 2014. Regional climate model assessment of the urban land-surface forcing over Central Europe. *Atmos. Chem. Phys.* 14 (22), 12393–12413. <https://doi.org/10.5194/acp-14-12393-2014>.
- Huszar, P., Belda, M., Halenka, T., 2016a. On the long-term impact of emissions from central European cities on regional air quality. *Atmos. Chem. Phys.* 16 (3), 1331–1352. <https://doi.org/10.5194/acp-16-1331-2016>.
- Huszar, P., Belda, M., Karlický, J., Pišoft, P., Halenka, T., 2016b. The regional impact of urban emissions on climate over Central Europe: present and future emission perspectives. *Atmos. Chem. Phys.* 16 (20), 12993–13013. <https://doi.org/10.5194/acp-16-12993-2016>.
- Huszar, P., Karlický, J., Dóbalová, J., Nováková, T., Šindelarová, K., Šváňík, F., Belda, M., Halenka, T., Žák, M., 2020. The impact of urban land-surface on extreme air pollution over Central Europe. *Atmos. Chem. Phys.* 20 (20), 11655–11681. <https://doi.org/10.5194/acp-20-11655-2020>.
- Jacob, D., Teichmann, C., Sobolowski, S., Katragkou, E., Anders, I., Belda, M., Benestad, R., Boberg, F., Buonomo, E., Cardoso, R.M., Casanueva, A., Christensen, O.B., Christensen, J.H., Coppola, E., De Cruz, L., Davin, E.L., Dobler, A., Domínguez, M., Fealy, R., Wulfmeyer, V., 2020. Regional climate downscaling over Europe: perspectives from the EURO-CORDEX community. *Reg. Environ. Chang.* 20 (2), 51. <https://doi.org/10.1007/s10113-020-01606-9>.
- Jánicke, B., Milošević, D., Manaví, S., 2021. Review of user-friendly models to improve the urban Micro-climate. *Atmosphere* 12 (10), 1291. <https://doi.org/10.3390/atmos12101291>.
- Johannsen, F., Soares, P.M.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. <https://ssrn.com/abstract=4729227>.
- Kache, P.A., Santos-Vega, M., Stewart-Ibarra, A.M., Cook, E.M., Seto, K.C., Diuk-Wasser, M.A., 2022. Bridging landscape ecology and urban science to respond to the rising threat of mosquito-borne diseases. *Nat. Ecol. & Evolut.* 6 (11), 1601–1616. <https://doi.org/10.1038/s41559-022-01876-y>.
- Katragkou, E., Sobolowski, S.P., Teichmann, C., Solmon, F., Pavlidis, V., Rechid, D., Hoffmann, P., Fernandez, J., Nikulin, G., Jacob, D., 2024. Delivering an improved framework for the new generation of CMIP6-driven EURO-CORDEX regional climate simulations. *Bull. Am. Meteorol. Soc.* <https://doi.org/10.1175/BAMS-D-23-0131.1>.
- Katzfey, J., Schlünzen, H., Hoffmann, P., Thatcher, M., 2020. How an urban parameterization affects a high-resolution global climate simulation. *Q. J. R. Meteorol. Soc.* 146 (733), 3808–3829. <https://doi.org/10.1002/qj.3874>.
- Kim, S.W., Brown, R.D., 2021. Urban heat island (UHI) intensity and magnitude estimations: a systematic literature review. *Sci. Total Environ.* 779, 146389. <https://doi.org/10.1016/j.scitotenv.2021.146389>.
- Kovats, R.S., Hajat, S., 2008. Heat stress and public health: a critical review. *Annu. Rev. Public Health* 29 (1), 41–55. <https://doi.org/10.1146/annurev.publhealth.29.020907.090843>.
- Kusaka, H., Kondo, H., Kikigawa, Y., Kimura, F., 2001. A simple single-layer urban canopy model for atmospheric models: comparison with multi-layer and slab models. *Bound.-Layer Meteorol.* 101 (3), 329–358. <https://doi.org/10.1023/A:1019207923078>.
- Laino, E., Iglesias, G., 2023. Scientometric review of climate-change extreme impacts on coastal cities. *Ocean Coast. Manag.* 242, 106709. <https://doi.org/10.1016/j.ocecoaman.2023.106709>.
- Lalonde, M., Oudin, L., Bastin, S., 2023. Urban effects on precipitation: do the diversity of research strategies and urban characteristics preclude general conclusions? *Urban Clim.* 51, 101605. <https://doi.org/10.1016/j.uclim.2023.101605>.
- Langendijk, G.S., Rechid, D., Jacob, D., 2019. Urban Areas and Urban–Rural Contrasts under Climate Change: What Does the EURO-CORDEX Ensemble Tell Us?—Investigating near Surface Humidity in Berlin and Its Surroundings. *Atmosphere* 10 (12), 730. <https://doi.org/10.3390/atmos10120730>.
- Langendijk, G.S., Rechid, D., Sieck, K., Jacob, D., 2021. Added value of convection-permitting simulations for understanding future urban humidity extremes: case studies for Berlin and its surroundings. *Weather Clim. Extrem.* 33, 100367. <https://doi.org/10.1016/j.wace.2021.100367>.
- Langendijk, G.S., Rechid, D., Jacob, D., 2022. Improved models, improved information? Exploring how climate change impacts pollen, influenza, and mold in Berlin and its surroundings. *Urban Clim.* 43, 101159. <https://doi.org/10.1016/j.uclim.2022.101159>.
- Le Roy, B., Lemonsu, A., Schoetter, R., 2021. A statistical–dynamical downscaling methodology for the urban heat island applied to the EURO-CORDEX ensemble. *Clim. Dyn.* 56 (7–8), 2487–2508. <https://doi.org/10.1007/s00382-020-05600-z>.
- Lindberg, F., Lindström, A., Stålnacke, V., Thorsson, S., Destouni, G., 2024. Observations and Modelling of Mosquito Prevalence within Urban Areas – A Case Study from Uppsala. *Urban Ecosystems*, Sweden. <https://doi.org/10.1007/s11252-024-01511-7>.
- Lipson, M.J., Grimmond, S., Best, M., Abramowitz, G., Coutts, A., Tapper, N., Baik, J., Beyers, M., Blunn, L., Boussetta, S., Bou-Zeid, E., De Kauwe, M.G., de Munck, C., Demuzere, M., Fatichi, S., Fortuniak, K., Han, B., Hendry, M.A., Kikigawa, Y., Pitman, A.J., 2024. Evaluation of 30 urban land surface models in the <sc>urban-PLUMBER</sc> project: phase 1 results. *Q. J. R. Meteorol. Soc.* 150 (758), 126–169. <https://doi.org/10.1002/qj.4589>.
- Liu, J., Niyogi, D., 2019. Meta-analysis of urbanization impact on rainfall modification. *Sci. Rep.* 9 (1), 7301. <https://doi.org/10.1038/s41598-019-42494-2>.
- Martilli, A., Clappier, A., Rotach, M.W., 2002. An urban surface exchange parameterisation for mesoscale models. *Bound.-Layer Meteorol.* 104 (2), 261–304. <https://doi.org/10.1023/A:1016099921195>.
- Masson, V., Grimmond, C.S.B., Oke, T.R., 2002. Evaluation of the town energy balance (TEB) scheme with direct measurements from dry districts in two cities. *J. Appl. Meteorol.* 41 (10), 1011–1026. [https://doi.org/10.1175/1520-0450\(2002\)041<1011:EOTTEB>2.0.CO;2](https://doi.org/10.1175/1520-0450(2002)041<1011:EOTTEB>2.0.CO;2).
- Masson, V., Lemonsu, A., Hidalgo, J., Voogt, J., 2020. Urban climates and climate change. *Annu. Rev. Environ. Resour.* 45 (1), 411–444. <https://doi.org/10.1146/annurev-environ-012320-083623>.
- Nicholls, R.J., Lincke, D., Hinkel, J., Brown, S., Vafeidis, A.T., Meyssignac, B., Hanson, S.E., Merken, J.-L., Fang, J., 2021. A global analysis of subsidence, relative sea-level change and coastal flood exposure. *Nat. Clim. Chang.* 11 (4), 338–342. <https://doi.org/10.1038/s41558-021-00993-z>.
- Nogueira, M., Soares, P.M.M., 2019. A surface modelling approach for attribution and disentanglement of the effects of global warming from urbanization in temperature extremes: application to Lisbon. *Environ. Res. Lett.* 14 (11), 114023. <https://doi.org/10.1088/1748-9326/ab465f>.
- Nogueira, M., Lima, D.C.A., Soares, P.M.M., 2020. An integrated approach to project the future urban climate response: changes to Lisbon's urban heat island and temperature extremes. *Urban Clim.* 34, 100683. <https://doi.org/10.1016/j.uclim.2020.100683>.
- Nogueira, M., Hurdud, A., Ermida, S., Lima, D.C.A., Soares, P.M.M., Johannsen, F., Dutra, E., 2022. Assessment of the Paris urban heat island in ERA5 and offline SURFEX-TEB (v8.1) simulations using the METEOSAT land surface temperature product. *Geosci. Model Dev.* 15 (14), 5949–5965. <https://doi.org/10.5194/gmd-15-5949-2022>.

- Oleson, K.W., Feddema, J., 2020. Parameterization and surface data improvements and new capabilities for the community land model urban (CLMU). *J. Adv. in Mod. Earth Syst.* 12 (2). <https://doi.org/10.1029/2018MS001586>.
- Prein, A.F., Langhans, W., Fossler, G., Ferrone, A., Ban, N., Goergen, K., Keller, M., Tölle, M., Gutjahr, O., Feser, F., Brisson, E., Kollet, S., Schmidli, J., van Lipzig, N.P.M., Leung, R., 2015. A review on regional convection-permitting climate modeling: demonstrations, prospects, and challenges. *Rev. Geophys.* 53 (2), 323–361. <https://doi.org/10.1002/2014RG000475>.
- Reckien, D., Creutzig, F., Fernandez, B., Lwasa, S., Tovar-Restrepo, M., Mcevoy, D., Satterthwaite, D., 2017. Climate change, equity and the sustainable development goals: an urban perspective. *Environ. Urban.* 29 (1), 159–182. <https://doi.org/10.1177/0956247816677778>.
- Rentschler, J., Avner, P., Marconcini, M., Su, R., Strano, E., Voudoukas, M., Hallegatte, S., 2023. Global evidence of rapid urban growth in flood zones since 1985. *Nature* 622 (7981), 87–92. <https://doi.org/10.1038/s41586-023-06468-9>.
- Rosenzweig, C., Solecki, W.D., Romero-Lankao, P., Mehrotra, S., Dhakal, S., Ibrahim, S.A. (Eds.), 2018. *Climate change and cities: Second assessment report of the urban climate change research network*.
- Schär, C., Frei, C., Lüthi, D., Davies, H.C., 1996. Surrogate climate-change scenarios for regional climate models. *Geophys. Res. Lett.* 23 (6), 669–672. <https://doi.org/10.1029/96GL00265>.
- Schär, C., Fuhrer, O., Arteaga, A., Ban, N., Charpilloz, C., Di Girolamo, S., Hentgen, L., Hoefler, T., Lapillonne, X., Leutwyler, D., Osterried, K., Panosetti, D., Rüdisühli, S., Schlemmer, L., Schulthess, T.C., Sprenger, M., Ubbiali, S., Wernli, H., 2020. Kilometer-scale climate models: prospects and challenges. *Bull. Am. Meteorol. Soc.* 101 (5), E567–E587. <https://doi.org/10.1175/BAMS-D-18-0167.1>.
- Schlünzen, K.H., Grimmond, S., Baklanov, A., 2023. *Guidance on Measuring, Modelling and Monitoring the Canopy Layer Urban Heat Island (CL-UHI)*.
- Schwingshackl, C., Daloz, A.S., Iles, C., Aunan, K., Sillmann, J., 2023. High-resolution projections of ambient heat for major European cities using different heat metrics. *Nat. Hazards Earth Syst. Sci. Discuss.* <https://doi.org/10.5194/nhess-2023-99> [Preprint].
- Sokhi, R.S., Moussiopoulos, N., Baklanov, A., Bartzis, J., Coll, I., Finardi, S., Friedrich, R., Geels, C., Grönholm, T., Halenka, T., Ketzler, M., Maragkidou, A., Matthias, V., Moldanova, J., Ntziachristos, L., Schäfer, K., Suppan, P., Tsegas, G., Carmichael, G., Kukkonen, J., 2022. Advances in air quality research – current and emerging challenges. *Atmos. Chem. Phys.* 22 (7), 4615–4703. <https://doi.org/10.5194/acp-22-4615-2022>.
- Stewart, I.D., 2019. Why should urban heat island researchers study history? *Urban Clim.* 30, 100484. <https://doi.org/10.1016/j.uclim.2019.100484>.
- Takane, Y., Kikegawa, Y., Hara, M., Grimmond, C.S.B., 2019. Urban warming and future air-conditioning use in an Asian megacity: importance of positive feedback. *Npj Climate Atmospher. Sci.* 2 (1), 39. <https://doi.org/10.1038/s41612-019-0096-2>.
- Takane, Y., Ohashi, Y., Grimmond, C.S.B., Hara, M., Kikegawa, Y., 2020. Asian megacity heat stress under future climate scenarios: impact of air-conditioning feedback. *Environ. Res. Communicat.* 2 (1), 015004. <https://doi.org/10.1088/2515-7620/ab6933>.
- Trusilova, K., Früh, B., Brienens, S., Walter, A., Masson, V., Pigeon, G., Becker, P., 2013. Implementation of an urban parameterization scheme into the regional climate model COSMO-CLM. *J. Appl. Meteorol. Climatol.* 52 (10), 2296–2311. <https://doi.org/10.1175/JAMC-D-12-0209.1>.
- UN-HABITAT, 2022. *Envisaging the Future of Cities: World Cities Report 2022. UN-HABITAT Report*.
- Wang, J., Miao, S., Doan, Q., Chen, F., Abolafia-Rosenzweig, R., Yang, L., Zhang, G., Zhang, Y., Dou, J., Xu, Y., 2023. Quantifying the impacts of high-resolution urban information on the urban thermal environment. *J. Geophys. Res. Atmos.* 128 (6). <https://doi.org/10.1029/2022JD038048>.
- Wondmagegn, B.Y., Xiang, J., Williams, S., Pisaniello, D., Bi, P., 2019. What do we know about the healthcare costs of extreme heat exposure? A comprehensive literature review. *Sci. Total Environ.* 657, 608–618. <https://doi.org/10.1016/j.scitotenv.2018.11.479>.
- Yang, P., Ren, G., Yan, P., Deng, J., 2020. Temporal pattern of surface wind speed and the “urban Stilling Island” in Beijing City. *J. Meteorol. Res.* 34 (5), 986–996. <https://doi.org/10.1007/s13351-020-9135-5>.
- Yue, C., Han, Z., Gu, W., Tang, Y., Ao, X., 2021. Research Progress for dynamic effects of cities on precipitation: a review. *Atmosphere* 12 (10), 1355. <https://doi.org/10.3390/atmos12101355>.
- Zhao, L., Oleson, K., Bou-Zeid, E., Kravynhoff, E.S., Bray, A., Zhu, Q., Zheng, Z., Chen, C., Oppenheimer, M., 2021. Global multi-model projections of local urban climates. *Nat. Clim. Chang.* 11 (2), 152–157. <https://doi.org/10.1038/s41558-020-00958-8>.
- Ziska, L.H., Gebhard, D.E., Frenz, D.A., Faulkner, S., Singer, B.D., Straka, J.G., 2003. Cities as harbinger of climate change: common ragweed, urbanization, and public health. *J. Allergy Clin. Immunol.* 111 (2), 290–295. <https://doi.org/10.1067/mai.2003.53>.