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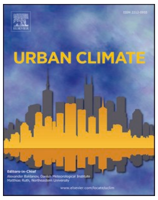

Towards better understanding the urban environment and its interactions with regional climate change - The WCRP CORDEX Flagship Pilot Study URB-RCC

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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 *(Convective permitting- down to large eddy* resolving *grid resolution)*	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 *(Convection permitting grid resolution) (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 FOCI, 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

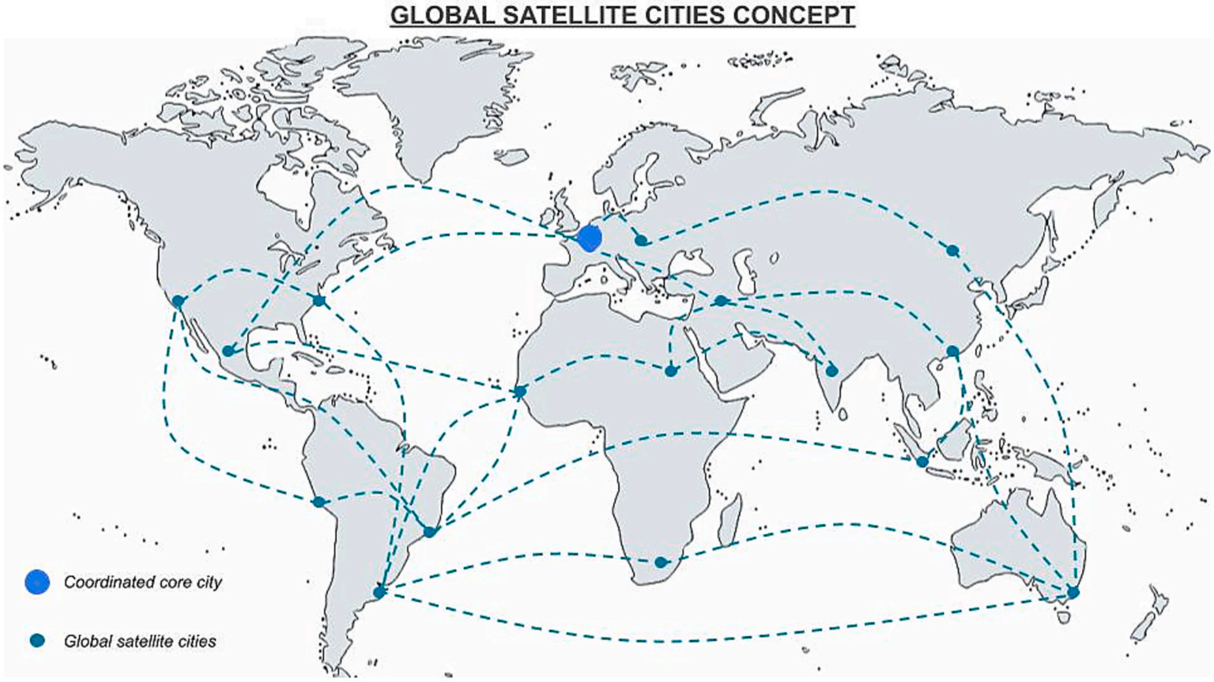

Fig. 1. Illustration of FPS URB-RCC "Global Satellite Cities Concept". This figure serves as an illustration, the final satellite cities are to be selected.

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

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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.

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