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The Need for Urban-Resolving Climate Modeling Across Scales

Ashish Sharma[1,2], **Donald J. Wuebbles**[2], **and Rao Kotamarthi**[3]

[1]Illinois State Water Survey, Prairie Research Institute, University of Illinois at Urbana-Champaign, Champaign, IL, USA, [2]Department of Atmospheric Sciences, University of Illinois at Urbana-Champaign, Champaign, IL, USA, [3]Environmental Science Division, Argonne National Laboratory, Lemont, IL, USA

Key Points:
- An accurate representation of urban areas and urban processes at microscale, regional, and global scales and their feedback across the scales is needed
- Advancing urban-resolving climate modeling will take us closer to the concept of Earth System Models as a model of systems
- The needed research direction will take time to conceive and achieve and will require concentrated efforts

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Correspondence to:
D. J. Wuebbles,
wuebbles@illinois.edu

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Author Contributions:
Conceptualization: Ashish Sharma, Donald J. Wuebbles, Rao Kotamarthi
Project administration: Ashish Sharma, Donald J. Wuebbles
Supervision: Donald J. Wuebbles
Visualization: Ashish Sharma
Writing – original draft: Ashish Sharma
Writing – review & editing: Ashish Sharma, Donald J. Wuebbles, Rao Kotamarthi

Abstract Increasing urbanization, evolving urban landscapes, and growing populations require an accurate representation of urban areas and urban processes at microscale, regional, and global scales and their feedback across the scales. Important urban processes should be represented in climate models, and current approaches used are discussed. We discuss strategies for urban-resolving climate research to capture the effect of climate on urban regions and the non-linear urban processes on climate. Advancing urban-resolving climate modeling will take us closer to capabilities that can truly capture relevant natural and human components.

Plain Language Summary Increasing urbanization, evolving urban landscapes, and growing populations require an accurate representation of urban areas and urban processes at microscale, regional, and global scales and their feedback across the scales. Here we discuss important urban processes that should be represented in climate models and current approaches used by the atmospheric science and urban modeling communities to represent these across space-time scales. We discuss some strategies for urban-resolving climate research to capture the effect of climate on urban regions and the non-linear urban processes on regional and global climate. Here we reason that advancing urban-resolving climate modeling will take us closer to capabilities that can that can truly capture relevant natural and human components.

1. Introduction

Cities only account for 2–3% of global land cover but are home to half of humanity. They have profound implications on local and regional meteorology, air quality, and sustainability (Baklanov et al., 2018) with far-reaching socioeconomic, ecological, and technological impacts (Chen et al., 2020; Keeler et al., 2019).

With increasing urbanization, urban migration, and more pronounced issues related to governance, equity, health, and climate change, cities now face immediate and long-term risks, vulnerability, and challenges. This now requires urgent strategies to increase adaptive capacity and develop robust solutions that provide co-benefits and reduce unintended consequences. Few examples of the issues cities face relate to potential biochemical, air quality, heat, extreme precipitation, and fire safety hazards. Winds may increase/decrease through street canyons and change weather effects (e.g., wind chill, urban heat island [UHI] effects, and precipitation). Temperature inversion over cities can adversely affect air quality, visibility, and urban health. Thus, accurately representing these city effects via urban-resolving integrated climate models can improve our scientific understanding of modeling urban processes across scales as well as improve the quality of life for city residents and solve issues related to urban security. Such a vision would make cities more resilient (Figure 1). For example, it would improve our ability to predict heat stress in different parts of a city given a heat wave, improve our ability to predict air pollution or urban flooding, and determine the degree to which (and how) cities create their own weather or experience weather differently from surrounding areas, the ability to evaluate different kinds of urban infrastructure choices (e.g., green/cool roofs, trees, urban farming, and new construction designs), and how urban processes impact global climate and vice versa.

For developing an integrated urban research framework, we identify urban-resolving models as a critical and doable component with some remaining open science questions needing to be addressed. Detailed urban models are important for understanding the impacts of the changing climate on city microclimates

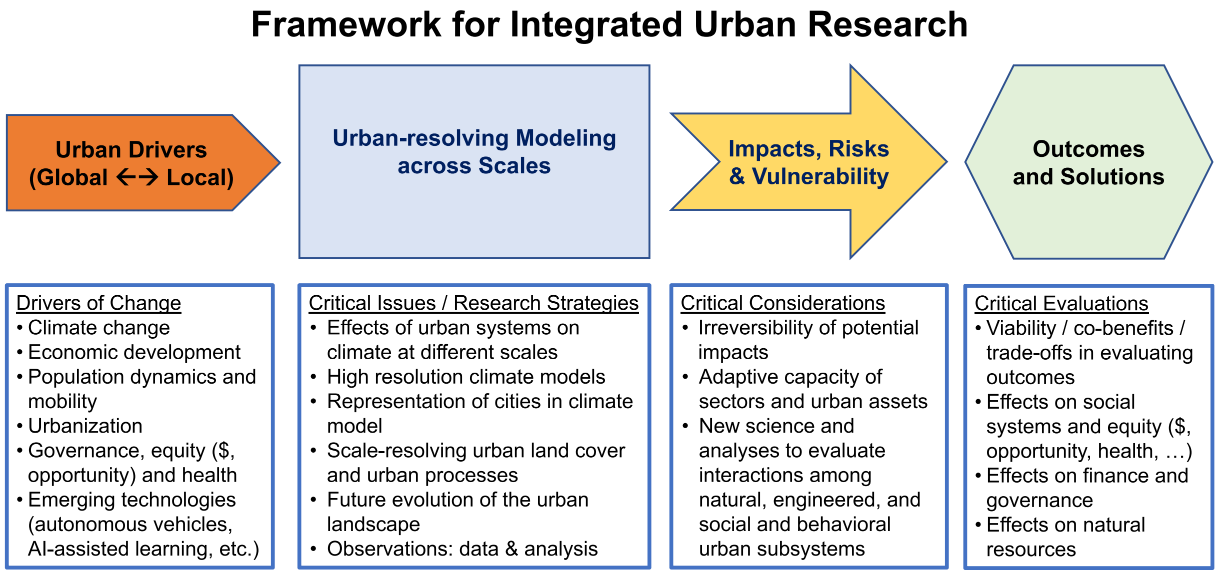

Figure 1. A framework for integrated urban research encapsulating global to local scales.

as well as the role that cities play in local, regional, and global climate change (Sharma et al., 2020; Wuebbles, Kotamarthi, et al., 2020). Developing building-scale models (Scherer et al., 2019), simulating urban atmospheric processes at kilometer to sub-kilometer scales (Barlow et al., 2017), and addressing the impact of global climate at city scales (McCarthy et al., 2010) are ongoing. Despite advances in numerical models and new measurement techniques from space and the ground, the progress in developing urban-resolving models is compartmentalized and slow. The models are currently unable to characterize land cover's relative heterogeneity, urban morphology, geometry, scale, and air pollutants at intra-city and city scales. With cities continuing to grow into megacities (UN, 2019), we are faced with a major challenge and an opportunity to advance multi-disciplinary urban research leading to advanced capabilities for urban-resolving climate modeling. If successful, such an approach will allow us to study and evaluate complex urban land-atmospheric interactions, for example, air and heat flow dynamics, transport of moisture, and changes in atmospheric composition due to outflows of pollutants and greenhouse gases from cities affecting the Earth system across spatial scales to inform building resiliency and sustainability.

These challenges are important but are not currently being addressed. While there are examples of recent efforts to address urban climate and air quality issues (e.g., MEGAPOLI project, Butler & Lawrence, 2009; and World Urban Database and Access Portal Tools [WUDAPT] to gather a census of cities around the world, Ching et al., 2018). There is no international consensus or a unified strategy to develop urban-resolving climate models to study direct and indirect effects of intra-city and city-wide processes on climate and the effects of changing the global climate on cities. Rather than taking a reactive approach to an urban crisis at a local or global scale arising due to the impacts of climate change or otherwise, the atmospheric and urban scientific community needs to take the leadership role in developing a comprehensive plan to improve urban health and metabolism and tackle urban issues across scales that can drive positive changes in urban infrastructure investments, urban quality of life and human growth. Figure 1 illustrates our vision for an integrated urban research across scales. Here we articulate key urban drivers of change across scales, critical issues and research strategies for an urban-resolving modeling framework, potential impacts, risks and vulnerabilities for improved urban health and metabolism, and critical evaluation metrics affecting outcomes and solutions.

In this commentary, we focus our attention on urban-resolving numerical models, a critical component of urban research framework. Specifically, here we discuss key urban processes, current approaches to modeling urban systems across scales, and critical issues for urban-resolving models across scales, provide strategies to overcome them, and give broad recommendations to the scientific community and agencies for achieving this vision.

2. Urban Processes Across Scales

The thermodynamic, physical, and morphological attributes of cities lead to a range of phenomena across spatiotemporal scales. Cities display unique microclimates (Grimmond, 2007; Kristovich et al., 2019) related to their characteristics (e.g., roughness, emissivity, albedo, and thermal conductivity) and other factors (e.g., concentrated energy use in buildings, transportation, and industry). The complex geometry and properties of cities lead to high turbulence intensities at spatial scale of about an approximately meter for seconds to minutes (Fernando, 2010). At the neighborhood scale (m to km scale for minutes to hours), canyon flows and thermally driven local mixing dominate (Letzel et al., 2008; Zajic et al., 2011). These flow patterns lead to the formation of micro-environments that affect ambient temperature, relative humidity, precipitation and the dispersion of air pollutants. Surface hydrological processes are also affected due to the dominance of impervious surfaces. Widely prevalent processes at the city scale (~100- to ~50-km range) relate to UHI effects, lake/sea breeze, slope and valley flow, and urban plumes and are generally diurnal or occur at daily time-scales (Chen et al., 2011; Harris & Kotamarthi, 2005; Lee & Fernando, 2013; Sharma et al., 2017). Flow dynamics within and city-wide scale affect rainfall and wind flow patterns (Freitag et al., 2018). Aerosols and pollutant emissions from industry, transportation, and buildings in cities affect atmospheric thermodynamics (radiation and clouds), significant variability in air quality over neighborhood scales, and influence convective storms (Kumar et al., 2019). Mesoscale land cover heterogeneity and gradients around large cities also modify storm and atmospheric dynamics at a regional scale (Freitag et al., 2018; Pyle et al., 2009; Sharma et al., 2017). Similarly, at longer time scales cities also exert synoptic and global-scale changes in large-scale circulations (Sánchez-Rodríguez et al., 2005) and air quality (Molina & Molina, 2004).

Over the last century, science has advanced the capability to capture atmospheric flow processes across scales, from approximately mm to tens of km scale to global (Kristovich et al., 2019; Randall et al., 2019). Seamless extension of models across spatial scales is hampered by the perceived inability of conventional closures and parameterizations to represent processes from mesoscale to microscale (e.g., processes related to turbulence and convection) (Emeis, 2015; Rai et al., 2019; Wyngaard, 2004). Thus, improved understanding of urban processes between m to km scales remains a vexing challenge for planetary boundary layer and urban studies.

3. Current Approaches

To account for mesoscale processes over cities, urban parameterizations at subgrid scales have been developed to represent the exchange of heat and moisture from urban properties to the atmosphere (Chen et al., 2011). These parameterizations vary in sophistication from simple bulk urban schemes (Taha, 1999) to single-layer (Kusaka et al., 2001) to multilayer urban canopy models, such as the building effect parameterization/building energy model BEP/BEM (Martilli et al., 2002; Salamanca et al., 2009). There has not been extensive evaluation of these models, but the largest existing urban model intercomparison did find that more sophisticated schemes do not necessarily perform better in capturing urban energy and water exchanges (Grimmond et al., 2011).

Small-scale processes are handled by microscale models that are generally used for small physical domains (less than 1–2 km) and small-time periods (less than a day) (Bruse & Fleer, 1998; Gowardhan et al., 2011). These include computationally expensive computational fluid dynamics (CFD) models based on “first principles” to simulate fluid motion. The CFD models are becoming more sophisticated in terms of numerical methods, mesh structures, and turbulence modeling approaches (Souch & Grimmond, 2006). For example, microscale CFD studies have ranged from quiescent periods dominated by thermal circulation (Luo & Li, 2011) to transition from thermal circulation to forced convection at city scale (Omidvar et al., 2020).

Past studies have attempted to downscale general circulation model (GCM) outputs to city-scale using mesoscale models (Hamdi et al., 2014; Kusaka et al., 2001; Lemonsu et al., 2013). Similarly, mesoscale model output has been fed off-line into CFD models (Baik et al., 2009) to study the hyper-local response to mesoscale variability, for example, intra-urban heat clusters called “islets” and trapped pockets of pollutions in urban canyons. But, thus far, GCM output has not been downscaled to microscales (approximately m) directly through multi-model nesting. Früh et al. (2011) used a combination of “dynamical-statistical” downscaling approach and interpolating output from a microscale urban-climate model in off-line mode to predict UHI effects at 50-m resolution. Conry et al. (2015) used a dynamical model chain that consists of global (CAM), regional (WRF), and microscale (ENVI-met) models to bridge the scale gap over Chicago. The PALM-4U (Parallelised Large-Eddy Simulation Model for Urban Applications; Banzhaf et al., 2018) model is being evaluated for scaling a microscale model to the city level within the Urban Climate Under Change project (Scherer et al., 2019).

While substantial progress has been made in modeling dynamical processes related to cities at microscale, mesoscale, and global scales, the treatment of chemical processes across scales is poor. Current chemistry models at microscales do not include higher-order chemical closure terms and the mixing from microscale to regional scales. At city scales, the detailed urban physics for dynamic processes is not currently coupled with chemistry. At global scales, atmospheric composition and emission records for many global cities are either unavailable or poorly known (Kumar et al., 2018), making the assessment of emissions in cities on global air quality and climate difficult.

4. Strategies for Urban-Resolving Models Across Scales

Here we articulate a few critical issues for urban-resolving models across scales and provide strategies to overcome them.

1. *Effects of urban systems on climate at different scales*: Establishing the effect of cities on climate at footprints beyond the city scale is the subject of ongoing research. Evidence of city-scale effects on regional climate includes changes in precipitation patterns, convection, temperatures, and air quality/pollution. However, there is a need for well-designed field observational campaigns to collect data sets for model evaluations and test prevailing hypotheses. Representing all scales of possible urban interactions in climate models will remain a challenge even if a need is established due to computational resource constraints. One strategy could be to represent the direct effects (e.g., urban expansion) of cities accurately at the microscale and mesoscale while representing indirect effects (e.g., biodiversity impacts of resources consumed within the city as well as the impacts of pollution released from cities) at global scales (Seto et al., 2012).
2. *What happens as models move toward a higher resolution?* As climate model resolutions increase, improved representation of urban phenomena in the models can be expected. For example, aerosol and gas phase pollutant emissions in coarser-resolution global models (e.g., $1° \times 1°$) are averaged across the model grid size and as a result cannot represent the nonlinearity in atmospheric chemistry and particle production. By increasing horizontal resolution, models can better capture the heterogeneity of emissions and non-linear chemistry due to higher concentration gradients. Development of scale aware parameterizations for urban scale atmospheric physics and dynamics will implicitly improve chemistry processes, especially related to chemical kinetics, emissions, transport, and deposition (Kumar et al., 2020).
3. *What is important for representing cities in climate models—resolution, complexity, or ensembles?* Climate model development optimizes the computational resources between increasing resolution, increased complexity of the climate models, and the need for longer-duration simulations and performing ensembles (Deser et al., 2020). Decisions regarding the right balance among these factors should be made based on the science questions and end-user needs (Ando et al., 2019; Wuebbles, Sharma, et al., 2020). The idea of purpose-built models advocated by the World Meteorological Organization (WMO) (Baklanov et al., 2018) is an avenue for model development branches that are targeted for city-scale issues that balance computational resources and stakeholder and decision maker needs.
4. *How to develop scale-resolving urban land cover and urban processes within the climate models?* Scale-resolving urban models would have to bridge microscale, regional and global scales that span a range of 5 orders of magnitude. It is not feasible to achieve this in a single model (Conry et al., 2015). We need to identify processes that are strongly non-linear and influenced greatly by urban phenomena and develop process representations that preserve this non-linearity within urban subgrid parameterizations of the climate models. For example, using improved mapping and probability density function (PDF) of urban land cover classification and building heights to represent subgrid-scale heterogeneity may be a way to incorporate the correct mosaic of land cover characteristics at varying scales. For example, subgrid urban parameterizations that can "*cook first then mix*" to the regional atmosphere should be implemented at the scales at which emissions are available, that is, at a resolution of a few km. We should consider creating a catalog of high-resolution case studies (say, 1 km or higher) over a wide variety of realistic/extreme conditions (meteorological and surface) to create a data set to test these parameterizations

and possibly use artificial intelligence to train on-the-fly parameterizations based on embedded super-parameterizations/high-resolution models.

5. *On future evolution of urban landscapes*: To understand the effects of cities at different scales, we need an improved understanding of the urban footprint that includes understanding the control volume (extent) of cities and land cover heterogeneity within the cities (Sharma et al., 2020). The conversion of rural/natural land to urban is a signal of increasing anthropogenic forcing on the climate system. Representing fast evolving cities is becoming more critical, especially as global climate models move from questions of global average change to regional and local changes. In addition, the recent innovations in communications, transportation, and infrastructure systems have led to the emergence of distributed large mega-city complex with some of these cities ~150 km apart with agriculture in between. With time, the mega-city complexes will be critical in shaping the integrated research directions and designing numerical modeling approaches for regional sustainability.
6. *Observations*: Observations are critical as we plan for the next generation of urban-resolving climate models for testing, evaluation, and validation across scales. Well-designed field observational data collection efforts targeted at understanding city-scale dynamical (temperature, clouds, and precipitation), biogeochemistry, land-atmosphere coupling, surface hydrology, atmospheric chemistry, and aerosols over an extended period of time and similar in scope to the Atmospheric Radiation Measurement (ARM) field observatories (Mather & Voyles, 2013) is required. There is also a plethora of observational data sets with technological advances and using cheap sensors for meteorological and air quality data at neighborhood scales from cities (e.g., Chicago's Array of Things; Catlett et al., 2017). However, concrete efforts for calibrating and evaluating the data quality of these measurements is lacking. Such efforts are needed for use of this observational data in model development and evaluation. Satellite platform collected data sets are increasing in spatial resolution and can be used for resolving urban scale phenomena, particularly for air quality/atmospheric chemistry applications (Lin et al., 2015). These along with new dedicated field campaigns and use of machine learning techniques can develop empirical relationships at microscales and evaluate at regional and global scales.

5. Next Steps

The overarching objective of this commentary is to motivate and "*set the stage*" for much needed urban-resolving integrated climate research. Toward this end, we propose the following recommendations and key directions as next steps.

1. Indeed, this proposed research direction will take time to conceive and achieve. This will require an ongoing commitment and perhaps an international forum under the WMO or International Association for Urban Climate for maintaining a dialog across the science communities for increased interactions between those who work on urban issues across scales, from local to global, including the modeling of the processes relevant across these scales.
2. The benefits of higher spatial resolution in models are necessary for capturing non-linear urban processes and advancing knowledge. We need to push the boundaries of enhancing spatial resolution using adaptive meshes and more powerful computers, integrating remote-sensing (satellite) observations, and investing in machine learning to complement high-resolution modeling across urban scales. Data assimilation capabilities could be used to improve urban climate models across spatiotemporal scales.
3. In efforts to improve numerical models across scales, the confluence of urban drivers of change, that is, economic activity, population dynamics/growth, and energy infrastructure and associated critical systems (transportation, water treatment, etc.) that underpin urban systems also need to be considered. Understanding current and future drivers of change in cities requires increasing interactions between scientists, stakeholders, and policymakers. Cities throughout the world need scientific guidance to steer the infrastructure investments rather than just reacting to the changes in severe weather after disasters occur. This will reduce adverse impacts, risks, and vulnerabilities and provide positive viable outcomes with reduced stress on social, natural, and engineered urban subsystems.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

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