REPORT

WORKSHOP ON URBAN SCALE PROCESSES

AND THEIR REPRESENTATION IN HIGH SPATIAL RESOLUTION EARTH SYSTEM MODELS

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Executive Summary

It is essential that numerical models used to study physics, chemistry, and biology affecting the Earth system at regional and global scales represent the effects of urban areas on climate and the effects of changing the climate on urban areas. At the same time, it is essential to develop state of the art, simple and accurate urban models to better understand the relevant processes and also to address issues related to urban security against the spectra of chemical, biological and radiological (CBR) hazards. Towards bringing these communities together, a 2.5-day international workshop was held at Argonne National Laboratory (ANL) in the Chicago area on May 22-24, 2019. This workshop brought together national and international experts to develop a roadmap for a better understanding of the issues associated with urban areas and at enhancing the capabilities of regional and global Earth System models (ESMs) in representing the atmospheric dynamics and chemistry, unique aspects of the biosphere and land use, and human dimensions of the urban environment. This workshop was especially important to those developing very high-resolution versions of regional and global models. The workshop also discussed existing datasets, including in situ and satellite observations, and the emerging smart city sensing technologies and their possible use in model development (e.g., the NSF-funded Array of Things network currently operating in Chicago and expanding to other cities).

The bullets below summarize many of the key findings from the workshop:

The Urban Footprint

- It is apparent that cities can influence the environment with a much larger footprint than its physical domain. Cities and the extended urban landscape influence weather and climate at local and regional scales, with a direct impact footprint that extends at least two to three times the actual urban spatial extent.
- Urbanization is causing significant, and detectable, changes in regional climate through temperature and rainfall modification.
- Another aspect of this issue is that many cities are growing. Increasing urbanization is causing significant, and detectable, changes in regional climate through temperature and rainfall modification. In essence, urbanization and the growth of cities are completely re-arranging the global flows of resources and energy, localizing and concentrating use and consumption in a small part of the Earth’s surface.
- Cities are not forests, buildings are not trees – cities have anthropogenic emissions, energy fluxes, mobility, impacted differently by extremes, and have different approaches for resiliency and human management – as a result, the footprint is much larger than the city itself.
- A further consideration is needed in how land surface models consider the urban environment.
- While it should be apparent that cities can influence the environment with a much larger footprint than its physical domain and the effects from cities locally and regionally are clear, it is not so clear as to whether these effects are significant enough to affect the climate at global scales.
The Hierarchy of Models

- A hierarchy of models going from a detailed representation of urban areas to global scales are needed to examine the effects of cities on our environment. The finer-scale models can be effective in testing and providing parameterizations for the mesoscale and global models.
- There are already notable successes in modeling the urban atmosphere on a hierarchy of scales, and there are challenges in making improvements within and between those scales. Maintaining and improving each element of the hierarchy will be essential.
- Metrics for evaluating models of all scales need to consider the ability to represent the impacts of extremes.
- Existing ESMs, which are especially used to understand global changes in climate, can already represent some aspects of urban processes, e.g., tiles in the NOAA GFDL model for urban canyons and types of roofs. The urban canopy affects internal building temperature, wall/roof heat, heat fluxes, and water fluxes. High atmospheric resolution is required to achieve precipitation accuracy and better representation of land processes.
- Significant progress has been made in developing and implementing Urban Canopy Models (UCMs) in global ESMs. The common practice is to embed a single-layer urban canopy model (SLUCM) in the lowest model level of ESMs and to provide surface fluxes of momentum, sensible, and latent heat as the lower boundary conditions to the planetary boundary layer (models, which comprises the urban canopy layer (UCL) and part of the roughness sublayer).
- The urban canopy parameterization has problems representing areas of very tall buildings as seen in the core of cities. They typically do not extend outside the lowest layer of the atmosphere. The parameter values are not well defined for all cities globally and the models may not be valid in extreme weather conditions. The heterogeneity of cities is also not well captured. Upscaling the urban effects through the planetary boundary layer is key to capturing the regional coupling but is poorly observed and modeled. Despite these limitations, they have been able to capture the basic properties of the urban heat island.
- It should be possible to build better parameterizations of urban areas in climate models using models that solve the fundamental fluid dynamics equations in an urban domain: CFD or microscale models. The lack of validating data is a large obstacle to progress in using CFD models for the urban atmosphere.
- ESMs often treat cities as comprising a relatively small footprint, represented by areas of a scale of 2-5 km on a side (4-25 km²). However, the aggregate footprint of an urban area, in terms of energy and water fluxes, is likely more in the range of an area of 25-50 km or more on a side (600-2500 km²), and some studies have suggested as large as 100 km on a side, or 10,000 km² or more.
- For studies focused on the global climate, an explicit urban representation in an ESM may not be required to capture the effects of emissions and surface changes.
- What isn’t clear is how big does a city or urban area has to be to make a difference in regional or global modeling. Do smaller cities and infrastructure like roads also make a difference – studies are needed to evaluate this.
- Because of their coarse spatial resolution and inadequacies in considering urban processes, policymakers should be warned that current ESMs should not be used directly for policy considerations at scales approaching that of the urban areas.
**Observations and Sensing Technologies**

- Emerging smart city sensing technologies offer a unique opportunity for use in model evaluation and development.
- There is an increase in the availability of data related to processes in urban centers, with the potential to deepen our understanding of urban-climate interactions. Some of this data is fueled by many projects collectively termed “smart cities.” Applying analytics and optimization methods to this Big Data helps cities plan, manage, make better decisions, and strategize how to adapt to and mitigate climate change.
- Data sources related to urban areas have rapidly increased in recent years with multiple technological advances. For instance, air quality data from regulatory measurement infrastructure (e.g., EPA sites) has traditionally provided regional-scale data, typically at temporal resolutions of 30-60 minutes. Experimental infrastructure such as Chicago’s Array of Things (AoT) project provides air quality at a neighborhood scale at 30-second temporal resolution. Similarly, networks such as Weather Underground provide neighborhood-scale meteorological measurements. As with AoT, these new sources currently lack the precision and accuracy of regulatory measurements, but this is rapidly changing as a result of both improved sensor technologies and advances in modeling algorithms, including the use of multiple data sources.
- Data from remote sensing devices (satellite-borne) is also increasing in both temporal and spatial resolution as well as quality.
- With the nearly universal use of mobile devices, cellular phone carriers and, increasingly, mobile phone hardware and application companies have collected detailed data about human movement, from which these companies (and their partners) are about to build sophisticated models forecasting traffic patterns not only on roadways but for individual points of interest and businesses. Such data can provide additional factors in modeling urban emissions from both vehicle traffic and buildings.
- With the continuous influx of new types of data, thanks to cheap, lightweight sensors, GPS, social networks, wireless communications, and the like, the ability to effectively organize and analyze information is becoming increasingly challenging. Consequently, cities, and scientists plumbing data for properties and impacts, require new methods of collecting, synthesizing, filtering, and processing data from many independent sources, as well as tools for data analytics, visualization, and integrating with computational models.

**Next Steps**

- All attendees agreed that one of the biggest outcomes from this workshop was that it demonstrated the need for increased interactions between those that work on urban issues across the scales from local to global, including the modeling of the processes relevant across these scales in the study of climate change.
- It was suggested that we need an ongoing committee and perhaps an international forum for maintaining a dialogue about these interactions across the science communities that were represented at this workshop.
- It was suggested that we aim at bringing these groups together on a regular basis for workshops, at a frequency of at least every 3 years.
1. Introduction
Cities and their associated urban areas have a much larger impact on the environment than their spatial footprint on the Earth’s surface. This is certainly true at local and regional scales, but also likely true at global scales as well (but this still needs to be established). At this time, more than half of the world’s population lives in urban areas (80% in the United States), and the global proportion is projected to climb to 70% by 2050 (Heilig 2012). Therefore, it is essential that numerical models used to study physics, chemistry, and biology affecting the Earth system at regional and global scales represent the effects of urban areas on climate and the effects of changing the climate on urban areas. At the same time, it is essential to develop state of the art, simple and accurate urban models to better understand the relevant processes and also to address issues related to urban security against the spectra of chemical, biological and radiological (CBR) hazards. However, the communities of scientists studying these different scales seldom interact with each other (Sharma et al. 2018b, 2017b; Silva et al. 2018).

Towards bringing these communities together, a 2.5-day international workshop was held at Argonne National Laboratory (ANL) in the Chicago area on May 22-24, 2019. This workshop brought together national and international experts to develop a roadmap for a better understanding of the issues associated with urban areas and at enhancing the capabilities of regional and global Earth System models (ESMs) in representing the atmospheric dynamics and chemistry, unique aspects of the biosphere and landuse, and human dimensions of the urban environment. This workshop was especially important to those developing very high-resolution versions of regional and global models. The workshop also discussed existing datasets, including in situ and satellite observations, and the emerging smart city sensing technologies and their possible use in model development (e.g., NSF-funded Array of Things network in Chicago). This workshop was jointly supported by the U.S. Department of Energy (DOE), U.S. Department of Defense (Army) (DOD), the National Oceanic and Atmospheric Administration (NOAA), and the National Aeronautics and Space Administration (NASA).

Although the total urbanized surface over the globe is relatively small (Schneider et al. 2009), considering urban centers house a majority of the world’s population, the interaction between local climate and urban landscapes have the ability to impact the health and wellbeing of a large number of communities. For example, although the municipality of Chicago comprises 2.8M people in a 600 square km area, it sits within an area extending to 6,000 square km with some 10M inhabitants in nearly 300 smaller cities, towns, and villages. Urban landscapes can have significant impacts on the environment through modifications to albedo, surface roughness, gas and aerosol concentrations, runoff, energy flows, and many other ways (Kristovich et al. 2019). As a result, urban centers and the extended urban landscape influence weather and climate at local and regional scales, with a direct impact footprint that extends at least two to three times the actual urban spatial extent. Urban areas have unique landscape characteristics including unique land cover features, built infrastructure for commercial, housing and transportation, high-density energy and water consumption. These characteristics determine urban-land-surface properties and give rise to unique urban microclimates. Thus, representing these urban microclimates in climate models is not only important to improve simulations over urban landscapes but is also necessary to improve the climate projections over regions surrounding the urban area (Conry et al. 2014, 2015).
A previous workshop on the influences of urban environments on climate, with an emphasis on how large observational studies can be used to aid the modeling community was held on August 27-28, 2013 at Argonne National Laboratory (ANL) (Drewniak et al. 2014). For that workshop, the goal was to identify urban processes important in influencing the predictive capability of regional climate models and global earth system models, the impacts of climate change that are important for future urban centers, data available or needed to develop a representative model of urban ecosystems, and how can cities use that information to improve the lives of their citizens. This workshop was aimed at building on the lessons learned from the prior workshop while taking advantage of the progress made over the past six years in both the observational capabilities, high-resolution urban scale models, and the improved spatial resolution and regional refinement in regional and global models.

A review of literature in the AMS centennial monograph on the urban boundary layer dynamics by Kristovich et al. (2019) and including the conclusions from the 2013 ANL workshop (Drewniak et al. 2014), as well as discussions with other scientists, led to identifying the following key issues and questions for discussion at this workshop. These identified issues are crucial to furthering understanding and representation in regional and global models related to treating the urban environments:

(i) There is a considerable gap in the current available urban scale modeling capabilities and the requirements for a set of reduced parameterization/subgrid models necessary for representing urban processes in regional and global models. How should we prioritize the urban processes that should be represented in regional and global models?

(ii) While there is considerable interest and activity in building urban scale models from the first principle-based computational fluid dynamic models (CFD models), these models currently lack many of the atmospheric physical process representation to capture the atmospheric dynamics. What can we do to expand these surrogate models to more accurately capture urban systems?

(iii) There is no set of standard/accepted urban scale datasets that could be used to evaluate the high-end CFD models for acceptable performance in producing urban microclimates. How do we build upon current urban research activities to collect and archive data for model validation? Are there non-traditional data sources that can also be used to build this dataset? Can we create an observational data testbed that can be used to test models?

(iv) There is a need for a hierarchy of models than span the time and spatial scales for representing urban microclimates. The CFD scale models will be expensive for performing simulations over climate time scales as standalone models or as a submodel to an ESM and the regional scale models (WRF-Urban) are not fully evaluated. How can we couple the different types of urban models, for example, (Conry et al. 2015), to establish a robust, yet computationally efficient model of urban climate? How can future exascale computational platforms be leveraged?

(v) The urban environment is extremely heterogeneous, but modeling representation of cities across the world fail to capture this heterogeneity due to the lack of availability of ultra-high-resolution land use datasets. One exception is that cities in the United States have available a 30-m resolution National Land Cover Database (NLCD) set of data, with ~45 cities included in the even more powerful National Urban Database and Access Portal Tool (NUDAPT; (Ching et al. 2009)) resource. There is thus a need to actively pursue developing these databases on a global scale. How do we collect and analyze large urban
datasets and use that data to inform models? How can we use generalizations, yet still account for the uniqueness of each urban center?

(vi) Generally, observational sites and sensors in cities are poorly placed and likely are non-representative of their neighborhoods. The development of dense cheap sensor networks provides an opportunity to bridge this gap (Catlett et al. 2017). However, using these datasets for evaluating models or process-scale model development will be a challenge due to data quality and consistency issues. Is there a pathway for using these datasets for rigorous scientific model evaluation and model development? Does the concept of Integrated Field Laboratory bridge the gap between the cheap/dense networked datasets and research quality data needs?

These topics and issues provided the foundation for the discussions at the workshop. At the same time, developing a pathway to attacking and solving these issues was a key goal of the workshop. Participants agreed that we have affected our landscape greatly and cities are a major factor in that change in the landscape. However, there is no clear definition of urban. The impact of urban on the climate system is not clear. Extremes in weather/fire have the public’s attention. However, urban climate extremes are many times missed as the focus is on the weather. Modeling extremes is difficult for urban areas due to poorly resolved coupling between urban surfaces and the atmosphere.

This workshop focused on climate scales. The participants focused on not just model scales, but also the scale of the problems associated with it — for example, what are global, regional, and local problems? The representation of the urban footprint in the models was one critical component. Cities are much larger than their downtown footprint, i.e., not 2-5 km but more like 25-50 km. ESMs have resolutions of ~0.5-1 degrees (50-100 km), so a city can be a sizeable fraction of a grid box. Many questions on urban scales were raised. A few key questions were: Do we just focus on the really big cities? What about the smaller cities and roads, etc.? Do that make the effective footprint even larger? What is the extent of a city that should be considered going into the ESM? Other topics discussed were related to transfer of albedo, heat, momentum, water, aerosols are all important in going from local to regional/mesoscale to global-scale modeling, urban weather and urban hydrology.

On the health, energy, water, food nexus, participants discussed that impact models (health, energy) need info from urban ESM models. Urban modeling needs to not just include physical effect on climate, but on energy and water infrastructure. Questions related to how do urban effects on climate influence energy systems (grid, energy demand) were raised. Participants also discussed issues related to the accuracy in models and what have we learned from the prior workshops hosted by our group and others.
2. Workshop Agenda and Summary
This section summarizes the presentations, panel discussions and breakouts held at the workshop. The agenda itself is provided in Appendix A.

DAY 1

2.1 Presentation: Urban treatment in ESMs: Current capabilities and gaps (Elena Shevliakova)
Earth System Models (ESMs) are complex and computationally expensive. They have been built to understand the Earth’s climate and how and why it is changing. Taking ESMs to higher resolution is important. So is the consideration of atmospheric chemistry, biogeochemistry, and the biosphere, but all of these add significant computation expense to the models. In contrast, the treatment of land processes is relatively cheap. Shevliakova stressed that urban areas only account for 0.4-0.9% of the global land. This only considers city centers and not the complete urban environment, which would be much larger. But urban areas have most of the global population and account for a large fraction of the carbon emissions.

Shevliakova brought the question related to the importance of enhanced representation of urban in ESMs? It depends on the question being asked. In terms of pure biophysical aspects at the global scale, the area of cities is too small to make a difference, and the GHG emissions are already included. But this does not consider all aspects of urban effects on a regional scale. These effects could include factors like urban heat fluxes, effects of the urban region on storms and precipitation, and climate feedbacks on the urban region.

Climate change is projected to increase risks for people’s assets, economies, and ecosystems in urban areas. Heat waves, sea-level rise, weather extremes, rainfall, and landslides are climate-related impacts that can produce significant impacts on populations in cities. Urban greening can contribute to mitigation.

ESMs can already represent some aspects of urban processes, e.g., tiles in the GFDL model for urban canyons and types of roofs. The urban canopy affects internal building temperature, wall/roof heat, heat fluxes, and water fluxes. GFDL urban research shows that accurate treatment of precipitation is required. High atmospheric resolution is required to achieve precipitation accuracy and better representation of land processes.

Finally, Shevliakova discussed the need for a hierarchy of models to fully address all of the issues associated with understanding urban-climate interactions.

2.2 Presentation: Current capabilities and gaps in Urban modeling (Fei Chen)
Today’s changing climate poses two formidable challenges: 1) the projected climate change by the IPCC will lead to more frequent occurrences of heat waves, severe weather, and floods, and 2) the current trend of population increase and urban expansion is expected to continue. The combined effect of global climate change and rapid urban growth, accompanied by economic and industrial development, will inevitably make people living in cities are more vulnerable to a number of urban environmental risks. Integrated cross-scale atmosphere-urban modeling including urban
turbulence processes, energy, air pollution, hydrology, ecosystem, human behavior is a valuable tool for society to address these urban environmental issues.

Chen highlighted that significant progress has been made in the past decade in developing and implementing Urban Canopy Models (UCMs) in global ESMs. The common practice is to embed a single-layer urban canopy model (SLUCM) in the lowest model level of ESMs and to provide surface fluxes of momentum, sensible, and latent heat as the lower boundary conditions to the planetary boundary layer (PBL) models, which comprises the urban canopy layer (UCL) and part of the roughness sublayer (RSL). This type of traditional flux coupling approach works in general for modeling rural surfaces (i.e., with relatively low surface roughness elements), it may not be valid for modeling urban surfaces where tall buildings may protrude into hundreds of meters above the ground. One outstanding question is whether this flux coupling strategy is able to represent the effectiveness of the impact of urban processes on the evolution of PBL structures in ESMs.

Chen also discussed that additional challenges will need to addresses modeling urban effects in ESMs. For instance, representing highly heterogeneous urban surfaces requires high-resolution building morphology and properties (e.g., building thermal conductivity) which are generally city-specific and difficult to obtain at a global scale. The WUDAPT initiative is a significant step forward but the scale dependence issue of urban data sets will likely remain a major challenge. It is equally important to correctly represent the urban human dimension. For instance, the air-conditioning use schedule and coverage is highly variable in downtown and suburban areas, implying a dominant uncertainty in capturing the anthropogenic heat critical for the formation of urban heat islands, due to lack of data for modeling human behavior at model-relevant scales (~1 km). With increased model resolution, our ability to effectively observe and model 3-D near-surface and planetary boundary layer (PBL) turbulence at multiple scales under mean and extreme conditions in complex urban areas is very limited. One issue raised is that current urban modeling systems may work well in normal situations, but there is a need to investigate the ability to apply them to extreme weather and climate conditions.

2.3 Panel Discussion: Federal agency and international perspectives
Panel: Corinne Hartin (DOE), Robb Randall (DOD), Ken Jucks (NASA), Jin Huang (NOAA), Alexander Baklanov (WMO), Don Wuebbles (discussant)

DOE
DOE/BER is focused on enhancing the predictability of the Earth system, including modeling its various components at finer and finer spatial scales that were not previously possible. Particularly in the past few years, DOE is now pushing the boundaries of enhanced spatial resolution using, e.g., adaptive meshes and more powerful computers, allowing researchers to explore the fine details of coastal and estuary processes and dynamics within E3SM. DOE is also investing in machine learning as a complement to high-resolution modeling, that currently emphasizes watershed systems. Given that DOE’s models are approaching resolutions able to represent details across urban canopies, we anticipate that modeling studies of urban regions will become increasingly important to future efforts to enhance the predictability of the Earth system. We also expect future urban investments to leverage observational data and possibly also machine learning. DOE’s user facilities are not currently involved in urban research.
NOAA
Global and regional scale and organized specific effort on this. Improving representation is still very useful, the global model is important – a large scale model is needed. GCMs can’t be used at all scales. The effects of the urban scale in the global models are not yet fully represented nor are its impacts fully understood. There is no current focus on specific urban strategies or nested modeling capabilities but in future NOAA would like to focus on these urban ESM systems. NOAA conducts observations on various platforms. It performs Hysplit modeling. We conducted a PBL workshop. NOAA has data assimilation capabilities. NOAA is interested in coastal inundation/water resources – urban flooding/climate process teams (observations, modeling teams and process representations in the model). NOAA is also interested in the prognostic approach – why models are successful from the process level. One of the specific programs for urban atmospheric chemistry research observation is within RISA.

DOD
This workshop is very important for the DOD mission. We are not able to prioritize, including biological and chemical weapons, vehicles and soldiers, climatologically unless we can account for and plan for changes in cities and their interactions with climate. We would like to focus on energy power/power generation in our systems, autonomous bots – we have to model and the human side needs consideration. We are interested in microscale urban processes as it affects military operations and troop movements. For example, we are interested in urban databases and complex terrain affects such as sea breeze.

WMO
For WMO one of the goals is urban sustainable development. It is much more important for seamless earth system prediction. At the same time, land-use changes are important. WMO crosscuts many urban focus areas with different aspects and scales. For example, urban climate, air quality, megacities and science needs; urban hazards; global climate change effects on megacities. All these aspects require a seamless approach for guidance for integrated urban weather, environment and climate services. Another interesting aspect is the urgent need to understand the interactions and the effects of the urban boundary layer and hydrological implications. We need seamless prediction capability across tempo-spatial scales, understanding of processes, earth system components, types of observations and data assimilation for user-oriented impact based urban forecast.

NASA
We are interested in capturing temporal and spatial resolutions of urban climate datasets from satellite observations. We do fund many projects on urban scales.

2.4 Breakout groups 1-3

Group 1 – Challenges for ESMs for Modeling Urban Systems (Lead: Kate Calvin)
Address: Enhancing the capabilities of global Earth System models (ESMs) in representing the atmospheric dynamics and chemistry, unique aspects of the biosphere and landuse, and human dimensions in the urban environment. Why is urban representation important? What is known?
What is important to represent in EMSs—what is included and what is not included? How does this picture change as ESMs go to a higher resolution?

This breakout group discussion focused on three key questions: (1) why is urban representation in an ESM important and what is important to represent? (2) what is known, unknown, and partially known? and (3) what happens as models move towards a higher resolution?

**Why is urban representation in an ESM important?**

The discussion initially centered around whether or not urban systems need to be represented in a fully coupled ESM or whether ESMs should be linked to meso- and micro-scale models instead. To answer this, participants thought it was important to identify the goal of the ESM modeling exercise and the intended science question. Are we interested in better estimations of global climate, quantifying the impacts on human systems, or estimating the potential reduction in climate change?

For studies focused on the global climate, urban is a source of emissions and a source of surface change. However, while emissions from urban systems are clearly large, an explicit urban representation in an ESM may not be required to capture these effects. The emissions used in the CMIP simulations capture urban sources. For surface changes, there was a debate among participants as to whether the surface change was large or small.

For studies focused on impacts on human systems, it was noted a large fraction of the population lives in cities and want to understand future climate change where they live. ESMs without an explicit urban representation may not accurately capture exposure to heatwaves. However, the CMIP6 effort to collect climate-related variables at the sub-grid level may help, as several ESMs have an urban tile and will capture differences in temperature between urban and non-urban land types.

For studies estimating the potential reduction in climate change, explicit representations of urban systems may be required. For example, if one was interested in quantifying the effects of 50% more efficient buildings or a transition to white roofs on the local climate, then an urban system representation would be required in the ESM.

Several participants raised the question: do different goals mean different models, different configurations of the same model, or more complex models? Does focusing model development on better representing global climate lead to a fundamentally different ESM than focusing development on impacts? And, what do users expect when they use ESM results?

**What is known, unknown, and partially known?**

There is a large literature examining the effect of aerosol emissions on climate, the biophysical effects of land use and land cover change on climate, the effects of building morphology on radiation, and the effect of urban heat islands on local temperatures. In addition, the importance of scale in modeling urban systems is well established. What is less well known is the effects of urban on climate at different scales, the magnitude, and linearity of feedbacks, biogeochemical feedbacks, and the future evolution of urban landscapes. For the effects of urban on climate at different scales, one challenge is to disentangle the signal from noise. The unknowns contribute to
the debate as to whether representing urban systems in an ESM is a pre-requisite for accurately representing climate. Do we need to represent urban to get global climate right? And what does it mean to represent urban?

*What happens as models move towards a higher resolution?*

Higher resolution does not only apply to horizontal resolution, but also vertical and process resolution. Whether urban matters and what needs to be represented changes with model resolution. Some benefits of higher resolution will just happen. For example, aerosol and pollutant emissions in coarser-resolution models (e.g., 1° x 1°) are smeared across large spaces. By increasing horizontal resolution, ESMs can better capture the point-source nature of these emissions. Other benefits of increased resolution require work. For example, as ESMs move to finer spatial scale, new physics and dynamics are required.

The question of ensemble size was raised in the discussion about high resolution. Should computing resources be devoted to larger ensembles or higher resolution? Can variable resolution help achieve both?

*Other items of discussion*

Finally, several important points were raised throughout the discussion. First, urban means different things to different people. We need to clearly define what we mean by urban and urban representations. Second, we need a list of research questions to address in order to determine the required urban representation. These questions may differ by agency. Third, we need more cross-community interaction, including ESMs, IAMs, urban modelers, urban planners, etc. Lastly, we need to provide more guidance on the use of ESM outputs. For example, grid cell average temperatures in a 100 km model may not be representative of temperatures in cities.

*Group 2 – Modeling of urban processes and their treatment in ESMs (Lead: Ashish Sharma)*

Address: the considerable gaps in the current available urban scale modeling capabilities and the requirements for a set of reduced parameterization/subgrid models necessary for representing urban processes in ESMs. How should we prioritize the urban processes that should be represented in ESMs?

Moderator Ashish Sharma initiated the group discussion by highlighting that the urban systems are a multiscale, interdependent, social, natural and engineered complex system. Therefore, we need to bridge urban scales at city-scales, local-scales, micro-scales. The tools for this have to be both complex and simple based on the need (Kristovich et al. 2019; Sharma et al. 2018a). This initiated a robust discussion on the following topics in group 2.

*Understanding the control volume of the city:* As modelers, we fail to define the control volume (extent) of the city. The commonly available land cover data is many times not a real representation of the extent and urbanization of a city. Moreover, with respect to modeling, all urban processes are embedded in the first layer — a big problem! It is not ideal to consider urban areas and inhabitants as a very small component of the numerical representation. A poor understanding of urban processes within one layer of the atmospheric model is a primary reason for significant errors in capturing the planetary boundary layer heights for urban areas. Atmospheric boundary
layer receives all the urban information via surface layer fluxes, but contributions related to blending height over urban areas are not captured well.

**Climate shocks and extremes over urban areas:** In addition to poor representation, climate shocks over urban areas add another layer of errors. Therefore, the ESM community needs to challenge current urban and non-urban parameterizations of physical processes under extreme weather cases; particularly BL parameterizations under hyper convective, or extra-neutral conditions for a range of geographical locations. For example, under extreme heat conditions mixing in the BL is underestimated, leading to the miss-representation of super-adibatic lapses typical of these conditions. The group agreed that we could overcome this challenge with inter-comparison modeling and observational studies for surface energy balance and signals for the initiation of large-scale convective processes and associated parameterizations. Also, there is a need for detailed experimental designs to evaluate and improve PBL schemes to understand the up-scale effect of these convective urban signals.

For temperature extremes, we understand the basic physics of the surface layer and BL. But, we miss a sinking signal in a very strong heatwave interacting with urban areas. For precipitation, we lack in our understanding of how extreme synoptic events interact with urban areas. At times, we miss location and intensity entirely. Similarly, the physical mechanisms for splitting the storms over the urban areas are not well understood. Even with very high-resolution building representation (e.g., NUDAPT; (Ching et al. 2009) and WUDAPT; (Ching et al. 2018) in the climate models and high roughness length, urban models still fail to reproduce storm splitting.

**Cloud-aerosol interaction with urban environments:** The group discusses that cloud-aerosol interaction with urban environments needs further exploration with an emphasis on aerosol transport, cloud formation, and impacts on surface energy balance. Addressing this issue will also allow us to understand how the global climate is manifested when it interacts with urban environments.

Water vapor transport in urban areas: Since most of the human settlement is close to a large water body or coastal areas, water vapor transport still needs significant representation. The contributions of latent heat flux from vegetation, anthropogenic heat, and surrounding ecosystems, and large water bodies still unknown. Again, new learning could be done via field studies, and modeling experiments for case studies, and new parameterizations for missing elements.

**Scale-dependent parameterizations:** The group identified that there is no scale-dependent parameterization for urban climate models. This is important as we move from micro- to meso- to global-scales as the effect of roughness elements in the urban canopy is muted!!! Therefore, there is an urgent need to design new ways to scale-up from one resolution to another. This is not a trivial problem as there are many factors that define what type of parameterization do we have to modify/design depends on the research questions. One solution that the group identified could be to use the probability distribution of buildings in an urban grid for sub-grid processes. Such a sub-grid model can resolve buildings (similar to cloud models) and provide feedback in the form of scale-aware parameterization for the mesoscale model and more importantly for ESMs.
**Observations:** The group identified that there is an urgent need for comprehensive new strategies for designing observational studies to close gaps in our understanding of urban processes at different scales, particularly those related to latent heat fluxes and thermal storage. Thermal storage is unknown in most cases and a source of uncertainty. This is particularly true in megacities with large under-ground infrastructure. The group agreed that new satellite observations (GOES-R/Hyperspectral) could aid in improving knowledge of this variable.

**Urban heterogeneity:** Urban Heterogeneity is the enemy for many above problems. Realistically, urban heterogeneity is the driver in the urban systems. This is a possible reason for localized convection/updraft at subgrid scales that can split the storm and thus the urban model does not capture it accurately. Urban heterogeneity also leads to intense strong anthropogenic heat and pollutant emissions from point source locations that intensify the urban climate. Buildings also significantly contribute to urban heterogeneity as they are complex in nature (Sharma et al. 2017a). The modelers are divided into identifying what variables to capture at mesoscales — the mean height, or deviation of height or something else. Many times, few tall and high energy-consuming buildings can contribute substantially to the boundary layer. But the model fails to capture such sources of heat as the mean statistics within the model grid box generally mute such effects! Similarly, small residential buildings and small cities are not well represented — a combined contribution is not worth neglecting in climate models. In general, NUDAPT/WUDAPT datasets can help with heterogeneity, but there is a need for new parameterizations.

**Human permitting modeling:** The group was discussed that there is an urgent need to integrate human behavior as a two-way interaction going forward. This is important as anthropogenic heat (AH), emissions, electricity, vehicles, movement of traffic can easily lead to 2-3 deg C changes in temperatures. Therefore, we need to carefully think about the indirect effects of AH activity in cities in GHGs and how public policies will impact energy supplies/demands, and how can we modelers represent them in ESMs at all spatial scales. For example, scenarios for decarbonization of cities will likely impact surface energy balance and GHG flows (i.e. all building w/solar panels), or off-stream power generation (i.e. mega solar farms).

**Other thoughts:** The group also discussed many other key processes that propagate across scales. For example, ventilation is a microscale process that allows advection and pollutant transport. It is city specific and human behavior dependent process. CO2 and CH4 will get well mixed, but aerosols will not get well mixed and needs to be accounted across scales. Finally, the group discussed that computing is a big hurdle as technology and process-based physics development go hand in hand. It is possible that in the near future CPU and GPU combinations may help solve the scale integration problem for ESMs.

**Group 3 – First-principles modeling at urban scales (Lead: Rob Jacob)**

Address: In building urban scale models from the first principle-based fluid dynamic models (CFD models) these models currently lack many of the atmospheric physical process representation to capture the atmospheric dynamics. What can we do to expand these surrogate models to more accurately capture urban systems? Transport and diffusion processes in street canyons are poorly parametrized. How can we better predict the occurrence of different flow patterns (e.g., channeling, vortex flow) as a function of ambient wind conditions? How can slope (upslope and
downslope) flows in an urban environment improve our understanding of air quality, visibility, and biochemical hazards?

There were additional questions given to the group in our breakout: Need for first principle-based models for urban modeling and their implementation in ESMs: What is their role? What are the key challenges these models have to overcome to become useful for developing urban representation in ESMs? Would making these models sub-grid (offline or online) be an eventual use of these models in ESMs? What are the other scenarios of using these models for either building ESMs or supporting urban analysis in conjunction with ESMs?

Right away, everyone agreed that first principles modeling is a necessary part of modeling urban systems at all scales. We define “first principles models” as one that's are using nearly the full Navier-Stokes equations to simulate the fluid motion. They don’t make the approximations found in weather or climate models. They can be usefully separated into 3 categories with increasing fidelity to the N-S equations: RANS, LES and DNS. That is also their order of computational expense. These models have resolutions on the order of meters and can cover domains up to 2km. RANS approaches are already used routinely to model airflow around buildings in both research and commercial applications. There are also examples in the literature of RANS models being used to improve the urban parameterizations of mesoscale models and those parameterizations are used almost without modification in ESMs. RANS can do a good job of capturing the impact of buildings in near-neutral atmospheres. LES and DNS can do better since they do not fully parameterize turbulence but their expense means they can only be run for a few simulated days (LES) or hours (DNS).

The biggest challenge in making these models more useful is finding validation data. As we increase the model fidelity from RANS to LES to DNS, there are fewer datasets available for validation especially 3D time-varying data. We note that this situation was also recognized at the previous workshop and has not improved much. Using first-principles models for “footprint analysis” could help locate measurements. There are basic physical aspects of the urban atmosphere that need to be improved in first principles models including representing real urban morphologies where the buildings aren’t all the same height and wind isn’t along the canyon; representing thermal effects such as heat transfer at building surfaces, radiation trapping, and reflections; including time-varying boundary conditions; allowing non-neutral, buoyant and moist atmospheres. The developers of first-principles models need to know what ESM grid size to target since it bounds the needed fidelity. We settled on 2 resolutions on either side of the atmospheric convection “gray” zone: 25 km and 3 km.

Using these first-principles models with ESMs offline is possible and already in use. A hierarchy of models is needed to go from global to microscale and back. The basic street-canyon model that forms most ESM parameterizations is not applicable to most cities. Additional offline runs of first principle models can help address that. Using them online with ESMs is limited by the huge difference in simulation speed with LES and DNS taking hours to simulated a few minutes or hours of atmospheric motion. Using RANS models online with mesoscale models has been demonstrated. To make this more routine, we need to improve the forcing of microscale models with mesoscale output accounting for the jump in resolution, time-varying forcing, and different turbulence closures. One way to possibly introduce the benefits of LES and DNS directly into
ESMs would be through data-model fusion such as AI-derived parameterizations that are informed from LES and DNS simulations.

There are other scenarios for using first-principle urban models with ESMs. In analogy with the “super-parameterization” approach for clouds and convection, where a 2D non-hydrostatic model is run at each course model grid point and its results integrated with the coarse grid, a low-res RANS urban model could be run at each city. As ESM groups pursue very high-resolution global models (1-3 km horizontal resolution), they will approach the domain size and simulation speed of RANS-based urban models allowing them to be integrated together as one system.

2.5 Presentation: Is there a need for a hierarchy of urban models? (Alberto Martilli)

This presentation was aimed at looking at the models that are able to represent the interactions between a city and its atmosphere, including the ability to represent the impact of the atmosphere on the city’s citizens. Two scales interacting include the mesoscale of the urban boundary layer and the microscale of the urban canopy layer. The state of the science to represent interactions between a natural system (atmosphere) and a human system (city and citizens) is currently represented by two types of models:

**Microscale CFD models:** These typically have the spatial resolution on the order of a meter and domain of a few kilometers. Three approaches include direct numerical resolution where turbulence is fully resolved, the large eddy simulation approach where turbulence is partially resolved, and the Reynolds Average Navier Stokes (RANS) approach where turbulence is fully parameterized.

- What they can do well? — represent impacts of obstacles on flow and pollutant dispersion for a near-neutral atmosphere.
- What needs to be improved? — non-neutral situations and building energy balance. Time-varying boundary conditions
- What they cannot do today? — Represent full PBL (planetary boundary layer) and interactions with mesoscale circulations

**Mesoscale models:** Mesoscale models typically have a spatial resolution on the order of a km, a domain size of around 100 km, and with simulations of several days to months. The first urban canopy parameterizations for these models started to appear around the early 2000s. Common characteristics include idealized urban surfaces (e.g., regular canyons), three types of active surfaces (walls, roofs, and roads) that exchange heat with the atmosphere, and the effects of shadowing and radiation trapping in the canopy.

- What they do well? — urban-rural temperature differences (UHI)
- What needs to be improved? — sensitivity to different urban morphologies, exchanges of heat and momentum between the canopy and above.

Future directions — we need to shrink the gap between micro and mesoscale models.

In the short term, this should happen by using computational fluid dynamics models to improve the treatment of urban canopies, while increasing vertical resolution. For microscale models, we need to develop techniques to force CFD models with mesoscale outputs as boundary conditions.
In the Medium-term: Embed fast high resolution simplified microscale models (like Quick-URB) in mesoscale models to represent the urban canopy. Target model evaluation to intra-urban comparisons, instead of the existing focus of urban vs rural.

Develop sub-models to better represent how cities exert a "pressure" on the atmosphere (building energy models, green buildings, street trees, heat emission from cars, solar panels, indoor/outdoor exchanges of heat and mass, etc.), and how the atmosphere "impacts" cities and citizens (estimate variables relevant for thermal comfort, etc.). Link to sub-models to improve the representation of interactions between city and atmosphere, and possible mitigation strategies.

In summary, there is a need for a network of urban models that link the mesoscale to microscale.

**Discussion (Led by Luis Bettencourt)**

Framework: It is well documented that in the current geological area – sometimes called the Anthropocene – humans have come to appropriate a large fraction of the Earth’s Net Primary Productivity and of its resources.

What is less discussed, however, is that urbanization and the growth of cities are completely re-arranging the global flows of resources and energy, localizing and concentrating use and consumption in a small part of the Earth’s surface. Among many other issues, this makes cities environments with very high-power densities (energy per unit time per unit area) and strong localized sources of wastes and pollutants, including aerosols and greenhouse gases, such as CO₂.

While these issues place the focus of any solution for global sustainability on cities, it is less clear if and when the detailed modeling of atmospheric transport of gases and heat requires a detailed consideration of cities in Earth Systems Models.

The answer seems to have to do with 2 main issues. One is about location – in space and time – of these emissions. This location certainly matters for people living in cities, but perhaps not for very long-term models that balance heat and mass over the entire earth in decades. Second, there is the issue of averaging. To the extent that we just want to know very aggregate quantities, such as CO₂ over continental scales, and the quantity of interest mixes relatively quickly, the detailed consideration of cities will not be necessary.

By foregoing detailed models of cities, Earth Systems Models do forego many important questions. These include the study of mechanisms at the origin of emissions, virtuous and vicious (nonlinear) cycles of consumption and emissions, and interactions with willing communities and policymakers capable of substantial agency on the issue of climate change. Models will thereby forego a closer scientific understanding of the fundamental sources of emissions (economic growth and human development, coupled current energy technologies), or detailed recommendations about how to deal with these issues at the centers of consumption and decision-making.

**Other models at the City Scale:** At the scale of cities, there are many other models dealing with many aspects of the built environment, energy, pollution, consumption and production. There are many models of traffic and associated energy consumption, building performance and energy use,
energy and temperature in detailed built environments, models of socioeconomic production and consumption and so on. Contact with these models is essential.

A Changing Data Landscape: The big transformation of the last decade has been away from very large computational models for prediction well into the future, and their substitution with smaller models refreshed by ambient data, via (Bayesian) data assimilation schemes. This makes the interface of physics-based models with models capable of learning and inference (including possibly AI) very important going forward. In many cases, over the short term in cities, data generated by sensors, cell phones, satellites, etc. may almost totally replace modeling. Modelers should answer then, what their contribution is in such situations.

These contributions must focus on a situation where extrapolation from ambient data is necessary, either exploring scenarios where the built environment or (energy) technologies change or projecting such changes into the future, e.g. under climate change.

Need for data access: Much of this new data is being produced by private companies, including high-precision remote sensing, building shapes, and mobility data. These companies tend to share data in ad hoc ways with researchers but are not transparent and replicability of results becomes harder.

Arrangements via Federal Agencies for access is necessary. For example, the NGA has access to digital globe high precision data in cities. Sharing this data can be mediated via other federal agencies.

Scientific questions: Although there are many important scientific questions associated with current Earth Systems Models, their focus on the distant future and on aggregated quantities foregoes many important problems where both mechanisms and predictions can be better understood. Having models that continue to improve on predictions for heat and emissions in cities, can handle exceptional circumstances, such as weather fluctuations, closures (e.g., the Beijing Olympics) and other peculiar events, and can generate more disaggregated verifiable predictions, say at the neighborhood level, would certainly increase the testability and confidence in ESMs.

2.6 Summary of the earlier ANL Workshop on Urban Scales (Beth Drewniak)
An Urban Workshop focusing on bridging the gap between measurements and modeling was previously held at Argonne National Laboratory in August 2013. The motivation for the workshop was driven by the significant modification urban landscapes have on the environment and the potential to impact local and regional climate. In addition, the large and growing population living in urban centers has led to the rise of smart cities to collect data and help planners make informed decisions. Therefore, the workshop objective sought to identify gaps in the current understanding of urban processes that will be important at climate model scales and determine future areas of focus for data collection and observatory design.

The workshop was split into four focus areas and four breakout sessions. Workshop activities centered around the current understanding of modeling and observing urban environments and interactions between urban design and climate. The breakouts included discussions on
observation/model comparisons, modeling the urban-climate connection, building urban observatories, and applications of urban-climate models.

The workshop identified four priority areas for future research:

1) **Cataloging data archives to develop model testbeds.** Data is needed for data assimilation, parameter evaluation, and to develop new parameters. Create a central repository so users can work with data that already exists and add new data as it is collected. Use current cities that already have big data as modeling testbeds for evaluation.

2) **Design field campaigns.** Integrate in-situ measurements and remote sensing and leverage alternative data sources. Collaborate with stakeholders and community members to sustain data collection and learn about the future direction of the city. Campaigns should go beyond the urban boundary to understand coupling across the rural-urban gradient.

3) **Build networks.** Networks should coordinate and organize long term data collection across a variety of data sources. Networks can be used to communicate across a wide range of scales and to connect different interest groups, integrating synergistic activities to maximize data availability and flow.

4) **Model development.** Models need to consider the unique properties of a city and heterogeneity. Create idealized cities for different regions, but don’t neglect cities change over time.

**DAY 2**

**2.7 Presentation: Observations in Urban Environrs such as The Array of Things (Charlie Catlett)**

Charlie Catlett provided an overview, background, and roadmap of an NSF-funded experimental urban measurement cyberinfrastructure, the “Array of Things” or “AoT” [Catlett et al. 2015, 2017]. The project was motivated by the challenge that many urban phenomena, from air quality to weather to vehicle and pedestrian flows, are highly localized. As such, regional approaches to measuring such phenomena, while tremendously valuable, are mismatched with respect to temporal and spatial dynamics and thus offer little help when investigating neighborhood-scale processes such as urban heat island, air quality, or traffic safety. The AoT project began with a series of scientific workshops, some discipline-focused (e.g., Drewniak et al 2013, Catlett et al. 2017) and some multidisciplinary (e.g., Catlett et al 2014, 2015). Each workshop produced input to the functionality desired for a class of measurement devices, each of which would cost several thousand dollars, deployed in quantities of hundreds across a major city (in this case, Chicago). AoT “nodes” thus today have several dozen sensors covering light, sound, vibration, meteorological, and air quality. AoT also implements “AI at the edge,” as each node includes both a fully remotely programmable Linux control computer and a dedicated Linux computer for user codes, such as machine learning code to analyze images or sound. These capabilities are aimed at understanding urban activity (pedestrian flow, traffic safety, noise pollution, etc.) and thus the nodes have microphones and both sky- and ground-facing cameras.

Based on Argonne’s open-source Waggle platform (Beckman et al. 2016), the concept introduced with this project is analogous to software-defined radio (remotely programmable to a range of frequencies and formats): Software-Defined Sensors. As of summer 2019, there were 120 AoT
nodes deployed throughout Chicago, supporting machine learning research as well as providing high-resolution measurements that have already been used to develop and parameterize 100m² horizontal resolution weather models (Jain et al. 2018). By late 2019 an additional 80 nodes will be installed. All AoT data is open and available both by bulk download and through an open, near-real-time API (Forgione and Catlett 2018). In 2020 a new generation of nodes with more powerful processing as well as new sensors will be deployed in Chicago and in non-urban settings such as on NSF’s National Ecological Observatory Network (NEON) through a $9M NSF Mid-Scale Research Infrastructure award (Beckman et al. 2019). During late 2019 and early 2020, the team will engage the science community in reviewing (a) the evaluation of all AoT sensors, and (b) options for both upgrading sensors and adding new measurements.

**Group discussion (led by Charlie Catlett, Petra Klein, and Pavlos Kollias)**

Findings from the discussion are below.

- State of low-cost sensor technologies - many participants reported on their use of various low-cost sensors, with an emphasis on air quality sensing.
- Some thought there was too much discussion on the lack of accuracy of individual observations rather than considering the value of having many observations over the urban area.
- Considerable discussion about strategies for sensor calibration as well as quality control and placement. Gas species, for instance, each have unique dispersion characteristics and interact differently with the environment. Some (e.g. Ozone) are the products of other pollutants rather than directly emitted.
- The Array of Things was discussed as a platform for at-scale testing of emerging sensors (recognizing that the experimental sensors in the currently deployed units are for evaluation, and the value of the infrastructure is in support of the rapid deployment of new sensor technologies for evaluation).

Q: You have lots of measurements at the surface. Do you have measurements like a wind profiler to look at the boundary layer?
A: There are two loopholes in the project and one of them is wind. We are not capturing the wind. The other one is CO₂. What happens to CO₂ concentration in the city with emission variety of cars passing is unknown.

Comment: It’s important to involve different measurement but we need to be careful. Sometimes without control, quality could be poor. WMO is preparing recommendations for the global measurement practice.

A View of the state of Urban Greenhouse Gas Measurement and Analysis Research Efforts

Atmospheric Measurements Testbeds
- Indianapolis – NIST
- Los Angeles NIST, NASA
- NE Corridor/ Baltimore to Washington NIST
- Boston
- Salt Lake City

The Atmospheric Observation Approach – Urban Greenhouse Gas Quantification
• Cities and urban centers are complex and localized
• Incoming winds bring trace gas mole fraction signals to the domain and mix these with emission/uptake within the city

Carbon Flux Meteorology of Biogenic Sources
• Large uncertainties in the carbon cycle are attributable to terrestrial ecosystems (on the order of 50% or greater)
• NIST Forested Optical Reference for Evaluating Sensor Technology (FOREST)
• Relate plant productivity based on eco-physiological meteorology to SI traceable radiometric observations ranging from the leaf to canopy level

Emissions Data Consistency & Accuracy – Harmonizing Results from Disparate, Independent Methods
• Join traditional inventory data methods w/ atmospheric observing and analysis results to gain increased confidence in emissions data & reports
• Strengthen the science base of nationally & internationally recognized GHG quantification methods enhancing uniformity and consistency in national emission reports and their underlying data

Urban Observations above the surface/canopy is critical. There should be considerations for an Urban Observatory. DOE has considerable experience in establishing surface-based observations
• Fixed and mobile observatories
• 24/7 operations
• Data quality control, value-added products
• Data Archive

But currently, no DOE fundamental research is aimed at urban systems. Generally, the United States is lagging in urban studies. Europe and Asia have taken the lead in urban studies for air quality and pollutant transport, and weather studies. Few cities working extensively are London, Paris, Helsinki, Beijing and New Delhi.

2.8 Presentation: Satellite datasets for urban (Eric Kort)
Space-based remote sensing is poised to provide a range of useful data products to improve and evaluate Earth System Models at the urban scale. The volume, resolution, and quality of this data is rapidly improving and can provide potentially important information about land surface changes through time. Most relevant data products include land cover type, land surface temperature, potentially energy balance, urban biological activity, nightlights imagery, and trace gases (both greenhouse gas and air quality). These data products could be directly incorporated in urban ESMs (in particular products like land cover), and some could be used to evaluate the accuracy and representation of emissions and transport at urban scales.

Overall points:
• There are a lot of datasets generated from space-based observations.
• The amount, type, resolution, and quality of this data is rapidly improving (particularly for trace gases).
• These datasets can be used in obvious, direct ways (defining of land-use type), but also can provide indirect insights (urban trace gas plumes showing transport dynamics).
• Opportunity for these observations to help ESMs—also the opportunity for ESMs that represent urban to be useful in other communities.

Types of data available:
• Land Cover
• Land Surface Temperature
• Energy balance
• Urban biological activity
• Nightlights
• Trace gases (greenhouse gases/air quality)
• Frequency, spatial resolution, temporal resolution can vary greatly
  – One often overlooked element—size/structure/characteristics of urban domains can (and will) change in 5-10-year periods.

Other points:
• Trace gas plumes contain a lot of information on transport and may provide a useful tool for evaluating urban transport representations
• High-quality urban representations in ESM’s could be of great value to other communities
• Urban domains can change rapidly in time and will change into the future
• Daily and seasonal variations may be important, maybe captured with direct/indirect measurements

*Group discussion (Led by Johannes Feddema)*
Cities and global climate—back to emissions
• CO2 vs. population

CLMU
  Canyon representation:
  • Impervious and pervious surface
  • Sunlit wall and non-sun lit walls
  Q: Are all the streets align parallel to the walls?
  A, JF: no. For the better or worse.

CLM5 improvements
• Expanded model capability to simulate multiple urban density classes w/in each model grid cell
• Include a more sophisticated and realistic building space heating & air conditioning (HVAC) sub-model
• A revised global dataset of urban morphological, radiative, and thermal properties utilized by the model, including a tool that allows for generating future carbon emission

Future Urban Design Scenarios
• Roof albedo
  o Energy change
In developing cities, it is especially important to have ground observations to provide ground truth. Land-use changes are important. We need to find a way to do a fair comparison, we need the Urban MIP. The building set up in WRF is different than the ones in ESM. There are lots of opportunities on how to set up the problem. In addition, urban modeling gets more interesting when you go to microscale but there’s a gap between regional scale and microscale.

2.9 Breakout Groups 4-6
Group 4 – Urban scale datasets including ecological and other datasets (besides land-use) (Lead: Dan Horton)
Address: There is no set of standard/accepted urban scale datasets that could be used to evaluate the high-end CFD models for acceptable performance in producing urban microclimates. How do we build upon current urban research activities to collect and archive data for model validation? Are there non-traditional data sources that can also be used to build this dataset? Can we create an observational data testbed to test models?

Introductory discussions not motivated by supplied questions:
- Model evaluation and fidelity goals differ across spatial scales. While urban microscale modelers often wish to evaluate their simulated data to environmental absolutes (e.g., temperatures on four different sides of a building) for design/engineered solutions, large-scale modelers often evaluate their simulations using relative measures, e.g., diurnal ranges, urban-to-rural gradients, scenario-based shifts from a baseline, etc.
- Both statistical fit and process-based evaluation were suggested, with the latter deemed to be desirable, however, observational constraints for process-based evaluation are quite rare and often require sophisticated infrastructure (e.g., flux towers & lidar) or field campaigns.
- To date, validation of urban tiles in ESMs has been limited
  - Limited by lack of hi-res observations
  - Limited by non-publication of tile-based data formats by ESM organizations.

How do we build upon current urban research activities to collect and archive data for model evaluation?
- On the modeling side:
  - ESM teams must archive and share high temporal resolution simulated tile-based data, particularly urban tiles. Without this data, no ESM urban tile evaluation (or analysis for that matter) is possible.
  - CMIP protocol should include tile-based data archival requirements.
- On the observation side: Primary takeaway: Leverage existing higher-res networks
Evaluation at urban scales is challenging due to the dearth of widespread high spatiotemporal observational datasets.

For model evaluation purposes, it would behoove the community (perhaps in a coordinated manner) to leverage existing observational networks, both longitudinal and temporary. For example:

- The NSF supported Long Term Ecological Research Network (LTER) is generally speaking, not urban-based. However, sensor networks have been established in both Baltimore and Phoenix [https://lternet.edu]. Current sensing capabilities in these networks may not provide all of the desirable evaluation data, but adding sensing capabilities to these established networks could provide a comprehensive observing platform in an urban environment – almost immediately and at a fraction of the cost of a new network.
- WMO GURME: project focusing on urban meteorology and environment with many pilot cities: Helsinki, Beijing, Shanghai, Paris, Mexico City [http://www.wmo.int/pages/prog/arep/gaw/urban.html]
- The International Association for Urban Climate hosts the Urban Flux Network [https://www.urban-climate.org/resources/the-urban-flux-network/], an archive of historical and current urban flux tower measurements. The archive is ideal for process-based evaluation.
- Field Campaigns: occasional massive observing operations in the form of field campaigns can provide excellent model evaluation testbeds.
  - The upcoming year-long DOE ARM campaign in Houston offers significant potential for Houston-based model evaluation
  - Field campaigns not strictly designed for urban climate can also be leveraged, e.g., the Lake Michigan Ozone Study [https://www-air.larc.nasa.gov/missions/lmos/] provides a few week snapshots of Chicago and its surroundings using an airborne, satellite, ground and marine-based observational network

Are there non-traditional data sources that can also be used to build this dataset?

- Crowdsourced/citizen science opportunities – present challenges with regard to trustworthiness, but both the community involvement/inspiration/agency and potential for massive data are attractive
  - Key challenges include the lack of longitudinal (over time) observation, standardization of gathered data, and quality control
- Google Maps: urban microscale modelers found promise in the Street view option, to constrain building and infrastructure properties
- Cell phones offer massive data-gathering possibilities, but their reliability is suspect.
  - Ph.D. student of Robert Bornstein is developing methods to improve reliability (email for details)
- Similar to Aircraft Meteorological Data Relay (AMDAR) reports, the potential exists to fit municipal or public vehicles with sensing capabilities, for in situ time urban obs.
- Cheap Sensors: pretty sure Mark will cover most of this, but some links were sent to me

- WMO Global Atmospheric Watch: [https://www.wmo.int/pages/prog/arep/gaw/gaw_home_en.html]
• An often-forgotten dimension, the Urban vertical, is challenging to observe. New and existing technologies may offer some assistance.
  • Drones outfitted with sensing capabilities could sample the urban canyon
    • May require FAA approval
  • Doppler weather radar is under-utilized by modelers, particularly for evaluation purposes. WSR88D has excellent coverage over most U.S. metropolises.
• Pigeon Patrol: https://twitter.com/PigeonAir?lang=en (!)
• Collaborative opportunities w/ social scientists: questions of urban resident behaviors (e.g., thermostat settings) could be answered in collaboration with social scientists that employ surveys
  • Tapping the network with established protocols.
  • The goal would be the addition of questions to existing surveys

Can we create an observational data testbed to test models?
• Absolutely, but it is pricey. Much better to leverage and build on existing networks.
• The Ideal:
  • Long term, highly horizontally & vertically sensored cities in heterogeneous climates & cultures
  • Until cheap sensor become reliable, probably not realistic
• In the interim:
  • Leverage existing efforts (e.g., LTER, Urban flux, GURME, ARM)
    • Key question: Would adding just a few sensing capabilities to extant networks make them “complete”

Key Recommendations
• For ESMs, an Urban Model Intercomparison Project is needed
  • Choose relevant/extant observed data against which to validate models
  • Start small, choose an individual well-sensored city/cities.
    • Use traditional and non-traditional observing networks
  • Build upon prior efforts (e.g., URBMIP, DICE)
  • Single column/tile inter-comparisons
  • Educate the community about urban representation in ESMs
  • Build toward urban-resolving models analogous to cloud-resolving models

Group 5 – Emerging sensing technologies and their use (Lead: Mark Potosnak)
Address: Emerging smart city sensing technologies and their possible use in model development. How can observational studies of urban regions be used to aid the modeling community? Generally, observational sites and sensors in cities are poorly placed and likely are non-representative of their neighborhoods. The development of dense cheap sensor networks provides an opportunity to bridge this gap. However, using these datasets for evaluating models or process-scale model development will be a challenge due to data quality and consistency issues. Is there a pathway for using these datasets for rigorous scientific model evaluation and model development?
Does the concept of an Integrated Field Laboratory (based on the earlier workshop mentioned above) bridge the gap between the cheap/dense networked datasets and research quality data needs?

Initial discussion

- There was a robust discussion of two issues that challenged the premise of the charge.
- First, some questioned the utility of low-cost sensors. One example comment, “There’s a quality question. If you buy 100 cheap sensors but if the quality is not good then it doesn’t help with the question.” Another participant noted that these low-cost sensors “lacked WMO quality.”
- Second, there was a discussion of what is learned from a dense network. For example, if the dense network is biased (all at one height or placed in one particular type of urban setting), you lose information about heterogeneity.
- But, there was a recognition that these low-cost sensors were essential for addressing questions of environmental justice. Also, these low-cost sensors might be the only economically feasible strategy in developing countries.

What is a successful strategy for deploying these types of sensor networks and how much is good enough?

- Building off the second point in the initial discussion, the issue of bias needs to be addressed. Most importantly, a dense network needs to be built both vertically and horizontally. In terms of horizontal placement, placing sensors in one type of location can introduce a bias. For example, in the Array of Things, sensors are all placed on traffic control signal poles (stoplights). That means the sensors are all above roadways. This can be an advantage since the variables measured can be compared across the city. But, the fine-scale (meters to 10s of meters) heterogeneity of going from street to sidewalk to rooftop is not measured.
- Vertically, the dense networks will allow model validation of street canyon effects and the surface energy budget (cheap skin temperature sensors). Also, drone flights could supplement the low-cost network.
- There need to be enough sensors to measure important gradients across the city. For the example of Chicago, the strategy of running transects of sensors along and from the lake is reasonable. For other cities, adapting dense sensor networks to local geography is key. Some important gradients to measure would be: urban to rural, local bodies of water and elevation. Also, social gradients (income, health outcomes) need to be considered.
- Another key is the temporal resolution. The relatively small number of fixed stations in urban areas often report data hourly, while many low-cost sensor networks report multiple readings per minute. This should be rapid enough to track weather moving across the city.

What is the pathway for using these datasets for rigorous scientific model evaluation and model development?

- Again, there was a robust discussion here. How can irregularly-spaced datasets be successfully incorporated into urban model comparisons? Again, the vertical issue was addressed. Models output the 2-m air temperature. This is a good height for considering pedestrian comfort. But many dense networks need to mount sensors above this height for security.
● One solution is to downscale: ESM -> WRF -> pedestrian models like ENVI-met. ENVI-met has a high enough spatial resolution to make the comparison. But, this is a computationally intensive approach.
● Again, the question of data quality was assessed. There was a recognition that if low-cost sensors produced data with a systematic bias, this could be addressed using big-data (spatial analysis) techniques. But there was skepticism about the quality of current low-cost networks. While efforts to develop protocols (WMO for meteorological and US EPA for air quality) are admirable, there are intrinsic tradeoffs with low-cost sensors.
● There are some urban networks for high-accuracy sensors (Oklahoma urban micronet), but these are relatively rare and it is difficult to fund them long term.
● One pathway is to use and evaluate the low-cost sensor network data with a recognition of its strengths. For example, there are data assimilation schemes that can account for errors in measurement fields. In traditional model-data comparison, the assumption is that measurement error is relatively small and that the data are ‘true.’ A Kalman technique accounts for errors in both models and measurements. While each individual sensor may lack utility as a reliable source of data, a sophisticated data assimilation scheme would leverage the spatial coherence and density to provide a robust dataset for comparison to urban models.
● Even with calibration issues, correlations in the dense network between sensors could be compared to model results. For example, the temperature might be correlated with distance from the lake (Chicago), and this should be reproduced in the model.
● Another way to validate ESMs in urban settings is downscaling with large eddy simulation (LES) models. But these models suffer from serious limitations, so care must be taken. For example, the LES models can depend on initial conditions and assumptions.

Does the concept of an Integrated Field Laboratory bridge the gap between the cheap/dense networked datasets and research quality data needs?
● Yes!
● There was a general agreement that low-cost, dense networks of urban sensors cannot replace intensive field campaigns and more mobile, high-accuracy sensing platforms. These mobile platforms could be used to assess the sub-segments of dense networks in systematic ways. Innovative approaches, like mounting high-quality sensors on transit buses or Lyft/Uber could be used to do quality control and analysis of dense networks.
● The question of who is responsible for quality control was addressed. For example, the Array of Things network is relying on the research community to understand and interpret the data. For model validation, this is a difficult approach. An effort that developed an Integrated Field laboratory could both perform an inter-comparison to the low-cost, dense array and also provide a more robust (Level 2) dataset for urban model validation. The comment was made that “bad data is worse than no data.”
● Gradients were discussed above, but the IFL would sample a rural-to-urban gradient. This could be paired with a low-cost network.

Summary of recommendation
● Establish best-practices guidelines for low-cost, dense urban sensor networks
  ○ What parameters should be measured? Greenhouse gases?
● Investigate what calibration strategies are most effective
Establish field campaigns (IFLs) that for assessing the low-cost, dense urban senor networks

**Group 6 – The need for ultra-high-resolution land-use datasets (Lead: Jason Ching)**

Address: The urban environment is extremely heterogeneous, but modeling representation of cities across the world fails to capture this heterogeneity due to the lack of availability of ultra-high-resolution land use datasets. One exception is that cities in the United States have available a 30-m resolution National Land Cover Database (NLCD) set of data, with ~45 cities included in the even more powerful National Urban Database and Access Portal Tool (NUDAPT) resource. There is thus a need to actively pursue developing these databases on a global scale. How do we collect and analyze large urban datasets and use that data to inform models? How can we use generalizations, yet still account for the uniqueness of each urban center?

The extreme heterogeneities in urban environments are being addressed in climate models based on applying an urban canopy framework but its progress is hampered by the limited availability of ultra-high-resolution land use datasets. However, NLCD and the WUDAPT (and its prototype, NUDAPT) are developed to fill this gap. Features, issues, and approaches for such modeling inputs to support varieties of fit-for-purpose environmental models over various scales and contexts are reviewed, and recommendations for expediting activities identified.

**Charge and Questions for Breakout Group 6:**
- Given the extreme heterogeneity of the urban surface, what are climate modeling approaches and their inputs at different scales
- Are the common data structure and archiving standards developed by WUDAPT suitable for environmental modeling, specifically in climate models on various scales?
- What input data are available? What spatial scale of urban heterogeneity is captured in these datasets and do we need to improve these resolutions for open access datasets?

**Perspective and Approach:**
A number of climate and other environmental models have been developed and used in a variety of applications. For the specific treatment of urban areas, the modeling resolution and input data requirements vary for different and varied Fit-for-Purpose (FFP) model applications. The scales range from global to regional to urban to block and finally to building scales. Data inputs and treatments of LULC in Land Surface Models (LSMs) vary between modeling systems and by scale; global-to-regional modeling is based on urban tiles in the CESM, GFDL and UKMET models. Urban components vary in their sophistication and vary from a simple surface albedo, roughness, infiltration change to an urban canyon (canopy) (UCP) parameterization equivalent to those found in most regional models e.g., WRF (Chen et al. 2011), some include a building energy model. CFD models need 3-D building data. Applications require current and future LULC projections. Urban to block and building scales model’s approach to resolving the high degree of LULC heterogeneity is based on incorporating UCPs to the modeling science. A comprehensive review of the scientific foundation can be found in Garuma (2018) and others. However, supporting UCP type data is currently limited to relatively few cities worldwide.

WUDAPT (World Urban Database and Access Portal Tools, (Ching et al. 2018, 2009) is an initiative of the International Association of Urban Climate and the Board of Environment of AMS.
Its objective is to develop model input data to resolve urban heterogeneities at relevant meso- to block-scales; its paradigm is to develop model data generation methods and an implementation strategy achieved through community-based collaborations, staged hierarchically, invoking highly innovative approaches and utilizing readily available, and accessible inputs on worldwide bases. The outcome is for model data on a worldwide scope, with quality aspects of consistency, scalable and infrastructure links to support wide ranges of “Fit for Purpose” applications including climate, weather, and other associated aspects to address a wide range of issues and needs. At Level 0, UCPs are in “ranges of values” from associated “lookup” tables of 10 urban LCZ (Local Climate Zone) classes (Stewart and Oke 2012). Thus, provision for UCP maps is derivable from LCZ maps by WUDAPT methodology that can be generated for any and all urban areas. At Level 1 and 2, the methodology, now under development and testing, uniquely geocoded UCPs everywhere in the urban domain will be generated, much like that in NUDAPT (Ching et al., 2009). At this level, the type of information is categorized into three-major “F” categories, Form (geometry), Fabric (material composition) content and Functionality (energy usage and waste products). The minimum resolution is at “block scale” thus making possible user-specified gridded input for FFP applications. This paradigm removes or ameliorates the traditional issues of scalability and the need for subgrid-scale treatments of the input data. The task then is to develop acceptable methodologies for each element in the 3F categories. For “Form” an innovative tool in WUDAPT called the Digital Synthetic City (DSC) based on the availability of building footprints and road networks using satellite and OSM data is being tested. For Fabric and Function WUDAPT is developing a suite of “bottoms-up”building tools incorporating Deep Learning AI techniques applied to building dictionaries such as TABULA, other sources of 3-D building and other urban objects information such as cityGML, and customized using Building Typologies (BT) and crowdsourcing (CS) methods. With and when these elements are in place, UCP data for models can be generated with a variety of approaches implemented with community collaborations so as to be available and achievable on a worldwide base.

Recommendations
Emerging activities now underway present synergistic opportunities to accelerate achieving the goals of generating appropriate urban LSM modeling data and supporting modeling infrastructure to facilitate the wide variety of FFPs needed by all urban centers. Examples include:

A. Methods developments, testing and refining methodologies that can generate Form-based urban parameters for all major urban centers.
   - Form-Based UCPs: Implement and sustain DSC approach beyond Testbed cities
   - Fabric (and Function) based UCPs: Explore the use of AI, Machine/Deep learning techniques in the development and approaches for bottom-up approaches,
   - Incorporate Vegetation

B. Identifying critical FFP modeling systems augmentation with LSM capabilities and or tools that can link FFP UCPS to various FFP applications,
   - Utilize current Level 0 approach, i.e., extend W2W (WRF) paradigm to other modeling systems
   - Develop interface links between Level 0, 1 and 2 data towards high priority model applications including upscaling UCPS to global and regional scale climate modeling systems
   - Collaboration, support, and sustain/augment WUDAPT Portal for FFP applications
   - Apply FFP UCPS to MPAS (icosahedral coordinate system)
2.10 Presentation: Urban, energy, exascale Earth System Modeling: a perspective from E3SM (Kate Calvin)

This presentation described the urban-related developments in the Energy Exascale Earth System Model (E3SM). Current research within E3SM is focused on the water cycle, biogeochemistry, and the cryosphere. The current version of E3SM (version 1) includes emissions from urban-systems and an urban land tile. However, the emissions are not separated from other sources (and thus smeared across 100 km grid cells), and the urban land representation is based on a somewhat simple urban canyon approach (identical to the approach in CESM). While there are not currently plans to further develop the urban model in the near-term, there are several ongoing developments that will facilitate urban-related research. First, E3SM is in the process of incorporating an energy system model through its inclusion of the GCAM model. GCAM represents interactions between energy, water, land, and climate. GCAM can simulate the effect of increased temperature on building energy demand and its associated emissions. Second, E3SM is developing a high-resolution atmosphere model (the Simple Cloud Resolving E3SM Atmosphere Model or SCREAM), targeting a horizontal resolution of 3 km. In addition, E3SM is testing the capability to run a very high-resolution land model, with a 1 km horizontal resolution over North America. Finally, the development of an urban watershed model within the river model is planned. These developments could enable future urban analyses.

DAY 3

2.11 Panel discussion: Revisiting urban in ESMs – How do we get to where we need to get to?
Panel: Ramaswamy, J.F. Lamarque, Fei Chen, Dev Niyogi (Discussant: Rao Kotamarthi)

Ramaswamy (NOAA GFDL)

Ramaswamy discussed the ongoing model development activities at NOAA and the challenges of including Urban models in these models. The trend in model development is towards increasing the spatial resolution of the models and increasing the complexity of the process representation to match the resolution. As the spatial scales and model complexity are increasing, we are approaching closer to the goal of the development of unified weather-climate models. For example, the NOAA FV3 solver with a stretchable grid provides a local refinement to capture high spatial resolution features in regions where they are desired. In July 2018, the FV3GFS has become operational at NOAA for making operational forecasts based on the same numerical solver core as used for the climate model with resolution ranging from 50 Km for the GFDL-AM4 and 1km for the regional Super HiRAM model. There are now a number of models around the world trying to achieve these high spatial resolutions and an effort to compare these cloud-resolving models is underway for a 40-day DAYMOND inter-comparison exercise with approximately 10 separate models participating. The FV3 based cloud-resolving modeling system is now being developed into a seamless modeling platform that can go from short-term forecast to climate scales.

Including detailed urban processes, scale models require that we identify who the stakeholders are and what they need. It is likely that stakeholders interested in urban impacts only need simple models that actually work for the purpose of understanding the Urban issues and don’t require the expensive fully coupled and high-resolution climate models. What is the ‘low-hanging fruit’ or a canonical case study that will demonstrate the need for a fully coupled model from the Urban-
regional-global scale? If we can identify this problem, then we could make a strong case for going down this path. There is a natural tension between advancing scientific understanding and meeting the needs of the stakeholders. The stakeholder interest usually lies in getting usable information and an understanding of the uncertainty. One pathway to consider would be to use sensitivity studies with fully coupled climate models to identify elements that should go into purpose-built models targeted to stakeholder needs.

The current and soon to be available ESMs with region refinement in grids and local scale LES type models forced with global models can be used to address (a) extreme events and their impacts on urban regions (b) extreme precipitation and its effect on urban hydrology (c) quantifying the uncertainty in models that is needed to make a compelling argument for including urban models in ESMs, such as addressing the signal-to-noise and attribution of climate impacts (d) understand model predictability issues and (e) Data and QC for proper evaluation of model biases and weaknesses.

Jean-Francios Lamarque
ESMs are used increasingly to address a wide range of issues well beyond their original design scope. While the original intent is to understand the. Energy balance and increase the carbon cycle in these models, the applications of the model outputs have evolved considerably. There is a competition for resources between increasing resolution, increased complexity of the models and the need for longer duration simulations and performing ensembles as shown in Figure 2.1.

![Figure 2.1](image)

**Figure 2.11.** Three different needs are driving model development, resolution (y-axis), ensembles (x-axis) and complexity (z-axis). Finding the optimum surface in this three-dimensional space as constrained by computational and storage resources is the model developers challenge.

The benefits of higher spatial resolution in models are necessary for non-linear processes, such as atmospheric chemistry. It should also be realized that spanning the scales for micro-scale mixing to current GCM scales spans a range of 5 orders of magnitude and is probably not feasible to do this in a single model. We should identify processes that are strongly non-linear and influenced greatly by urban phenomena and develop process representations that preserved this non-linearity in a sub-grid of the model. For example, using PDFs of the variables to represent sub-grid scale distributions may be a way to go. We have devised methods for coupling the sub-grid tiles with the non-linear processes to the atmosphere above. Sub-grid models that can “cook first then mix”
from the urban to the regional atmosphere should be implemented at the scales at which emissions are available i.e. at a resolution of a few km. We should consider creating a catalog of high-resolution (say 1km or higher) over a wide variety of realistic/extreme conditions (meteorological and surface) to create a dataset to test parameterizations and possible use artificial intelligence to train on-the-fly parameterizations based on embedded super-parameterizations/high-resolution models. Thus, there may be possible avenues for putting urban processes in ESM’s without reaching a super-high spatial resolution.

Dev Niyogi
Urban areas are the drivers of the economy, culture, and creativity and thus play a critical role in how we think and plan for the future. Blending emerging computational technologies with meteorological understanding can develop the tools that can help us build resilient cities. There can be a number of ways an urban region can be defined, based on population density, economy, pollution levels or the vegetation density. However, we choose to define the extent of an urban region it is apparent the urban regions have a much larger footprint than the physical boundaries we ascribe to them. Urbanization has already been shown to cause detectable changes in regional climate through precipitation and temperature modifications. We need to study urban climate and represent the urban impacts in climate models because these studies can provide a metric for evaluating the modeling ability to represent extremes and perform population-centric GDP and impact analysis. The effect of urban regions on climate includes (a) creation of urban heat islands (b) the temperature impact is beyond the urban core and extends to regional (c) urbanization is likely impacting the rainfall from the Indian summer monsoon with heavy rainfall trending upwards in primarily urban regions. There are several approaches to developing representations of urban models in ESMs. Datasets such as WUDAPT (Ching et al. 2018) that represent urban regions can be modified for ESMs and adapting modeling techniques such as procedural modeling. It should be recognized that ESMs need urban also because downscale gives the appearance of resolution but cannot provide precision – problem needs to be also looked up as a scale-up approach rather than scale down.

Fei Chen
WRF can downscale to the local scale, so the boundaries between different models are decreasing and resolution has improved in the past few years. There is good progress for urban building mapping for drainage and mitigation (e.g., urban drainage in the DOE ESM). New observations in recent years in different parts of the world. All the modeling tools are being further developed to address specific scientific questions. You can’t ask one model to do everything you want. We have to think about the degree of complexity in the model to address a given question.

There are several challenges: you have to make sure that ESMs have consistency, e.g. treatment of green roofs. We have a wide and diverse data from satellite such as albedo, land cover for input to WUDAPT. But are these consistent? For instance, some models have albedo as a pre-scripted property, but some models have calculated albedo as a predictive variable. Just to ensure internal consistency and different data source are important. Looking forward, this workshop came up with exciting work: Above all, there are tremendous opportunities in the modeling community. How do we move forward with this? When we put world-class experts in the same room, we’re not short of ideas.
Some final thoughts:
1) Coupling method of urban & ESM, inner comparison of the models and WUDAPT are great but how do we move forward?
2) How do we assess the uncertainties in urban models?
3) The fragmented funding causes incoherent and lack of holistic model development.

3. Discussion and Findings
This section takes the outcomes from the workshop and discusses the understanding that came out of the workshop plus discusses major findings. These findings are then summarized in the Executive Summary.

3.1 The urban footprint
From the very beginning of the workshop, it was clear that models of all scales, from urban to global, need to consider and convey what impact, or “footprint” urban areas have on climate and weather, and what is an appropriate scale of resolution to represent the urban area\(^1\) and it’s a footprint. ESMs often treat cities as comprising a relatively small footprint, represented by areas of a scale of 2-5 km on a side (4-25 km\(^2\)). However, the aggregate footprint of an urban area, in terms of energy and water fluxes, is likely more in the range of an area of 25-50 km or more on a side (600-2500 km\(^2\)), and some studies have suggested as large as 100 km on a side, or 10,000 km\(^2\) or more. Transfer of albedo, heat, momentum, water, ozone, and aerosols are all important in considering the urban footprint. The long atmospheric lifetime of greenhouse gases means that their emissions can readily be considered in the modeling. The grid for a typical ESM today has a horizontal resolution of about 0.5-1.0 degrees or about 50-100 km, so truly treating an urban area adequately can be a sizeable fraction of a grid box.

What isn’t clear is how big does a city or urban area makes a difference in regional or global modeling. Do smaller cities and infrastructure like roads also make a difference – studies are needed to evaluate this. At this point, we are left with the question of what extent and with what accuracy do cities need to be considered in ESMs.

In addition, many cities are growing and their footprints are changing. Increasing urbanization is causing significant, and detectable, changes in regional climate through temperature and rainfall modification (see Figure 3.1, a conceptual diagram). For example, the urban heat island effects appear to have an impact on the monsoon in India.

Another aspect of climate modeling is that the results often need to be useful for stakeholders and policymakers looking at resilience and adaptation analyses and potential actions. This is especially true for regional modeling studies, either using refined grids over regional areas in an ESM or using a separate regional model (like WRF); it is very questionable to use existing global ESM results for such local and regional adaptation analyses. Feedbacks between land use and climate are important across all scales. It is important that urban effects be represented accurately in those analyses.

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\(^1\) Here we are discussing land use rather than the boundaries of any given municipality. To illustrate, the City of Chicago (municipality) covers 589 km\(^2\) while the urban area including Chicago and contiguous settled land is roughly 5,500 km\(^2\). Similarly, the municipality of Shanghai is 6,300 km\(^2\) while the contiguous metropolitan area extends west to Nanjing and South to Hangzhou, an urbanized land area of nearly 60,000 km\(^2\).
Whatever the definition, it should be apparent that cities can influence the environment with a much larger footprint than its physical domain. The effects locally and regionally are clear. What is not so clear is whether these effects are significant enough to affect the climate at global scales.

![Conceptual diagram of major urban climate issues (from the presentation by Dev Niyogi). UHI = Urban Heat Island.](image)

### 3.2 Modeling the effects of the urban across scales: Current state and gaps

Computational technology, when blended with scientific meteorological understanding, can develop tools that can help with predicting and managing the impact of climate change on cities and help develop climate-ready cities through design and infrastructure planning.

It is clear that there needs to be a hierarchy of modeling tools that can help address the impacts of the science across scales. There are already notable successes in modelling the urban atmosphere on a hierarchy of scales, and there are challenges in making improvements within and between those scales. Maintaining and improving each element of the hierarchy will be essential.

Urban areas are parameterized in global climate models usually via an urban canopy concept which includes internal building temperature, wall/roof heat, heat fluxes, and water fluxes. As global climate modeling turns from questions of global average change to regional change, representing urban areas becomes more important. Quantitative understanding of the urban impact on regional climate is still lacking but it is known that urban landscapes can change their climate compared to the surrounding vegetated areas. The conversion of rural land to urban is itself an anthropogenic forcing on the climate system. Including these effects are important to project future climate change over areas where most of the world’s population lives.

The urban canopy parameterization has problems representing areas of very tall buildings as seen in the core of cities. They typically do not extend outside the lowest layer of the atmosphere. The parameter values are not well defined for all cities globally and the models may not be valid in extreme weather conditions. The heterogeneity of cities is also not well captured. Upscaling the urban effects through the planetary boundary layer is key to capturing the regional coupling but is
poorly observed and modeled. Despite these limitations, they have been able to capture the basic properties of the urban heat island.

It should be possible to build better parameterizations of urban areas in climate models using models that solve the fundamental fluid dynamics equations in an urban domain: CFD or microscale models. These models can be usefully separated into 3 categories with increasing fidelity to the Navier-Stokes equations: RANS, LES and DNS. That is also their order of computational expense. RANS approaches are already used routinely to model airflow around buildings in both research and commercial applications. There is at least one example of using a RANS model online with a weather model to bridge the scale gaps but this is far from routine. There are also examples of RANS models being used to improve parameterizations in larger scale models. LES and DNS models offer the possibility to explicitly calculate the interaction between the urban canopy and the planetary boundary layer but the expense of these models is still prohibitive. These models have shown promise in representing the impact of obstacles like buildings on flow and calculating pollutant dispersion. However, they still lack fundamental properties such as a moist atmosphere diabatic heating. There is a rich area of research to explore in bridging the scale gap between all these models by forcing CFD models with mesoscale outputs or embedding fast RANS models inside of mesoscale or high-resolution climate models. Although expensive, computation resources have advanced to the point that CFD models can compute problems larger and more complex than can be observed. The lack of validating data is a large obstacle to progress in using CFD models for the urban atmosphere.

3.3 Observations and Datasets: Current state and gaps

There is an increase in the availability of data related to processes in urban centers, with potential to deepen our understanding of urban-climate interactions. Some of this data is fueled by many projects collectively termed “smart cities.” Applying analytics and optimization methods to this Big Data helps cities plan, manage, make better decisions, and strategize how to adapt to and mitigate climate change.

Data sources related to urban areas have rapidly increased in recent years with multiple technological advances. For instance, air quality data from regulatory measurement infrastructure (e.g., EPA sites) has traditionally provided regional-scale data, typically at temporal resolutions of 30-60 minutes. Experimental infrastructure such as Chicago’s Array of Things (AoT) project provides air quality at a neighborhood scale at 30-second temporal resolution. Similarly, networks such as Weather Underground provide neighborhood-scale meteorological measurements. As with AoT, these new sources currently lack the precision and accuracy of regulatory measurements, but this is rapidly changing as a result of both improved sensor technologies and advances in modeling algorithms, including the use of multiple data sources (Zheng et al. 2013).

Data from remote sensing devices (satellite-borne) is also increasing in both temporal and spatial resolution as well as quality. For example, today the Tropomi satellite (Vreeken et al. 2012) provides daily measurements of multiple gas species at a resolution of 5x8 km, and the Tempo satellite (Naeger et al. 2019), projected to be operational in the 2022 timeframe, will provide such measurements on an hourly basis at a resolution of 3x5 km. Satellite data from infrared sensors is already used for research ranging from rainfall (Sun et al. 2018), and satellite-based nighttime light
and microwave backscatter data is available for estimating the geographic extent and density of urban areas, respectively (Frolking et al. 2013).

Data published by municipalities is also rapidly expanding, providing detail regarding urban infrastructure (e.g., high-resolution topology of urban buildings, greenspaces, and infrastructure from Lidar scans) and its use. For example, the City of Chicago publishes average traffic speed at 10-minute intervals along 1,250 road segments (representing 300 linear miles), estimated based on GPS tracked bus speeds. Many cities also publish data regarding green spaces, roadways, and building footprints. The city of Toronto, for instance, maintains a database of every single tree in the city, which has been used to study the impact of green space on health (Kardan et al. 2015).

With the nearly universal use of mobile devices, cellular phone carriers and, increasingly, mobile phone hardware and application companies have collected detailed data about human movement, from which these companies (and their partners) are about to build sophisticated models forecasting traffic patterns not only on roadways (e.g., Google Waze and similar navigation applications) but for individual points of interest and businesses [https://www.theguardian.com/technology/2016/nov/22/google-bar-shop-busy-real-time-live-data-black-friday]. Such data can provide additional factors in modeling urban emissions from both vehicle traffic and buildings.

However, with the continuous influx of new types of data thanks to cheap, lightweight sensors, GPS, social networks, wireless communications, and the like, the ability to effectively organize and analyze information is becoming increasingly challenging. Consequently, cities, and scientists plumbing data for properties and impacts, require new methods of collecting, synthesizing, filtering, and processing data from many independent sources, as well as tools for data analytics, visualization, and integrating with computational models.

3.4 Other Gaps in Knowledge
The impact footprint of cities at the global scale is important and we will need to continue to explore that topic. The scales for modeling is also important that go from very detailed that answer urban questions but also be able to understand what it tries to tell us to regional scale and the global scale. We haven’t defined how this will happen. Both sensors and satellite help us understand what’s going on in the city and how human beings are playing roles and how energy change throughout the day and more. Testing and validating are definitely a huge topic to think more about.

Policymakers are concerned about health, water, energy and many other aspects. We know severe weather often play roles in destruction, particular global model underestimates the precipitation and severe parameters (extreme flood, drought, temperature) in some degree (projections). What’s going now is that policy makers use the model as the way they are and the point of this workshop is that urban is a sense that we’re not treating urban processes sufficiently over time and how this may affect the climate over time. So, the use of downscaling remains important as a means of achieving this. We know things can get better with higher resolution, e.g., clouds and precipitation, but how well will we represent energy fluxes and role of cities. We continue to think the footprint of the city in represent in the models how does it affect the models. We should come up some research agenda and fine tune what will happen to do a better job. Meanwhile, we need to warn
policymakers that current ESMS should not be used directly for policy considerations at scales approaching that of the urban areas.

3.5 Going forward
All attendees agreed that one of the biggest outcomes from this workshop was that it demonstrated the need for increased interactions between those that work on urban issues across the scales from local to global, including the modeling of the processes relevant across these scales in the study of climate change. It was suggested that we need an ongoing committee and perhaps an international forum for maintaining a dialogue about these interactions across the science communities that were represented at this workshop. It was suggested that we aim at bringing these groups together at a regular basis for workshops, at least every 3 years.

The confluence of economic activity, population dynamics/growth, and energy infrastructure and associated critical systems (transportation, water treatment, etc.) underpin urban systems. As an example, understanding future energy needs and how to generate and deliver this energy, plus assess the vulnerability of the energy sector, requires increasing interactions between climate scientists, stakeholders, and policymakers. In our thinking across scales, we need to also consider these interactions and how they can be enhanced. 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 (note that cities in Asia, India, and Africa are growing quickly, so have a special urgency).
References


——, A. Sharma, M. J. Potosnak, L. S. Leo, E. Bensman, J. J. Hellmann, and H. J. S. Fernando,


Appendix A

Agenda for the Workshop on Urban Scale Processes and their Representation in High Spatial Resolution Earth System Models

May 22, 2019

08:30-09:00 Coffee, tea and light refreshments
09:00–09:30 Welcome, Scope of the workshop: Science (Don Wuebbles (Univ. Illinois)); Logistics (Rao Kotamarthi (Argonne))
09:30–10:00 Presentation: Urban treatment in ESMs: current capabilities and gaps
Speaker: E. Shevliakova (NOAA)
Address: Why is urban representation in an ESM important? What is known? What is important to represent in ESMs – what is included now and what is not included? How does this picture change as ESMs go to higher resolution?
10:00-10:30 Presentation: Current capabilities and gaps in Urban modeling
Speaker: Fei Chen (NCAR)
Address state-of-the-art and where urban modeling needs to go
10:30-10:50 Break
10:50-12:00 Panel Discussion: Federal Agency and International Perspectives (discussant: Don)
Corrine Hartin (DOE), Robb Randall (DOD), Ken Jucks (NASA), Jin Huang (NOAA), International (Alexander Baklanov) – 5 minutes each then discussion
12:00-01:00 Lunch – Box lunches provided to all participants
Talk during lunch: Emerging Computational Platforms for HPC – Speaker: Katharine Riley, Argonne (Rao to introduce)
01:00-01:15 Introduction to Breakout Series 1 (Rao Kotamarthi)
01:15-02:45 3 Breakouts (Groups 1, 2, 3)
Group 1 – Challenges for ESMs for Modeling Urban Systems (Lead: Kate Calvin PNNL))
Address: Enhancing the capabilities of global Earth System models (ESMs) in representing the atmospheric dynamics and chemistry, unique aspects of the biosphere and landuse, and human dimensions in the urban environment. Why is urban representation important? What is known? What is important to represent in ESMs – what is included now and what is not included? How does this picture change as ESMs go to higher resolution?
Group 2 – Modeling of urban processes and their treatment in ESMs (Lead: Ashish Sharma (Univ. Illinois))
Address: the considerable gaps in the current available urban scale modeling capabilities and the requirements for a set of reduced parameterization/subgrid models necessary for representing urban processes in ESMs. How should we prioritize the urban processes that should be represented in ESMs?
Group 3 – First principles modeling at urban scales (Lead: Rob Jacob, Argonne)
Address: In building urban scale models from first principle-based fluid dynamic models (CFD models) these models currently lack many of the atmospheric physical process representation to capture the atmospheric dynamics. What can we do to expand these surrogate models to more accurately capture urban systems? Transport and diffusion processes in street canyons are poorly parametrized. How can we better predict the occurrence of different flow patterns (e.g., channeling, vortex flow) as a function of ambient wind conditions? How can slope (upslope and downslope) flows in an urban environment improve our understanding for air quality, visibility, and biochemical hazards?

02:45-03:10 Break
03:10-04:30 Talk on the need for a hierarchy of urban models
   Speaker: Alberto Martilli (CIEMAT Madrid) - 30 minutes
   Group discussion for 50 minutes led by Luis Bettencourt.
   There is a need for a hierarchy of models than span the time and spatial scales for representing urban microclimates. The CFD scale models will be expensive for performing simulations over climate time scales as standalone models or as submodels within an ESM. Have regional scale models (WRF-Urban) been adequately tested and/or what is needed to do so? How can we couple the different types of urban models to establish a robust, yet computationally efficient model of urban climate? How can future exascale computational platforms be leveraged?

04:30-05:00 Summary of the earlier ANL Workshop on Urban Scales
   Speaker: Beth Drewniak (Argonne)
05:00-05:30 Daily summary, feedback and discussion – led by Beth Drewniak
   Note: Breakout summaries to be prepared overnight
06:00-07:30 Reception at the Argonne Guest House, Hosted by the University of Illinois, Urbana-Champaign

May 23, 2019

08:30-09:00: Coffee, tea and light refreshments
09:00-09:15 Setting up the 2nd day (Lead: Rao)
09:15-10:20: Summaries from Breakout Groups 1, 2 and 3
10:20-10:45: Break
10:45-12:15 Presentation: Observations in Urban Environs such as The Array of Things
   Talk by Charley Catlett – 30 minutes
   Group discussion for 60 minutes led by Charley Catlett, Petra Klein (Univ. Oklahoma) and Pavlos Kollias (SUNY Stonybrook) on new sensing technologies and their use in urban model development
12:15-01:15 Lunch - Box Lunch (short Tour of ANL led by Rao for anyone wanting to see Lab)
1:15-02:45 Presentation: Satellite datasets for Urban
   Speaker: Eric Kort (Univ. Michigan) – 30 minutes
   Group discussion for 60 minutes led by Johannes Feddema
02:45-03:10 Break
03:10-04:40 3 Breakouts (Groups 4, 5, and 6)

Group 4 – Urban scale datasets including ecological and other datasets (besides land-use) (Lead: Dan Horton, Northwestern Univ.)
Address: There is no set of standard/accepted urban scale datasets that could be used to evaluate the high-end CFD models for acceptable performance in producing urban micro-climates. How do we build upon current urban research activities to collect and archive data for model validation? Are there non-traditional data sources that can also be used to build this dataset? Can we create an observational data testbed to test models?

Group 5 – Emerging sensing technologies and their use (Lead: Mark Potosnak (DePaul Univ.))
Address: Emerging smart city sensing technologies and their possible use in model development. How can observational studies of urban regions be used to aid the modeling community? Generally, observational sites and sensors in cities are poorly placed and likely are non-representative of their neighborhoods. The development of dense cheap sensor networks provides an opportunity to bridge this gap. However, using these datasets for evaluating models or process-scale model development will be a challenge due to data quality and consistency issues. Is there a pathway for using these datasets for rigorous scientific model evaluation and model development? Does the concept of an Integrated Field Laboratory (based on the earlier workshop mentioned above) bridge the gap between the cheap/dense networked datasets and research quality data needs?

Group 6 – The need for ultra-high-resolution land use datasets (Lead: Jason Ching (UNC))
Address: The urban environment is extremely heterogeneous, but modeling representation of cities across the world fail to capture this heterogeneity due to the lack of availability of ultra-high-resolution land use datasets. One exception is that cities in United States have available a 30-m resolution National Land Cover Database (NLCD) set of data, with ~45 cities included in the even more powerful National Urban Database and Access Portal Tool (NUDAPT) resource. There is thus need to actively pursue developing these databases on a global scale. How do we collect and analyze large urban datasets and use that data to inform models? How can we use generalizations, yet still account for the uniqueness of each urban center?

04:40-5:10 Presentation: Urban, energy, Exascale Earth system modeling: a perspective from E3SM (Kate Calvin, PNNL)
05:10-5:30 Daily summary, feedback and discussion – led by Don Wuebbles
Note: Breakout summaries to be prepared overnight
May 24, 2019

08:30-09:00: Coffee, tea and light refreshments
09:00-09:10: Setting up the 3rd day (Lead: Beth Drewniak)
09:10-10:15: Summaries from Breakout Groups 4, 5 and 6
10:15-10:30: Break
10:00-11:30: Panel discussion: Revisiting Urban in ESMs – How do we get to where we need to get to?
Panel: Ramaswamy (NOAA GFDL), JF Lamarque (NCAR), Fei Chen (NCAR), Dev Niyogi (Purdue Univ.); each talk for 7 minutes followed by 60-minute discussion (Discussant: Rao Kotamarthi)
11:30-12:00: Next steps, writing assignments, etc. (Lead: Don)
12:00: Meeting Adjourned
Appendix B

Participants in the Workshop

Photo of workshop participants from August 23 (some attendees are missing). There are also reflections affecting the quality of the picture.
# Appendix C

**List of Workshop Participants**

<table>
<thead>
<tr>
<th>Name</th>
<th>Affiliation</th>
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<tbody>
<tr>
<td>Asrar, Ghassem</td>
<td>Pacific Northwest National Laboratory</td>
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<tr>
<td>Baklanov, Alexander</td>
<td>World Meteorological Organization (WMO)</td>
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<td>Barzyk, Julia</td>
<td>US Army Research Office</td>
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<tr>
<td>Bettencourt, Luis</td>
<td>Mansueto Institute for Urban Innovation</td>
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<td>Beyers, Johannes</td>
<td>Klimaat Consulting &amp; Innovation</td>
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<td>Bornstein, Robert</td>
<td>SJSU</td>
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<td>Bou-Zeid, Elie</td>
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<td>Calvin, Katherine</td>
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<td>Chen, Amy (Shaowen)</td>
<td>University of Illinois at Urbana-Champaign</td>
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<td>Chen, Fei</td>
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<td>Ching, Jason</td>
<td>UNC-Institute for the Environment</td>
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<td>Drewniak, Beth</td>
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<td>Feddema, Johannes (Johan)</td>
<td>University of Victoria</td>
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<td>Ghude, Sachin</td>
<td>Indian Institute of Tropical Meteorology</td>
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<td>Geometto, Marco</td>
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<td>Gonzalez, Jorge</td>
<td>The City College of New York</td>
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<td>Graham, Robin</td>
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<td>Hartin, Corinne</td>
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<td>Horton, Daniel</td>
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<td>Ramaswamy, Venkatachalam</td>
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