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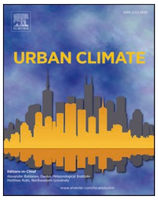

Urban climate and resiliency: A synthesis report of state of the art and future research directions☆

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ABSTRACT

The Urban Climate and Resiliency-Science Working Group (i.e., The WG) was convened in the summer of 2018 to explore the scientific grand challenges related to climate resiliency of cities. The WG leveraged the presentations at the 10th International Conference on Urban Climate (ICUC10) held in New York City (NYC) on 6–10 August 2018 as input forum. ICUC10 was a collaboration between the International Association of Urban Climate, American Meteorological Society, and World Meteorological Organization. It attracted more than 600 participants from more than 50 countries, resulting in close to 700 oral and poster presentations under the common theme of “Sustainable & Resilient Urban Environments”. ICUC10 covered topics related to urban climate and weather processes with far-reaching implications to weather forecasting, climate change adaptation, air quality, health, energy, urban planning, and governance. This article provides a synthesis of the analysis of the current state of the art and of the recommendations of the WG for future research along each of the four Grand Challenges in the context of urban climate and weather resiliency; *Modeling, Observations, Cyber-Informatics, and Knowledge Transfer & Applications.*

1. Introduction & synthesis

The Urban Climate and Resiliency-Science Working Group (i.e., *The WG*) was convened in the summer of 2018 to explore the scientific grand challenges related to climate resiliency of cities. The WG leveraged the presentations at the 10th International

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☆ By the Working Group of the 10th International Conference on Urban Climate (ICUC10)

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Conference on Urban Climate (ICUC10)[1] held in New York City (NYC) on 6–10 August 2018 as input forum. ICUC10 was a collaboration between the International Association of Urban Climate, American Meteorological Society, and the World Meteorological Organization. It attracted more than 600 participants from more than 50 countries, resulting in close to 700 oral and poster presentations under the common theme of *"Sustainable & Resilient Urban Environments"*. ICUC10 covered topics related to urban climate and weather processes with far-reaching implications to weather forecasting, climate change adaptation, air quality, health, energy, urban planning, and governance. ICUC10 was one of a series and reports of recent international conferences addressing climate resilience for cities. Oher key international conferences include CityIPCC conference (Cities and Climate Change Science Conference - CitiesIPCC,[2] Edmonton, Canada, 5-7th March 2018), in particular requirements for upscaling urban data science for global climate solutions (Creutzig et al., 2019), and the UN Habitat3 conference where the New UN Urban Agenda and Sustainable Development Goals (SDGs) include urban sustainability.[3] A recent relevant complementary report is given by the Grimmond et al. (2020), where guidelines from the World Meteorological Organization (WMO) for science-based services to support safe, healthy, resilient and climate friendly cities are outlined, specifically for Integrated Urban Hydrometeorological, Climate and Environmental Services (IUS).

The WG consisted of more than 25 urban climate scientists, 13 university faculty, three national laboratory scientists, two postdoctoral fellows, and eight doctoral students. Table 1 shows the WG participants. Its members met before the meeting, attended conference sessions, and reconvened after the meeting to reflect on the key emerging scientific challenges required to further advance the field of urban climate and weather in the context of increased resiliency to extreme weather and climate events. The WG organized the recommendations for research along the lines of the following four Grand Challenges: *Modeling, Observations, Cyber-Informatics, and Knowledge Transfer & Applications.* This article provides a synthesis of the recommendations of the WG for future research along each of these Grand Challenges in the context of urban resiliency. The following sections provide expanded analyses and recommendations, followed by an extensive literature list.

(i) **Summary on the Modeling Grand Challenge**

Over-Arching Recommendations:

- To satisfy end-user demands, weather prediction and regional climate models are moving into an era of convection-permitting modeling on the kilometer grid resolution, a scale critical for assessing high-impact weather and climate extremes. In such high-resolution modeling over complex urban environments, a full theoretical understanding and modeling the 3-D nature of turbulence is still lacking.
- In the general earth-system modeling framework, the representation of the nexus between urbanization, water, agriculture, and energy is also still in an early stage.

It is thus imperative to improve the understanding of cross-discipline and cross-scale inter-actions in and around cities, from surface interactions to cloud life cycles, to lay a foundation for the building of better urban models for diverse applications. Following is a list of areas needing further consideration and development.

Specific Recommendations on Urban Modeling:

- ***Incorporate human-process in urban modeling:*** Urban canopy models (UCMs) commonly rely on a horizontally averaged approach, where the roughness-sublayer is portrayed as a single column, often representative of statistically homogeneous urban geometries. Urban surfaces are, however, statistically heterogeneous at the scales of interest and are also comprised of a wide range of length scales. Current theories are hence limited in their predictive capabilities, and such a deficiency calls for improved physical-based parameterizations that can account for the complex 3-D flow field and its heterogeneity. Future efforts to incorporate complicated 3-D effects will need to account for the hierarchical structure of scales within urban canopies.
- ***Improve weather/climate prediction of extremes for coastal cities:*** Current models still lack skill in providing forecasts at the spatiotemporal scales demanded by stakeholders. To assess interconnected weather-infrastructure-environment impacts and hazards, a concerted effort is required to integrate models across disciplines (weather, hydrology, biomass, agriculture, and energy) pertinent to coastal cities.
- ***Harness big data:*** Newly available large datasets provide opportunities to improve urban model development and application. The concepts of local climate zones (LCZs) and of the World Urban Database and Access Portal Tools (WUDAPT) were thus widely discussed at ICUC10. A significant challenge is still the data availability at urban model- relevant scales (a kilometer).

(ii) **Summary on the Observational Grand Challenge**

- ***Representativeness of observations:*** Experimental data should be thoroughly investigated at relevant representative urban spatiotemporal scales.

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[1] 10th International Conference on Urban Climate/14th Symposium on the Urban Environment - American Meteorological Society (ametsoc.org)

[2] Cities and Climate Change Science Conference — IPCC

[3] UN Habitat III Conference – United Nations Sustainable Development

Table 1
Working group participants.

Name	Affiliation	Subgroup
Faculty		
Prof. Jorge E Gonzalez	The City College of New York (CCNY)	MOD
Prof. Bob Bornstein	San Jose State University	MOD
Dr. Fei Chen	National Center for Atmospheric Research	MOD
Prof. Masoud Ghandehari	New York University	CYB
Dr. Jeffrey Luvall	NASA	CYB
Prof. Chandana Mitra	Auburn University	KTA
Prof. Dev Niyogi	Purdue University	KTA
Prof. Prathap Ramamurthy	The City College of New York (CCNY)	OBS
Prof. Rae Zimmerman	New York University	KTA
Prof. Sue Grimmond	University of Reading	OBS
Prof. Elie Bou-Zeid	Princeton University	OBS
Prof. Matt Georgescu	Arizona State University	KTA
Dr. S. Miao	Beijing Institute of Urban Met	OBS
Prof. Jamie Voogt	University of Western Ontario	OBS
Prof. Qi Li	Cornell University	OBS
Dr. Mark Arend	The City College of New York	CYB
Post-Doc and students (with Advisor)		
Rabindra Pokhrel	CCNY (Prof Jorge E Gonzalez)	MOD
Luis Ortiz	CCNY (Prof Jorge E Gonzalez)	MOD
Meiling Gao	NCAR (Dr. Fei Chen)	MOD
Megha Shrestha	Auburn Uni (Prof Chandana Mitra)	KTA
Will Morrison	University of Reading (Prof. Sue Grimmond)	OBS
Daniel Comarazamy	CCNY (Prof. Jorge E. Gonzalez)	MOD
Jiachuan Yang	Princeton Uni (Prof Elie Bou-Zeid)	MOD
Ashley Broadbent	Arizona State University (Prof. Matt Georgescu)	KTA
Michael Allen	UC-Santa Barbara (Prof. Jamie Voogt)	KTA
Mariana B. Alfonso Fragomeni	University of Georgia (Prof. Marshall Shephard)	KTA

CYB=Cyber Informatics
KTA = Knowledge Transfer
MOD = Modeling
OBS=Observations

- ***Logistics:*** Scientists should develop better liaisons with local governments to gain the necessary permissions for sensor placement and other miscellaneous needs. In large cities, security and insurance could be major impediments for the conduction of field studies that could be avoided with better communication with City Administrators.
- ***Data Redundancy:*** It is imperative that data across all sensors in field experiments are recorded, quality controlled (QCed), stored, and eventually shared.
- ***Public Datasets:*** Government agencies collect a variety of data for use in studies of the Urban Boundary Layer (UBL). These data can be used to validate and force UCMs.
- ***QA/QC:*** Current field experiments collect data from a variety of sources (fixed, mobile, and remote), and care should be taken to implement the necessary and relevant quality control (QC) protocols. Urban climate scientists should also be wary of the blind use of current technologies like machine learning to interpret large datasets.

(iii) **Summary on the Cyber Informatics and Data Management Grand Challenge**.

Urban Cyber-informatics was defined by the WG as "*the collection of digital information and the approaches for processing and analysis of both environmental data and that relevant to the theater of urban operations.*" These challenges and opportunities are further elaborated as follow;

- ***Organic/administrative and Citizen generated data:*** These datasets consists of:
- (a) **Socioeconomic data** on wealth, health, and education
- (b) **City administration data**, including logistics of operation (e.g., waste) and financial matters, but only available in data rich cities
- (c) **Health data**, collected for public health monitoring and epidemiological studies (e.g., vector borne, water borne, infectious); for environmental diseases (e.g., air quality and toxic chemical exposure, and heat stress); and for hospital admissions for various disease conditions)
- (d) **Crowd-sourced data**, generated from the rapid growth of social media and information technology, which has resulted in large volumes of social data, such as patterns of mobility.
- ***Sensor data:***

Fig. 1. ICUC10 Participants.

- **Remote/spaceborne**: The large spatial coverage and legacy of spaceborne data is of great value, and its respective imagery delivers good spectral resolution; however. The spatiotemporal resolutions are not simultaneously delivered at high fidelity. Emerging developments in high resolution interferometric synthetic aperture radar will be a great asset for urban climate studies of extreme processes when deployed.
- **Remote/ground based and airborne**: Data processing techniques for ground based remote sensing instruments (lidars, radars, sodars, and radiometers) are being advanced by co-operating them for allow for multiple spatial and temporal scales to be identified; this is particularly important in complex urban-coastal environments.
- **In-situ (static/mobile)**: For in-situ instruments designed for high sensitivity and high accuracy, mobile applications require precision time/space signatures. The emergence of low-cost micro sensors and the internet of things is promising, but need be statically located resulting in wide-spread applications. The time/space data processing challenges of mobile in-situ sensors is somewhat resolved, but then shifts to challenges presented from managing large amounts of sensor data.

(iv) **Summary on the Knowledge Transfer & Applications Grand Challenges**.

Climate change has prompted a stronger focus on the identification of vulnerable populations and on optimal strategies for mitigation and adaptation, based on local environments and needs. This focus on local environmental needs has gained momentum in the 2000s when the impact of extreme events on humanity at different scales were more frequently seen throughout the world. Knowledge transfer and application (KTA) are two key components to understanding urban sustainability and resiliency. Urban climate research is pointless from the sustainability point of view if KTA is not considered through all process from the beginning to the end.

Bridging the gaps in KTA is easier said than done. Many fundamental urban climate experiments (ranging from observational campaigns to numerical modeling efforts) have been performed but not much progress has been made when it comes to knowledge dissemination and application at the ground level. One of the main causes for this may be the separate silos in which researchers and stakeholders reside, maintaining a continued disconnect from each other. In addition, the communication gap between scientists and decision makers who understand the language of cost and benefits associated with the implementation of urban sustainability measures remains. Along with this comes the inherent communication gap between scientists-stakeholders and the citizenry. Finally, the range of research performed to date (e.g., modeling) lacks a systematic basis for comparison, rendering it difficult to communicate anticipated impacts associated with varying, for example, heat mitigation strategies.

The knowledge gaps related to urban climate research continue to build with each new contribution to the field. A number of systemic problems are evident in order to gain from and build upon this knowledge and to move forward in fruitful directions. Some have pointed to the need for interdisciplinary thinking, collaboration, scale of discourse, and urgency.

The WG thus recommends a unified vision to address the resiliency of urban environments that is driven primarily by stakeholders and that incorporates detail physical processes in local environments, bounded by large scale forcing, such as changing climates, as illustrated in Fig. 2. This vision is consistent with and complementary to WMO-IUS (Grimmond et al. 2020), which recommends combining observational networks, high-resolution forecasts, multi-hazard early warning systems and climate services to assist cities in setting and implementing mitigation and adaptation strategies for the management and building of resilient and sustainable cities. (See Fig. 1)

Detail review of the current state of the science and recommendations follow below for the four main *Grand Challenges* outlined above.

2. Summary of grand challenges in urban climate modeling

Working Group co-chairs: Robert Bornstein and Fei Chen.

Members: Meiling Gao, Marco Giometto, Qi Li, Luis Ortiz, Rabindra Pokhrel, Jiachung Yang, Shiguang Miao.

This section provides a review on the current progress and challenges in the area of urban climate modeling, based on presentations at the ICUC-10 Conference and on discussions at the one-day Workshop held after ICUC-10. In summary, despite significant progress over the last two decades to develop, implement, and evaluate urban-process models for weather and climate applications, such efforts still face several grand challenges as outlined herein.

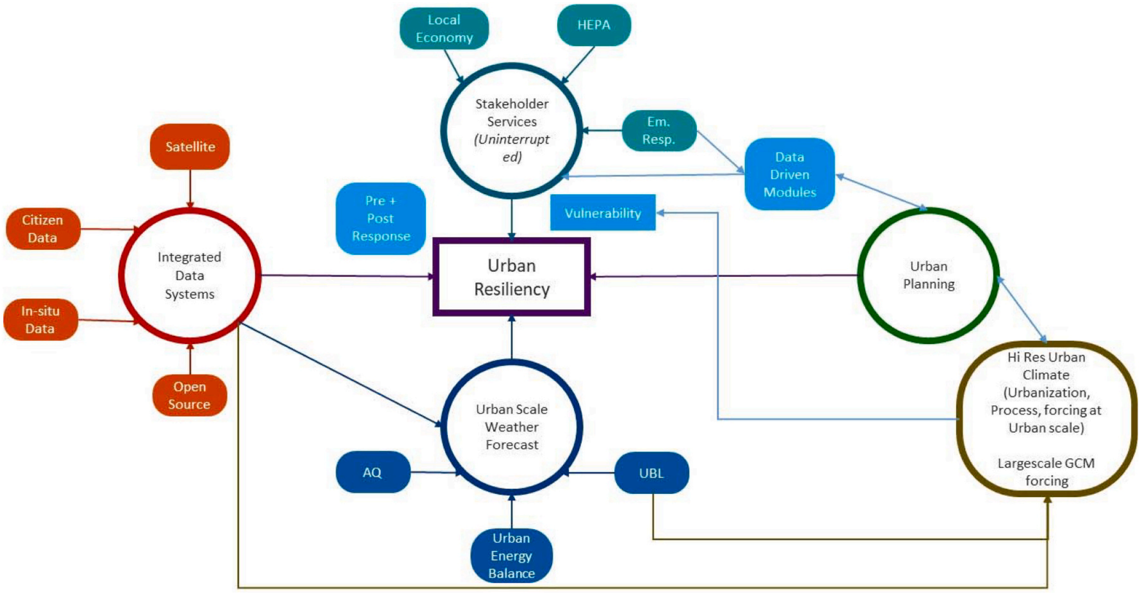

Fig. 2. Framework for Environmental Services for Coastal-Urban Resiliency.

To assess the progress, before the actual ICUC-10 the working group posed the following general guiding questions for its members when they covered their assigned conference sessions:

1. How can we effectively observe, predict, and model both 3-D near surface atmospheric turbulence at multiple scales under mean and extreme conditions, as well as its associated planetary boundary layer (PBL) variables, and how are these influenced by the unique topological and energetic surface heterogeneity characteristics of complex cities?
2. How can we use these observations and models to gain an improved understanding of the diurnal cycle of environmental flow fields over a range of natural and urban systems, including tropical, subtropical, and cold climate, and how can this understanding serve to advance both near-term weather forecasts and long-term climate predictions under extreme conditions?

After ICUC-10, the working group had a one-day meeting to discuss and summarize current progress and to develop ideas of how to address the above grand challenges in ur-ban modeling. They identified the following three priorities in urban modeling research:

1. Human-process modeling
2. Improved extreme weather/climate predictions for coastal cities
3. Urban big data.

2.1. *Priority #1: Human-process modeling*

Urban canopy models (UCMs) within Reynolds-averaged Navier-Stokes (RANS) weather models commonly rely on horizontal grid-averaged approaches, in which the urban roughness-sublayer (RSL) is represented as a single column. This column is often assumed representative of statistically homogeneous urban geometries, such as cube arrays and uniform vegetation canopies. Examples of such theories include the classic Monin-Obukhov Similarity Theory (MOST), and solution for flows within vegetation canopies (Cionco, 1965). By their nature, however, urban surfaces are statistically heterogeneous at the scales of interest for UCMs, and they also comprise a wide range of length scales. Current theories are thus limited in their predictive abilities, and this deficiency thus calls for improved physically based parameterizations that can account for the complex 3-D heterogeneous urban flows, as well as for its impacts on turbulent mixing. Future efforts to incorporate these complicated 3-D effects will need to account for the hierarchical structure of scales within urban canopies, from canyon to regional (Britter and Hanna, 2003). Future PBL turbulence closures will also need to account for these complexities (Jimenez and Kosović, 2016; Martilli et al., 2018). This is necessary, as the assumption of horizontal homogeneity is violated on a spatial scale of only a few kilometers, at which mean urban circulations are produced. Most mesoscale weather models still rely on MOST relationships to compute vertical momentum and scalar fluxes (such as heat, moisture, and pollutant). As spatial resolution in such models, however, approach the "grey area" of turbulence (< 1 km), near-wall parameterizations need to account for such complex 3-D exchanges.

Computational fluid dynamics (CFD) models have been used to study microscale to regional urban scale flows and transport processes. Large-eddy simulations (LES) are also an increasingly popular modeling method, such as the building-resolving PALM-4 U model (Maronga et al., 2018; Salim et al., 2018; Resler et al., 2018). When physical process or chemistry models are coupled to such microscale LES or RANS models, they need thorough validation (Kanani-Sühring et al., 2018). General guidelines for standardized practices for the development and validation such microscale models are still needed. It would be thus beneficial to the modeling community to provide such guidelines, especially for high-fidelity models that focus on resolving interaction between multiple physical and/or chemical processes. It is now common to assess impacts from extreme climatic and weather events on humans by driving microscale models with outputs from a mesoscale weather or climate model. It is still unclear how two-way coupling between such different spatial-scale models should be carried out, and if two-way coupling is superior to current one-way downscale approaches. Additional efforts are also needed to use existing urban observational data sets (e.g., NYC Mesonet) in this validation process and for development of urban-scale data assimilation methodologies.

Recent progress has been made to also integrate human-dimension models into urban scale weather and climate models. Masson et al. (2018) have improved building-energy simulations by incorporation of resident behavioral data concerning building energy use. To account for the heterogeneity in building occupancy parameters and in air conditioning use, Xu et al. (2018) introduced a “cooled fraction” parameter in WRF-Urban. Current approaches generally use energy use schedules and densities based on building type (Ortiz et al., 2016; Salamanca et al., 2015; Gutiérrez et al., 2013), but Capel-Timms et al. (2018) recently proposed a model to dynamically estimate building energy heat fluxes from neighborhood scale parameters. The large-scale urban energy model of Allen et al. (2011) also estimated anthropogenic heat flux (i.e., metabolic, vehicle, and building) components from empirical relationships derived from population, traffic, and building density data. Current urbanized weather models, such as WRF-Urban coupled with the Building Effect Parameterization (BEP, Martilli et al., 2002) and the Building Energy Model (BEM, Salamanca et al., 2010) use gridded building density datasets, but BEM still relies on pre-defined schedules and appliance energy parameters. Vehicle heat is not, however, included in BEM, and metabolic heat may only be included as a BEM sub-component.

Indoor conditions, however, have remained mostly in the domain of single building energy models (Buechler et al., 2017) and CFD models (Gilani et al., 2016; Aryal and Leephakpreeda, 2016; Buratti et al., 2017). A need thus exists to assess indoor heat and air quality risks at scales more relevant to policy makers, such as for neighborhoods (Sailor and Baniassadi, 2018; Crank et al., 2018). Cities also play a critical role in the redistribution of regional water resources (Wang, 2018) and they are also major pollutant sources. Technology innovation (e.g., electric cars, wastewater treatment) and ongoing adaption efforts (e.g., solar panel deployment) are also likely to modify urban hydroclimates at the micro- and meso-scales. Such processes also need to be accounted for in future models. Issues exist related to data availability, unified data formats, and ways to integrate human-dimension data into urban climate studies. To assess impacts from urban climates on humans and how their activities in cities act as spatially localized climate forcers, it is imperative to soon expand the human dimension in urban modeling.

Modeling a variety of adaptation and mitigation strategies for climate change has been explored for different cities (e.g., Sharma et al., 2016, 2018). Common strategies reported at ICUC-10 were to improve indoor comfort, reduce heat stress, and reduce UHI effects. Green roof, cool roof, efficient HVAC systems, increased thermostat set points, and PV Technologies were each studied using the BEP + BEM scheme in WRF (Fig. 3), and all these technologies were found to improve indoor heat balances (Pokhrel et al., 2020) Local- and micro-scale heat stress mitigation alternatives by the use of trees in urban landscapes were also explored as efficient heat mitigation strategies (Fujiwara et al., 2018). Cost-benefit analyses were, however, lacking for the various mitigation alternatives. Still unanswered are the effects of these alternatives on climate and human stress, which suggests an exploration of passive methods to mitigate heat stress.

A need also exists to make complex models accessible to general users and to develop simple models for them. Weather and climate models are more useful to scientists, emergency managers, and policymakers when they connect to GIS mapping and analysis tools, but GIS techniques are not yet widely integrated within the atmospheric research community (Wilhelmi and Brunskill, 2003; Armstrong, 2015). At ICUC-10, GIS4WRF was used to combine GIS and climate models (https://github.com/GIS4WRF/gis4wrf/blob/master/README.md). The effort also used QGIS Plug-in for pre- and post-processing within WRF. Belgacem et al. (2018) has also used QGIS to describe the urban form for wind field related work. (see Fig. 4

Fig. 3. Sample of photos from ICUC10. (Left: Poster session: Right Late Prof. Sergej Zilitinkevich giving an explanation to a colleague from his invited plenary talk).

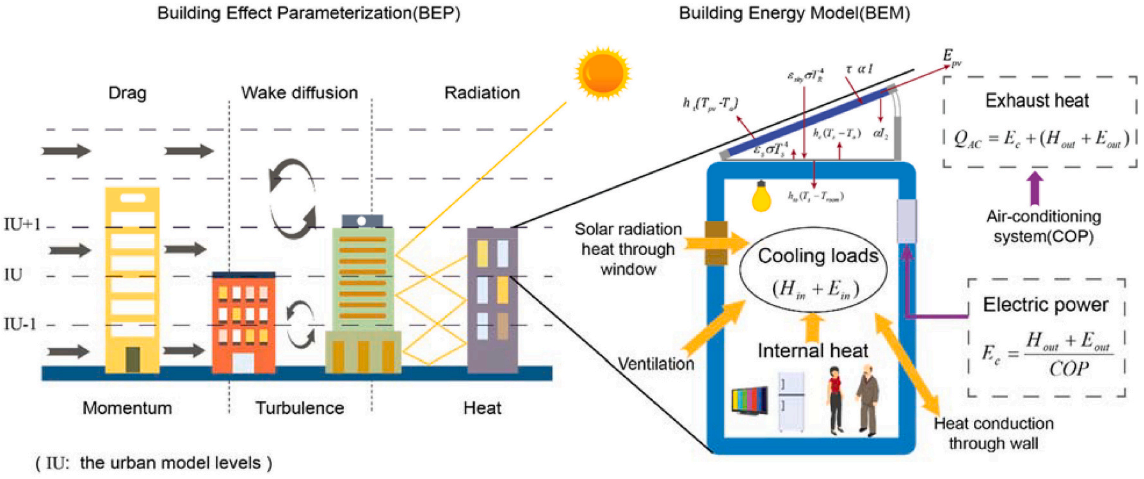

Fig. 4. Latest configuration of BEP + BEM to incorporate building energy technologies and indoor air quality (Pokhrel et al., 2020).

2.2. Priority #2: Improved weather/climate prediction of extremes events in coastal cities

Current prediction models still lack skill for forecasting at the temporal and spatial scales demanded by urban state holders and policy makers. Assessment of interconnected weather-infrastructure-environment impacts and hazards requires concerted efforts to integrate models across the weather, hydrology, biomass, agriculture, and energy disciplines. Recent efforts to partially addresses this challenge include WRF-Hydro (Gochis et al., 2018), which links surface and sub-surface hydrological processes to WRF. Other efforts include WRF-Urban (Chen et al., 2011) that couples BEM (Salamanca et al., 2010) to WRF, and WRF-Crop (Liu et al., 2016) that links dynamic crop models to the Noah-MP land surface parameterization in WRF. Such integra-ted modeling will be invaluable in the quantification of feedbacks from extreme events, such as from dry soils leading to extreme heat events (Fischer et al., 2007; Lorenz et al., 2010), which might intensify in urban environments (Li and Bou-Zeid, 2013; Ramamurthy et al., 2017).

Coastal urban communities are important as they occupy a dynamic interface between land, sea, and atmosphere, and they are subjected to unique stresses aggravated by climate change. While key drivers of coastal and urban climate processes have been each reasonably well established, the interaction between them and their dynamic feedbacks that influence near surface energy, mass, and momentum transport are still not well understood (Allen et al., 2011; Nicholls, 1995). Coastal microclimates are characterized by sea breezes, as the differential heat capacity between the sea and land leads to a sharp contrast in surface temperature that introduces a distinct air circulation pattern (Calmet and Mestayer, 2015); the UHI is known to amplify this land-sea gradient (Childs and Raman, 2005). Daytime sea breeze circulations cause cooling over coastal land areas and lead to high spatial variabilities in humidity and aerosol distributions. They also produce systemic impacts on convective storms, e.g., Ntelekos et al. (2008) used radar and disdrometer observations along with meso-scale modeling to observe summertime thunderstorms in the Chesapeake Bay area. They concluded that the thermal environment within the breezes impacted both storm evolution and rainfall distribution, with aerosol effects dominating UHI effects. This result contrasts to other studies that found UHIs dominant, e.g., Shepherd (2005) found that the Houston metropolitan area UHI initiated a strong convergence zone that accelerated the sea breeze front and increased its vertical velocity. Keeler and

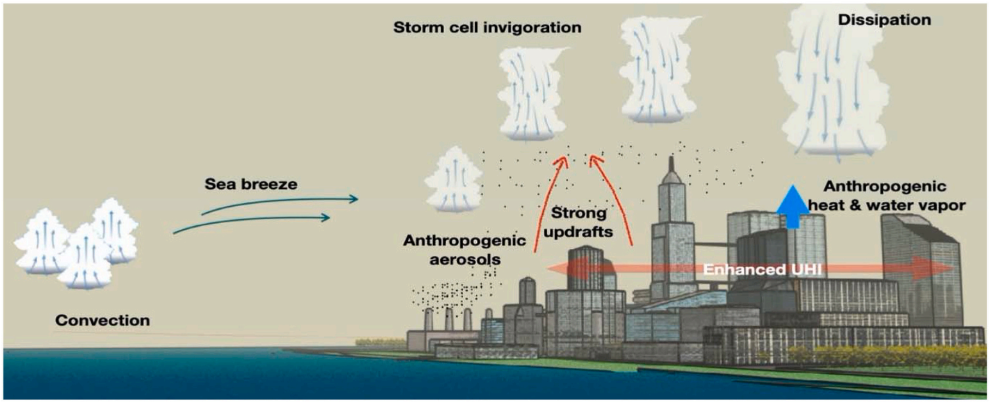

Fig. 5. Schematic describing the key dynamics in coastal urban environments, e.g., strong sea-breeze convergence, anthropogenic aerosols, and high turbulence that influence cloud formation and precipitation (Source: P. Ramamurthy).

Kristovich (2012), however, found that a lake breeze front slowed because of an UHI in the Great Lakes region. On longer time scales, Sequera et al. (2015) and Lebassi et al. (2005) found increased sea-breezes over a 30-year period in the Los Angeles basin due to an amplified land-sea thermal gradient from both an UHI and warmer inland rural areas. These diverging conclusions show our lack of our understanding of the ocean-urban-rural intersect and of its frontal dynamics (Fig. 5). Key questions on coastal-urban environmental modeling of extremes include:

- What are the phenomenological differences between coastal urban and inland urban boundary layers (UBLs)?
- How do internal BLs that form in coastal urban areas impact convection?
- How do coastal-urban gradients influence the initiation and evolution of convective clouds, as compared to pristine areas?
- How does the transport of momentum and heat in the convective UBL vary during convective periods?
- What are the dominant scales of transport along the transect from pristine coastal to urban convective BLs?
- What is the impact of sea breezes on BL development, when influenced by urbanization?
- What is the influence of turbulent transport in coastal urban environments on convective clouds?

2.3. *Priority #3: Use of urban big data sets*

Newly available data provide new opportunities to improve urban model development and application. For instance, LCZs and WUDAPT (Ching, 2018) have been widely discussed at ICUC-10 (Brousse et al., 2016; Cai et al., 2016; Danylo et al., 2016). They both classify urban land-use patterns in a consistent manner for use in climate and social studies. Numerous presentations at ICUC-10 used WUDAPT land class zone classifications to study climate and air conditioning demand for different cities in Europe, Africa, Asia, and the Caribbean region.

As more LCZ datasets become available for cities around the world, classification and evaluation methods, as well as data quality, vary significantly (Kotharkar et al., 2018; Verdonck et al., 2017). A study in Ukraine (Danylo et al., 2016), for example, showed a classification accuracy of 75%, while that in Guangzhou was 84% (Cai et al., 2016). It is thus critical to develop unified data QA/QC guidelines. The invited presentation on WUDAPT by Mills highlighted the need to generate microscale urban building data. WUDAPT at a 100 m resolution makes it possible to study the interaction between climate and buildings at a microscale level.

The large challenge of including human behavior into UCMs is the availability of data at model-relevant scales (kilometer). Larger cities like NYC are adopting open data policies that may provide the necessary information (https://www1.nyc.gov/site/planning/data-maps/open-data.page).

2.4. *Working group recommendations*

It is imperative to improve the understanding of cross-discipline, cross-scale interactions in and around cities from the surface up to clouds, laying foundations to building better urban models for diverse applications. Following is a list of areas needing further consideration and development:

1. **Modeling urban canopy processes:** At convective scales, flows become fully 3-D, and are far more: complex than 2-D turbulence, transient, and intermittent. A general lack understanding exists of interactions between 3-D atmosphere turbulence processes with the additional sources of energy induced by tall structures and trees, anthropogenic heating, traffic, etc. How to model the interactions between the urban canopy and ABL at scales ranging a few meters to kilometers? How can LES and other modeling approaches be used to inform cross-scale modeling? How to develop better coupling between meso-scale and microscale models, both in one-way (downscaling) and two-way (downscaling and upscaling) modes.
2. **Modeling urban underlaying surfaces:** How to represent: urban soil, vegetation, hydrology, and ecosystems, especially their effects on evaporation; radiation budgets; surface heat fluxes; and source and deposition of GHGs and biogenic volatile organic compounds (VOCs)? Is the current "tile or mosaic" approach appropriate for modeling urban land use?
3. **Urban data consistency:** Diverse methods exist to represent the static and dynamic characteristics of urban land-use and land-cover, including WUDAPT, remote-sensing data, and local surveys. Are those data consistent, and do they inform the specification of urban model parameters? How to integrate new data sources (e.g., WUDAPT)? How do we assess the impact of the uncertainties in those data on model predictions?
4. **Urban forecast of high-impact weather and climate extremes:** Are current models technically ready for location-specific megacity predictions of storms and floods, as this would involve a multifaceted approach, including dynamics, thermodynamics, hydro-logical processes, and accurate aerosol and cloud models. Current research, however, often focuses on only one of these processes and yet still has significant uncertainties.
5. **Model evaluation: benchmark and metrics**: More observational data at the right temporal and spatial scales are needed, e.g., vertical profiles, to assess model capabilities to simulate the vertical structure and height of the UBL. How to expand existing networks of surface stations to satisfy modeling and prediction needs? How can newer modeling tools (LES, CFD) be used to benchmark urban canopy models?
6. **Urban data assimilation:** New technologies, such as lidars, sodars, fiber optical temperature measurements, UAVS, HOBOs, and TinyTags provide atmospheric variables in greater spatial detail, both horizontally, and even more critically, vertically. How can these new data and other conventional urban-scale observations be assimilated into operational forecast models? Heterogeneities in urban areas require that extreme care be taken to ensure the spatial representativeness of urban measurements. Because of

logistical constraints, traditional data-assimilation techniques for rural areas are likely not appropriate for urban areas. The more pressing issue, however, is the absence of equivalent local-scale measurements, as in rural areas.

Observational measurements and modeling both require clear statements of their intended application, so that the compromises between approaches to achieve their goals (e.g., practical constraints, costs, and permissions for siting) are the correct ones.

3. Summary of grand challenges on observations of the urban environment

Working Group co-chairs: Eli Bou-Zeid & Prathap Ramamurthy.

Members: Jamie Voogt, Qi Li, William Morrison.

Observations are critical to study and understand extreme weather and climate processes in urban environments, as they have the least a-priori assumptions or biases about how the physical processes operate at various spatial and temporal scales. Models require initial conceptual frameworks for their formulation, and this can only be developed through observations. Extreme weather and climate processes present new historical challenges due to the complexity of in-situ observations of the event, the conditions that led to it, and their interaction with the urban environment. Detailed observations thus remain critical to expand and deepen our physical understanding of urban climate, as well as to parameterize, verify, and evaluate urban models.

The rapid improvements in sensing technology, and the widening range of available sensors, sensor networks, and data streams are opening many new possibilities to better understand urban climates. They also raise new challenges to develop new approaches to evaluate the quality of these massive data sets and to analyze them to better inform theory and models. Given the complexity of scale and its interacting effects, if care is not taken in these analyses, the “signal” and the “noise” may be confused. We thus assess the current state of knowledge in urban observations, the most consequential current trends, and the critical knowledge gaps in the field with emphasis on extreme processes, such as heat waves, cold spells, and precipitation. We also highlight the general direction in which the urban community is moving by use of resources from ICUC10.

3.1. *Observations: A brief historical perspective and current status*

Observations reveal unknown phenomena and uncover unexpected trends, e.g., the recent path-breaking study of Jiang et al. (2018) found a slowdown in US pollutant emission reductions in the past decade. They observed that Nitrogen Oxides (NO_x) released from traffic was slowing down as expected, but industrial emissions were increasing. The first urban climate measurements occurred in London in the early 1800s, when careful observations with more than one thermometer were undertaken by Luke Howard (Mills, 2008) to identify and explain the UHI effect. Numerous urban experiments have since been carried out to study various urban processes and they have greatly contributed to our current fundamental understanding of urban climate. The vast majority of urban experiments conducted between 1970s–1990s were dispersion studies, primarily focusing on pollutant transport (Hanna, 1971; Wanner and Hertig, 1984; DePaul and Sheih, 1985; Hoydysh and Dabberdt, 1988). These early observations contributed immensely in the characterizino of key parameters relevant to urban transport processes, particularly the aero-dynamic roughness length and displacement thickness. They moreover aided in the parameterize-tion of momentum transport in the urban surface layer. Several studies during this period also focused on UHI effects, and the early Oke and Cleugh (1987), Oke (1988, 1995) studies were critical to development of a framework to understand the urban surface energy budget. In the 2000s several experiments were conducted to quantify urban carbon dioxide fluxes (Nemitz et al., 2002; Roth et al., 2003; Moriwaki and Kanda, 2004; Velasco et al., 2005; Coutts et al., 2007; Ramamurthy and Pardyjak, 2011; Gately et al., 2015). These experiments, apart from understanding sources and sinks in urban areas and their seasonal behaviors, also aided in understanding of scalar transport processes in urban environments.

In recent history, integrated city-scale field studies have linked multiple processes such at the various scales pertinent to urban climate. The recent Study of Urban Impacts on Rainfall and Fog/Haze (SURF) experiment was led by the Beijing Institute of Urban Meteorology (IUM, Liang et al., 2018). It was highlighted at ICUC10 as a city scale experiment with the objectives of investigating urban summer precipitation and winter haze, with boundary layer physics as the integrative variable.

Recent high-resolution mesoscale modeling has taken center stage in the urban climate community, while ICUC10 discussions pointed out some limitations of these models, they also highlighted how observations can aid in closing these significant knowledge gaps. For a thorough historical perspective refer to the recent text on urban climate by Oke et al. (2017). The WG concluded that significant observations are required to advance the current state of urban modeling, and this section summarizes the overarching knowledge gaps thus identified.

3.2. *Critical areas of observational research for mean and extreme climate and weather processes*

We will describe the key observational areas needed to be addressed in the coming years to improve our overall knowledge of urban climate. We have used the broad range of topics discussed at ICUC10 to identify these areas of interest.

3.3. *Priority #1: Urban climate dynamics*

Here we detail state of urban climate processes, particularly relating to the transport of momentum, heat, and scalars.

Urban Boundary Layer Characteristics. Most observations are within the urban surface layer, with few studies focused on the urban mixed layer. Barlow (2014) in a comprehensive review of urban meteorology suggested that basic details such as the depth of the mixed layer, fundamental to study pollutant dispersion and cloud formation, is unavailable from most studies. Baklanov et al. (2011) in a seminal assessment of current BL research and understanding underlined that urban mixed layers are the least understood. ICUC10 reflected this deficiency, as only a few studies (Kotthaus et al., 2018; Liu and Liu, 2018; Melecio-Vázquez et al., 2018a; Melecio-Vázquez et al., 2018b;) presented mixed layer measurements and most did not report BL heights. As highlighted by the invited talk by Zilitinkevich (2018) the BL is dynamic and continuously evolving, and in convective BLs large scale turbulent eddies impact surface layer transport. It is thus highly critical that future experiments observe the urban BL in its entirety.

Urban RSL Dynamics. Despite several studies conducted in the urban surface layer, transport dynamics in the RSL is not well understood. It is known that surface layer similarity scaling, commonly used in numerical models to determine surface layer fluxes, is inapplicable in the urban RSL (Roth, 2000). Current models, however, due to a lack of an appropriate framework still use aerodynamic resistances based on surface layer similarity to quantify RSL fluxes. This has led to poor model performance, particularly with heat fluxes. This issue remains elusive despite the large input by the RSL observational community as reflected in ICUC10, with a few exceptions (e.g., Shah et al., 2018). For efforts at understanding and mitigating UHI effects, our lack of understanding of RSL dynamics is a severe limitation. Extensive street to neighborhood scale field experiments are necessary to improve our current knowledge.

Observations at the Boundaries of Cities. The WG identified one area that needs significant attention: the boundaries between cities and rural areas, and between cities and the coast. Examples where this topic was advanced include Turku, Malmo, and New York City (Johansson and Yahia, 2018; Melecio-Vázquez et al., 2018b; Suomi et al., 2018), all of which highlighted the complexity of coastal urban atmospheres. Interaction between the advected marine and convective urban BLs give rise to complex flow and transport phenomena. Melecio-Vázquez et al. (2018a) have observed the formation of thermal internal boundary layers (IBLs) in a coastal environment. Few details are available, however, due to lack of comprehensive observations at such interfacial boundaries. Coastal cities around the world are highly vulnerable to extreme events; in the US alone several billion dollars have been spent in the past decade in recovery efforts due to extreme events along its Gulf and Atlantic coasts. While hydro-meteorological extremes are mainly due to modifications in large scale climate patterns, the devastating impacts are almost entirely felt in urban centers. It is thus extremely vital that comprehensive observations are conducted along such interfacial boundaries to understand the dynamics of extreme events.

Anthropogenic Influences. Anthropogenic influences on UHIs, CO_2 emissions, and pollutant dispersion received considerable attention at the conference. Adelia et al. (2018), Ouyang et al. (2018), and Sargent et al. (2018) all reported anthropogenic influences on UHIs in Boston, Singapore, and Honk Kong, respectively. New airborne measurements with traditional aircrafts quantified GHG emissions over NYC (Ren et al., 2018), while Karion et al. (2018) described the creation of CO_2 and CH_4 in the northeastern US. While strong improvements have been made in this area in the last decade, the WG finds that technological gaps still exist in the integration of the various datasets. Most numerical modeling frameworks can absorb anthropogenic sources, but a WUDAPT-like framework is necessary to structure these observations.

Extreme Events. Urban observations during extreme weather events generally remain sparse. Pullen (2018) discussed the infrastructural challenges due to extreme urban flooding and storm surges along the New York/New Jersey coastline. The need for more local scale observations to enhance modeling capabilities under extremes is essential. Tsiringakis et al. (2018) and Avinash et al. (2018) observed urban impacts on precipitation processes in Jakarta and Bangalore, respectively, and both concluded that urban peripheries receive anomalously higher rainfall as compared to city centers. Both used radar observations, but high-resolution observations of extreme precipitation and flooding events are currently unavailable. While polarimetric radar data is available in most major cities, its resolution is too coarse to study intra-urban variability. Integration of radar data with near ground measurements (like from rain gages) is required to facilitate studies in urban areas.

For extreme heat, several studies used only numerical models to study the heatwave dynamics and they proposed mitigation strategies. Comprehensive observations of critical meteorological variables during heatwave events remains rare. Dynamic differences in BL state during regular periods versus extreme events needs to be synthesized, and necessary modifications need to be made in numerical prediction frameworks.

Urban Soil Characteristics. Urban soil is a principal component of its microclimatic system and it strongly impacts various dynamic processes in the surface-atmosphere continuum, particularly its water and energy cycles (Zuckerman, 2008). Natural soil profiles consist of many layers with distinct properties, and urban soils do not necessarily have the same profiles as natural ones. An urban soil in a metropolitan area has typically been moved, graded, and/or or compacted over time, often during construction and demolition activity. The movement of soil and the addition of non-native soils is also relatively common in developed areas. Because of the way in which soil has been altered, great variations exist in its characteristics within an urban land parcel. Soil studies in urban areas have found that compaction, low organic matter content, and low levels of contamination usually from air deposition or from historical uses on site are common attributes of urban soils (Zuckerman, 2008). To what extent they influence the role of the soil as a key component in the land-atmosphere continuum is unknown and their impact on the urban energy and water cycles and on street, neighborhood, and city scales is also poorly researched. ICUC10 and recent forums or peer-reviewed contributions have not provided new data on urban soils. That current numerical models thus use non-urban soil parameterizations in urban grid cells is a large factor in their poor performance in modeling latent heat fluxes. With cities around world aggressively pursuing greening strategies to mitigate UHIs, it is extremely vital to study urban soils.

3.4. Priority #2: Emerging technologies

Here we detail the current and upcoming trends in sensor technologies that can be used to enhance urban observations, as presented at ICUC 10. These include new low-cost smart sensors powered by the internet of things (IoT), unmanned aerial vehicles, CubeSat, and urban scale satellite measurements.

Low-Cost Smart Sensors. A common logistical constraint in urban meteorological observations is instrumentation cost, which restricts our ability to sample at adequate spatial resolutions. In the last decade, electronics miniaturization and progress in communication technologies, have enabled development of low-cost, low-power sensors that can be spatially distributed and that can communicate with one another or to a centralized server. Technologies such as Arduinos and Raspberry Pi's can be used to sense, control, and communicate. A few ICUC10 studies illustrated these technologies, e.g., a shoebox size sensor with high accuracy to monitor CO_2 was developed and tested by Hrisko and Ramamurthy (2018) and it can be expanded to accommodate other scalar sensors. Dienst et al. (2018) developed a low-cost sensor to monitor air quality that can be mounted onto mobile platforms. These compact low-cost sensors are highly effective for studies in developing countries and have the potential to revolutionize urban experiments, as they can quantify detailed spatial variabilities in meteorological parameters, and they can also be used to sense indoor environments. Vant-Hull et al. (2018) used Arduino based sensors to study how residences in low-income communities experienced a NYC heatwave event. The sensors weigh less and have a smaller footprint than traditional ones, which can be exploited to place them in UAVs to sense the UBL.

Ground and Satellite Based Remote Sensing. Currently an array of ground based remote sensing technologies (e.g., Doppler Lidar, Ceilometer, Scintillometers, Microwave Radiometers) are available to provide a 4-D view of the urban atmosphere and its regional setting. This instrumentation has advantages over traditional single point measurements, e.g., they can capture UBL structures in high detail. Ceilometer and microwave radiometers can sense scalar concentrations up to 10 km, and microwave radiometers are a passive technology that can quantify both the temperature and humidity at various vertical levels. Moreira et al. (2020) has shown that their performance is reasonable within the ABL and thus these technologies are increasingly adopted in urban observation campaigns (Liang et al., 2018). The variability and uncertainty information from these will become increasingly valuable for model evaluation and urban climate analyses. Satellite based remote sensing datasets have been available for some time for urban applications, and NASA LandSat and MODIS data have been frequently used to study UHIs and the impact of urban materials on local microclimates. The data have also been used to create high-resolution urban maps, and a new generation of geostationary satellites now have made continuous observations possible. While the spatial resolution of these satellites is of the order of 2–4 km, their temporal resolution is sub-hourly, which makes them interesting for new urban climate applications. Two such systems, the NOAA's GOES-R and the Japan Meteorological Agency Hamamury were introduced at ICUC10. Chrysoulakis et al. (2018) and Hrisko et al. (2018b) high-lighted the potential of these platforms to study urban surface energy budgets, an area vital to designing/developing new urban climate applications.

3.5. Priority #3: Integration between urban testbeds

In the past few years, several urban hydro-meteorological observatories have sprung up on different continents: NYC, London, Beijing, and Berlin. These cities now boast continuous measurements of critical meteorological variables, including turbulent fluxes of momentum and scalars, and of BL profiles of wind and thermal characteristics. Several presentations in ICUC10 used data from these observatories (Melecio-Vázquez et al., 2018b; Scherer et al., 2018). These observatories include ground based remote sensing instruments, as well as eddy covariance instrumentation. NYC and Berlin also host an urban climate network, while Beijing has 100 s of sensors to track particulate matter and precipitation, and they are coordinated by its local meteorological agency. These networks are supported by local governments and have access to various supplemental datasets, e.g., the Beijing and NYC research groups have access to high-resolution building datasets as well to as sub-grid level energy use data. Observations from these networks are used to improve forecast urban numerical modeling for mean and extreme conditions. This development could be strategically used to accelerate our understanding of urban environmental processes. The WG thus recommends that joint observation campaign and data sharing protocols be developed to improve coordination between testbeds.

3.6. Recommendations by the working group

Assessing the science presented at ICUC10, the WG recommends the following guidelines for ongoing and future urban field experiments:

1. *Representativeness of observations.* Experimental data should be thoroughly investigated for the scales they represent. For example, a general urban experimental set-up will involve data from multiple sensing platforms, and the data thus obtained will be highly sensitive to the height at which the measurements were made, orientation of the sensor, and wind direction. This information should be carefully recorded and the data from each sensor should be individually assessed for the temporal and spatial scales they represent.
2. *Data redundancy.* It is imperative that all data, across all sensors, in field experiments are recorded, stored, and eventually shared. In a field set up, multiple sensors could measure the same variable, e.g., common variables such as temperature and humidity are measured by most instruments. It is thus important to preserve this redundancy.
3. *Explore Public Datasets.* US government agencies such as NOAA and NASA collect a variety of data that could be used to study UBL dynamics. The Automated Meteorological Data Relay (AMDAR) and Aircraft Communication Addressing and Reporting System (ACARS) datasets contain information on wind, humidity, and temperature profiles for US metropolitan areas. The NASA AeroNet program has hourly observations of aerosol optical thickness at different wavelengths at multiple urban areas around the world. These datasets can be used to validate and force urban climate models.

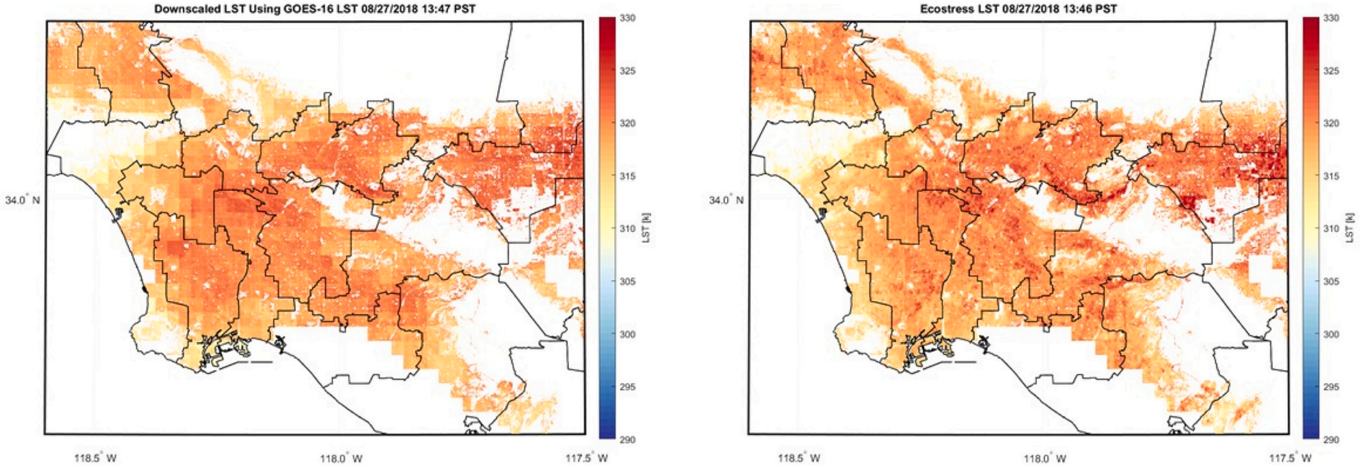

Fig. 6. A multi-sensor approach for UHI studies. Right panel shows downscaled GOES-16 (2 × 2 km) Land Surface Temperatures (LSTs) adjusted by (Left) ECOSTRESS (37 × 50 m) data for Los Angeles, CA. (Source. J. González).

4. *QA/QC.* Current field experiments sample data from various sources (fixed, mobile, and remote) and care should be taken to implement necessary and relevant QC control proto-cols.
5. *Logistics.* Scientists should develop better liaisons with local governments to gain necessary permissions for sensor placement and other miscellaneous needs. In large cities, security and insurance could be major impediments for conducting field studies that could be avoided with better communication with City Administrators.
6. *Scientists should be wary* of using current technologies like machine learning to interpret large datasets, as these technologies are essentially black-box models. Urban climate scientists should coordinate with data scientists to design suitable tests/algorithms to interpret these large datasets.

4. Summary on grand challenges on cyber informatics and data management

Working Group co-chairs: Jeff Luvall & Masoud Ghandehari.

Members: Mark Arend, Jorge E. González.

If we define Urban Cyber-Informatics as an organized "*collection of digital information and approaches for the processing and analysis of both environmental data and the data relevant to of urban systems,*" then the following sources explored at ICUC10 could be the place to start: *Organic/Administrative Data, Sensor Data, and Citizen Generated Data.*

4.1. Priority Area #1: Organic/Administrative data

Socioeconomic data. Includes data on wealth, health, education, etc. In the US these data are available through the census, most efficiently at the urban census tract level (approximately 1000–3000 people). In most of the rest of the world (e.g., many European countries) this information is highly aggregated to satisfy privacy protection regulations. In other places (i.e., much of the developing world) the information is not available nor organized, but in the latter case the UN has many useful data assets.

City administration data. This includes operational (e.g., waste removal) or financial (e.g., budget) information available in data rich US cities and increasingly for other US cities. These data may also be available in some developed world cities, and research and industry driven organizations are also creating coalitions between major global cities. These data are often reported on aggregated levels, despite the consensus that city data should be fully open. The data sets are not large and emerging artificial intelligence techniques (machine learning, etc.) enable integration and synthesis of social and administration data with other data types, including the sensor data described below.

Public health data. This includes data collected for public health monitoring and epidemiological studies. They include information on vector and water borne infectious, environmental diseases (e.g., from air pollutants, toxic chemicals, and heat stress), and hospital admissions for a variety of disease conditions. Availability, access, and use of these data are often restricted by privacy laws, national interests, expenses, and difficultly in collection (e.g., time series and population sampling size).

4.2. Priority Area #2: Sensor data

Remote/spaceborne. The opportunities and challenges in satellite-based data are clear. The large spatial coverage and legacy of spaceborne data is of great value, and respective imagery platforms (e.g., optical, thermal, radar, etc.) deliver good spectral resolution, but the spatial and temporal resolution are not simultaneously delivered at a high fidelity. Although optical micro satellites are exceptions, unlike many other satellite data these data are not entirely open source. Emerging developments in high resolution interferometric synthetic aperture radar will be a great asset when deployed. Data processing and analysis of satellite data are quite advanced, compatible with investments in source data generation.

Luvall and Hulley (2018) specifically addressed planned NASA International Space Station (ISS) Venture Class instruments of relevance to urban systems. The *ECOsystem Spaceborne Thermal Radiometer Experiment on the Space Station (ECOSTRESS)* is a five channel, ~ 37 × 50 m resolution thermal instrument on the International Space Station (ISS). The Global Ecosystem Dynamics Investigation (GEDI, 2019) produces high resolution laser-ranging observations of the 3-D Earth surface. Teledyne has on the ISS the *DLR Earth Sensing Imaging Spectrometer* (DESIS), a hyperspectral imager deployed in May 2018 for production of commercial data products. The *Hyperspectral Infrared Imager* (HyspIRI) is a 30 m resolution hyperspectral, 60 m resolution multispectral channel mid/thermal infrared instrument. These instruments build on NASA funded research that use aircraft based urban remote sensing

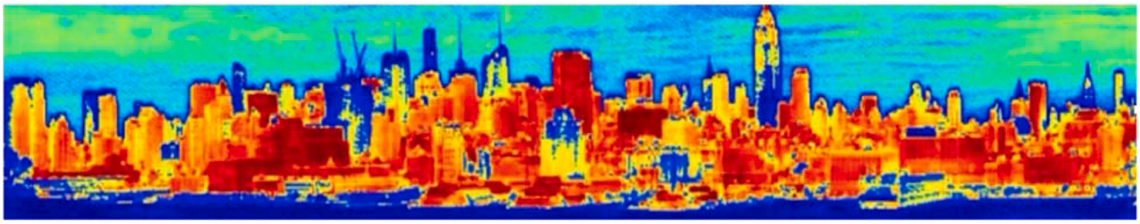

Fig. 7. Surface temperatures in midtown Manhattan, measured by longwave hyperspectral imaging (Caplin et al., 2019).

instruments to develop techniques for assessing UHIs. HyspIRI provides global datasets necessary to monitor and study urbanization impacts on a global scale. Fig. 6 illustrates an example of blended satellite remote sensing data for cities

These massive data sets are generated from a wide variety of satellite and ISS based sensor systems. The NASA Earth Exchange (NEX) in January 2017 contained 2.3 PB, with an additional 1.5 PB added in during the rest of the year. New satellites and ISS instrumentation from NASA, NOAA (GOES-R series), and the international community, with their enhanced spectral, spatial, and temporal resolution, will accelerate these data volumes. The 3-D measurements of the earth surface by Lidars such as ICESAT-2, a laser altimeter can measure the elevation of ice sheets, glaciers, and sea ice across the temperate and tropical regions. It will also survey forest vegetation worldwide. GEDI also provides high-resolution laser images of the Earth forests and topography from the ISS. The complexity and volume of data available thus presents a significant challenge for their use for both research and in the application of research results to benefit society.

Remote/ground based and airborne. Examples exist of this modality, but the techniques are not widespread across urban areas. Some exceptions exist, such as USGS aerial imagery and a wide area of ground-based imagery of urban surface temperatures (Fig. 7) and of leaks of refrigerant gasses (Ghandehari et al., 2017; Ghandehari et al., 2018; Caplin et al., 2019). Examples also exist of ground-based sensing for the measurement of atmospheric quantities, providing invaluable information particularly for meso-scale modeling and for the analysis of urban atmospheres and coastal waters. Data processing techniques for ground based remote sensing instruments (lidars, radars, sodars, radiometers, etc.) are advancing by using them in a manner that allows for multiple spatial and temporal scales to be identified. This is particularly important in complex urban-coastal environments, where the heterogeneity of landscapes and seascapes, coupled with the complexities of urbanization, presents dynamic situations that require adaptive data management techniques that depend on climate conditions. Adaptive data processing techniques are being advanced, along with the above advancements in sensing platforms.

In-situ (static and mobile) data. Data from in-situ observations are distinguished from remotely sensed observations as in-situ measurements are taken at the same location as the sensing system that makes the measurement. Such systems can remain fixed and perform static measurements, or they can be mobile integrating the observed quantity Arend, 2012. The management of data streams from mobile measurements present challenges, as the representativeness of the quantity being observed depends on the selection of the integration time relative to the dynamics of the quantity. For in-situ instruments designed for high sensitivity and accuracy, mobile applications require precision time/space signatures to process the data. The emergence of low-cost micro sensors and the internet of things (IOT), however, should result in wide-spread applications of statically located in-situ sensors (Yang, 2018). The time/space data processing challenge of mobile in-situ sensors is thus somewhat resolved, but it then shifts to challenges presented from managing large amounts of sensor data. The quality of many micro sensors is still questioned for regulatory applications. The lack of resources to support their deployment, maintenance, and massive data processing also presents challenges, but techniques are becoming more advanced as applications become more realizable.

4.3. Priority Area #3: Citizen behavior and citizen generated data

City managed data. Cities across the world are opening a variety of data related to transport, waste, health, etc. When combined with advanced analytics, the interpretation of city operations through these data is leading to better quantifications of the day to day patterns of human behavior (Johnson et al., 2017a). Non-emergency community reporting portals, designed to help municipalities better deliver services, is growing rapidly. This data stream not only serves as a source of information for city managers, but as an instrument for citizens to engage in city functions. The openness of this information is of great value and in some cities widely used. The availability of this data source (via 311 hotlines) is not widespread across the US, and not necessarily available worldwide. Fig. 8 illustrates an example of citizen mobile data collection using bicycle loops for air quality

Crowd-sourced data. The rapid growth of social media and information technology has resulted in a large volume of a range of social data, such as patterns of mobility and sentiment. While some of these data are open source, the private ownership of platforms prevents a full benefit from these data streams. The emergence of citizen generated data, particularly with respect to individual exposure and health related information (Caplin et al., 2019), is promising to circumvent some of the challenges with availability at the level of individuals.

5. Summary on grand challenges on knowledge transfer & applications

Working Group co-chairs: Dev Niyogi & Chandana Mitra.
Members: Rae Zimmerman, Matt Georgescu, Ashley Broadbent,
Mariana B. Alfonso Fragomeni, Megha Shrestha, Michael Allen.

Changing climates and their resulting hazards has prompted a stronger focus on the identification of vulnerable populations and on the optimal strategies for mitigation and adaptations based on local environments and needs (Emrich and Cutter, 2011; Binita et al., 2020; Bellinson and Chu, 2019). This focus on local environmental needs has gained momentum in the past two decades as the impacts of extreme events on humanity at different scales has become more frequently throughout the world and since data are becoming more readily available.[4]

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[4] https://www.ncdc.noaa.gov/monitoring-content/billions/docs/lott-and-ross-2003.pdf;https://www.theguardian.com/environment/2014/aug/11/extreme-weather-common-blocking-patterns

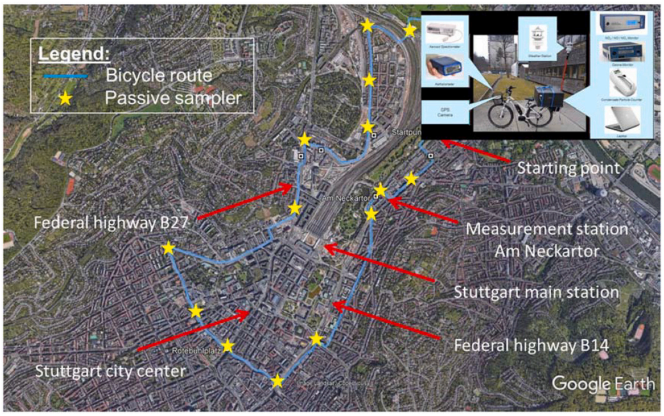

Fig. 8. Sample of mobile applications for urban air quality studies in Stuttgart, Germany (courtesy of Samad and Vogt, 2020).

Knowledge transfer and application (KTA) are two key components needed to understand urban sustainability and resiliency. The three main aspects of an urban climate and resiliency framework typically addressed in urban climate studies of extreme weather events include: urban climate (meteorology) modeling, observational data, and GIS/cyber informatics. These areas have shown immense scientific progress, but still have gaps in data sharing, scalability, application, and innovation. It is also challenging to integrate the social, biological, and physical aspect of urban climate, partly due to the poor correspondence between the temporal (data collection intervals) and spatial (administrative units and landscape units) scales (Wentz et al., 2014). As a result, the transferability and scalability of urban climate research often requires more information related to processes and the broader system to enable application from the sustainability point of view.

Bridging the gaps in KTA is challenging. Many fundamental urban climate studies (ranging from observational campaigns to numerical modeling efforts, as mentioned in the previous sections) have been performed, but limited progress has been made in knowledge dissemination and application at community levels. One main cause for this may be the silos in which researchers and stakeholders interact within, which produces a challenge to maintain connections with each other. A communication gap also remains between scientists and decision-makers who understand and can act on the cost and benefits associated with implementation of urban sustainability measures. The overall usefulness and usability of scientific products is oftentimes not evaluated (Niyogi and Andresen, 2011; Pyke et al., 2007; Perry et al., 2016). A communication gap also exists between scientist-stakeholders and the citizenry (CRED, 2009). Finally, the range of research to date (e.g., modeling work) lacks a systematic basis for comparison, rendering it difficult to communicate anticipated impacts associated with varying heat mitigation strategies (as a example).

Critical issues highlighted at ICUC10 re KTA-

- An increasing knowledge gap exists and builds with novel contributions to the field of urban climate. Scientists are working in their own domains or with their cohorts, which often does not translate into a systems framework or cross-group communications. This lack of a systemic approach creates disconnections and hinders forward movement in fruitful directions.
- Although scale is a critical factor in thinking about how to frame and implement knowledge applications, it is also recognized that no one scale is likely to be adequate. Flexibility or adaptability with respect to scale rather than the adherence to any single scale should thus be considered as the norm to advance urban climate KTA.
- Engaging and convening people to collaborate is often not sufficient to generate or reach consensuses. An understanding of how people process information about urban climate and what are the barriers are critical for addressing this problem. Knowledge processing is likely to be different for different audiences.
- A lack of understanding exists of the effects of human intervention in urban environments. For example, infrastructure-based services both contribute to and are affected by adverse environmental conditions. It is thus difficult to isolate and quantify urban effects on this complex environment, but it should be the goal in terms of the systems framework needed for assessment and solutions.
- Principles of risk perception and communication across types of stakeholders are necessary for knowledge generation and adoption processes. An extensive literature exists in this area that needs to be used for urban climate communication issues.
- Much of the knowledge generated refers to benchmarks or thresholds without rigorously thinking about what that means across space (geographies), time, cultures, types of knowledge, and state of knowledge, and how this transcends those dimensions. One important aspect of organizing knowledge and transforming it into action is a holistic view of all the elements that are/could affect the urban measurement.
- Not only should the lack of data be a consideration, but how to organize and evaluate already existing data needs consideration. This relates to points made above about scale, domain, or region of focus. Global scientists are generating a myriad of data that need to be assembled within useable, scalable portals.

- Knowledge transfer from scientists to both decision-makers and stakeholders is not continuous and is a two-way process. Scientific jargon should be simplified so that actionable science can be promoted, and science to practice needs should be a top agenda item for urban climate scientists.
- Assessment of urban integrated services to measure the resiliency of global cities in varied climates is needed. A need also exists to effectively transfer scientific knowledge to stakeholders and decision-makers so cities can be more resilient to future climate change induced extreme weather events.

Knowledge related to urban climate is interlinked to adverse manifestations of climate change and extreme weather events. This integration is linked to the human use of the environment and to services that affect the environment. Infrastructure services and the coupled natural human systems are thus an essential focus for generating knowledge and for closing knowledge gaps.

Urban climate as a discipline has evolved from a subset of micrometeorology, boundary layer, and air quality modeling to an independent entity that includes meteorological energetics, processes, and human and ecological activities within (and influenced by) the urban form and function. This broadening is a result of years of focused studies that have developed insights at different scales. As a result, how urban areas affect the weather and climate at multiple scales is now relatively well understood. As a result, *the time has come* for that understanding to be translated into decision-making models that include output from these improved weather and climate models. Urban feedbacks need to be explicitly considered and integrated into regional planning processes for the development of sustainable regional and urban systems. The recommendations listed from this assessment are not exhaustive or the exact path ahead, but they are intended to help initiate discussions needed within the community to develop the next era of *applied* urban climate information that aids decision making. Such discussions will improve the livability of cities and will aid in urban planning, climate adaptation, mitigation, and resiliency (Chapman, 2015).

5.1. Recommendations made by the ICUC10 WG

1) Envision the need for urban climate to evolve as a convergent theme for an interdisciplinary, systems framework that fosters and builds transdisciplinary and multidisciplinary collaborations that scales up the discourse regarding sustainable urban systems.
2) Recognize urban systems, not only as a city and its form and functioning, but also as a part of the broader urban-rural transect, whose resiliency and sustainability is intricately and interactively coupled and that needs investigation as part of urban climate studies.
3) Urgently undertake research related to understanding and translating the findings from research to applications that impact urban systems decisions and livability, especially in addressing future hazards.
4) Recognize that many cities have inequity in services offered that can be confounded by race, economic disparity, and other socioeconomic factors. Future urban climate research needs to explicitly address social equity and access as part of hazard mitigation, risk reduction, and adaptation solutions.
5) Organize workshops and community reports that will synthesize urban climate research and outcomes for critical evaluation and assessment, including integration into national and international climate assessments.
6) Develop an urban climate assessment framework that documents observed changes within cities, develops projected climate and societal pathways, and helps develop adaptation and mitigation measures by working with local stakeholders.
7) Embed a participatory research framework within urban climate research, in which assessments of community needs, bottle necks for decisions, and future requirements are undertaken in a systematic and sustained manner.
8) Restructure and further develop urban climate education to disseminate scientific knowledge through a working curriculum. It is important to build a younger enthusiastic workforce that will continue urban climate science.
9) Create a data and collaboration portal that foster an open exchange of information, knowledge co-creation, and FAIR (Findable, Accessible, Interoperable, and Ready to Use/reusability) data exchange. This is required for modeling studies to advance, educational activities to evolve, and the community to develop products for use by broader stakeholders. An example of such a data portal is the WUDAPT (World Urban Data Analysis and Portal Tool), as outlined in this report. Open data and collaboration portals like WUDAPT should be adopted and supported by the urban climate science community to close existing knowledge gaps.
10) Develop easily accessible urban climate principles and example case studies to help communities address climate adaptation, mitigation, and SDG2030 pathways for a variety of climatic regimes across different scales.
11) Develop the measurements of environmental emissions and impacts necessary to make cities resilient to climate changes at different scales. Required emission data include GHGs and anthropogenic heat, which impact the livability and health of urban populations. Ecosystem functions, with considerations for the equity of adaptive tools and solutions are needed for city planning.

Declaration of Competing Interest

None.

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