MEETING SUMMARIES

DEVELOPING A RESEARCH STRATEGY TO BETTER UNDERSTAND, OBSERVE, AND SIMULATE URBAN ATMOSPHERIC PROCESSES AT KILOMETER TO SUBKILOMETER SCALES

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With the majority of people experiencing weather in urban areas, it is critical to understand cities, weather, and climate impacts. Increasing climate extremes (e.g., heat stress, air pollution, flash flooding) combined with the density of people means it is essential that city infrastructure and operations can withstand high-impact weather. Thus, there is a huge opportunity to mitigate climate change effects and provide healthier environments through design and planning to reduce the background climate and urban effects. However, our understanding of the underlying urban atmospheric processes are primarily derived from studies of separate aspects, rather than the complete, human–environment system. Air quality modeling has not been widely integrated with aerosol feedbacks on local climate, while few city-greening scenarios have tested the impacts on boundary layer pollutant dispersion or the carbon cycle. Building design guidelines have been developed without incorporating the impact of waste heat on local temperatures, which, in turn, determines building performance. Integration of such feedbacks is imperative as they define, rather than just modify, urban climate.

THE INTEGRATION OF URBAN ATMOSPHERIC PROCESSES ACROSS SCALES WORKSHOP

What: A Met Office/Natural Environment Research Council Joint Weather and Climate Research Programme workshop brought together 50 key international scientists from the United Kingdom and the international community to formulate the key requirements for an urban meteorological research strategy. The workshop was jointly organized by the University of Reading and the Met Office.

When: 16–18 November 2016

Where: University of Reading, Reading, United Kingdom

There is an urgent need to link processes that people experience at street level (human scale) to processes at neighborhood, city, and regional scales. As these scales have traditionally been the focus for specialists in different fields, few observation and model systems cross these scales. However, understanding the interactions between these scales is critical for the design of future parametrizations

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and observation networks. Although models and observational methods are emerging that permit research into scale interactions [e.g., high-resolution numerical weather prediction (NWP), large-domain computational fluid dynamic (CFD) models, remote sensing, extensive sensor networks, vertical remote sensing], an integrated approach across methodologies is currently lacking.

To tackle these scale interactions requires diverse skills from a wide range of research communities. This is a daunting challenge. However, improved understanding of urban atmospheric processes such as clouds and precipitation, heat transfer, and convection would enable improvements in urban system models to provide seamless hazard prediction at all time scales. Hence, an initial focus on the meteorological aspects of the research challenge may be a more manageable problem, even though the scope is still large. As such, it was identified that within the United Kingdom there is an urgent need to develop an urban meteorological research strategy that integrates interactions and feedbacks on all scales.

MAIN FINDINGS/SCIENCE BACKGROUND. The workshop was structured around three questions:

1) What are the key scientific challenges in observing and modeling urban atmospheres from minutes to decades and from building to regional scales?
2) How can atmospheric observations, models, and theory be better integrated to tackle these challenges?
3) Which atmospheric feedbacks across which scales are critical to include across urban system models (including building design, engineering, planning, air quality, hydrology, etc.)?

Following short provocative keynote presentations and intense discussion across the wide variety of issues, two distinct science challenges were identified that cut across the three workshop questions, namely, *heterogeneity* and *anthropogenic drivers*.

1) Urban areas are heterogeneous within and across a range of scales (obstacles at 1–10 m, neighborhoods at 10^2–10^3 m, city scale at 10^3–10^5 m). Heterogeneity impacts the mean flow and turbulent structures generated by the obstacles across these scales, which interact with the turbulent characteristics of the boundary layer. Urban meteorology has relied on traditional Monin–Obukhov similarity theory (MOST) with assumed horizontal homogeneity to parametrize the turbulent flux terms in mesoscale models. However, given the extensive size (and ever taller) roughness elements, and the relatively narrow boundary layer, the applicability of MOST is severely limited. With surface characteristics changing at many length scales MOST, and extensions such as blending height theory and tiling, have to be questioned. The current representation of the turbulent exchange of momentum (drag), heat, moisture, pollutants, and radiation at all scales across the urban system all need to be formally reconsidered. Treatment of clusters of

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tall buildings, deep urban canopies, and vegetation effects all need to be addressed.

The key problem is how we describe subgrid-scale patchiness and its impact on momentum, scalar exchange, and radiative forcing. This includes challenging examples such as isolated groups of tall buildings and spatially extended deep urban canopies requiring vertically distributed processes to be included in urban parametrizations. We lack the observational knowledge to describe the scale interaction between variations in surface-induced turbulence and the stochastic nature of turbulence in the planetary boundary layer. Observations are fundamental to the development of both a theoretical understanding and the models used. To capture the scale interaction in the urban boundary layer, with tall but sparse roughness elements (e.g., buildings do not close the canopy as a forest may in leaf-on state), will require new measurement technologies and deployments. The shedding of heat, moisture, and momentum from preferentially radiated volumes with roof characteristics (e.g., heights, shapes) and packing densities that modify the interaction with air aloft are going to require new measurement technologies to be developed.

With NWP moving toward grid lengths of *O*(100) m, we approach terra incognita (Wyngaard 2004) and the building gray zone (where we need to resolve large building blocks). We face the challenge of parametrizing turbulence at very different scales generated by a very nonuniform surface. This includes dealing with stochastic transitions between filtered and explicitly represented scales. One challenge is the diurnal evolution of the boundary layer, where the turbulence scales may no longer be resolved at night. Models with grid lengths of *O*(100) m may resolve the energy-containing eddies of a convective boundary layer when they are forced by a uniform rough surface, but the characteristics of these eddies may change substantially with a more irregular urban surface that creates localized peaks in scalar fluxes.

The workshop discussions highlighted the need to agree on very specific research questions in order to develop a robust theoretical framework beyond MOST. To tackle some of the research questions, we need high-quality long-term datasets, horizontally and vertically distributed through the boundary layer, over well-characterized urban areas. It is essential that we design appropriate observational campaigns, as well as measurement and evaluation techniques, in collaboration with a community that includes modelers.

2) While "dead" (unpopulated) cities pose many physical problems associated with the grand challenge above, anthropogenic drivers dramatically change the properties of urban areas. This includes, for example, urban energy, heat, water, CO_2, and spatial and temporal variability. The dynamic changes of a city at subdaily, weekly, seasonal, and longer time scales must be accounted for (e.g., travel patterns, heating/cooling to retrofitting buildings, changing urban morphology, and land cover).

It is critical that the fundamental data required to capture these anthropogenic processes be properly employed. This requires developing close collaboration between those stakeholders with this expertise (and also the likely end users of integrated weather, climate, environment, and water services from improved predictive capability), for example, the energy sector, transport, water management, building materials, building management, planning, and the urban meteorological and atmospheric chemistry communities, to ensure these data are available and realistic. As a city evolves with technological, weather, climate, and environmental changes, the services provided need to be dynamic in response to the people living in the city. The inclusion of human behavior is critical to providing realistic two-way interactions with the urban–human environment system. However, the complex nature of these feedbacks requires the human system to be incorporated into the physical system, requiring an integrated research community with, for example, the socioeconomic, political, psychological, and health disciplines working together with climatologists, meteorologists, atmospheric chemists, and others.

RECOMMENDATIONS. To expand upon these two grand challenges, breakout groups considered how research could tackle each challenge in turn. Hypothetical proposals were developed. From these, it was evident how a research program could begin to make significant contributions toward solving some of the challenges facing the urban community. The proposals demonstrate the key need of taking a coordinated and integrated approach between different groups and methods. For example, new frameworks designed to treat heterogeneous surface exchange at scales ranging from *O*(100) m to *O*(1) km can be developed using large-eddy modeling and wind tunnel modeling, but multiscale measurements of real canopy and boundary layer flows are essential to understanding these processes. The need to

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test fundamental instrument applicability and the probable need to develop suitable urban-specific measurement technologies is likely. Similarly, while specific questions (e.g., concerning urban moisture transport) may be addressable through modeling, ultimately anthropogenic drivers in real cities will need to be studied. A combination of modeling and observational studies is essential to advance our knowledge, possibly focused on a single city to start with, so as to build up a comprehensive dataset and conceptual understanding of the process interactions between the building scale, the city scale, and the mesoscale.

Consensus from the workshop suggests benefits from the following initiatives:

- An integrated approach across all aspects of urban areas and not isolated individual studies is required.
- An urban "laboratory" at a fixed site is needed to bring together different communities and measurements/modeling efforts. This would enable short-term intensive observation periods (IOPs) to be embedded into well-understood long-term datasets. Historically, the difficulties associated with long-term funding to facilitate such an initiative have meant many missed opportunities of well-bounded IOP studies. To address questions of change (e.g., technology, understanding, behavior, land cover, climate), ensuring that quality-controlled datasets, with extensive data storage (i.e., raw, processed datasets) and with extensive urban metadata (biophysical, behavioral, etc.), are available allows for numerous and repeated solutions to be considered.
- Four-dimensional observations of multiple variables are needed. Theoretical understanding and frameworks designed to address MOST at neighborhood scales and heterogeneity at short scales are critical. We need to understand the transfers of heat, mass, and momentum from the urban canopy layer (UCL), roughness sublayer (RSL), inertial sublayer (ISL), and beyond to develop new model parametrizations.
- Development and deployment of appropriate measurement and modeling techniques/parametrizations requires coverage of scales ranging from within the UCL through the RSL and the ISL, to the city scale, the boundary layer scale, and mesoscale.
- Turbulence schemes and urban surface exchange parametrizations for Wyngaard's terra incognita need to be developed.
- Cross-cutting research collaboration between social sciences and a range of atmospheric/environmental sciences will be fundamental to the development and deployment of an urban environmental system model.
- Longer-term funding is essential for long-term facilities, whereas development work requires funding for short-term-focused blue skies exploration.
- Data assimilation techniques in heterogeneous areas impacted by human activities need to be developed.
- Satellite-derived data have increasing potential. New deployments would permit many traditional challenges between the pixel scale and land-cover variability to be addressed.
- With extensive nontraditional data sources in cities [e.g., mobile phones, social media, vehicle usage characteristics (windscreen wipers, speed)], there are opportunities through data mining to significantly enrich urban environmental system modeling [e.g., data assimilation (DA), assessment].
- Linking with end users, with particular application needs or concerns, is critical to ensuring the benefit of improved predictive capacity is taken through to service provision.

Although, it is unclear how much this research will enhance NWP at scales larger than the urban area, it is likely to significantly improve weather and climate services for the management of cities and their inhabitants. This has the potential to improve the prosperity, health, and safety of urban residents. And with global sources of greenhouse gases being disproportionately urban, there are likely many other benefits to better cities, beyond their borders.

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