The integration of urban atmospheric processes across scales.

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What
A Met Office/Natural Environment Research Council Joint Weather and Climate Research Programme workshop brought together 50 key international scientists from the UK and international community to formulate the key requirements for an Urban Meteorological Research strategy. The workshop was jointly organised by University of Reading and the Met Office.

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Introduction

The workshop was structured around three questions:

1) What are the key scientific challenges in observing and modelling urban atmospheres from minutes to decades, and from building to regional scale?
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.)?

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 underlying urban atmospheric processes are primarily derived from studies of separate aspects, rather than the complete, human-environment system. Air quality modelling has not been widely integrated with aerosol feedbacks on local climate, whilst 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 are imperative as they define, rather than just modify, urban climate.

There is an urgent need to link processes that people experience at street level (human-scale) to processes at neighbourhood, 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 design of future parametrisations 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 UK there is an urgent need to develop an Urban Meteorological Research strategy that integrates interactions and feedbacks on all scales.

Main findings/science background

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 parametrise the turbulent flux terms in meso-scale 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 turbulent exchange of momentum (drag), heat, moisture, pollutants and radiation at all scales across the urban system all need to be formally re-considered. Treatment

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

The key problem is how we describe sub-grid 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 parametrisations. 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 theoretical understanding and models. 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 towards grid lengths of O(100 m) we approach *Terra incognita* (Wyngaard 2004) and the building grey zone (where we need to resolve large building blocks). We face the challenge of parametrising turbulence at very different scales generated by a very non-uniform 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 alter substantially with a more irregular urban surface that creates localised 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 characterised urban areas. It is essential that we design appropriate observational campaigns, measurement and evaluation techniques in collaboration with a community that includes modellers.

2. *Anthropogenic drivers*. While 'dead' (unpopulated) cities pose many physical problems associated with the grand challenge above, human interaction dramatically changes the properties of urban areas. This includes urban energy, heat, water, CO_2 *etc.* spatial and temporal variability. The dynamic changes of the city at sub-daily, weekly, seasonal and longer timescales must be accounted for (e.g. travel patterns, heating/cooling to retrofitting buildings, changing urban morphology and land cover).

It is critical the fundamental data required to capture these anthropogenic processes are properly employed. This requires developing close collaboration between those with this expertise (and also the likely end-users of integrated weather, climate, environment and water services from improved predictive capability), e.g. 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 the city evolves with technological, weather, climate and environmental change, the services provided need to be dynamic in response to the people living in the city. The inclusion of human behaviour 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 social-economic, political, psychological and health disciplines*, etc*. working together with climatologist, meteorologists, atmospheric chemists, *etc*.

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 programme could begin to make significant contributions towards 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 to treat heterogeneous surface exchange at scales ranging from O(100 m) to O(1 km) can be developed using large eddy modelling and wind tunnel modelling, but multi-scale measurements of real canopy and boundary layer flows are essential to understand the processes,. But the need to 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 modelling, ultimately anthropogenic drivers in real cities will need to be studied. A combination of modelling and observational studies is essential to advance our knowledge, possibly focussed on a single city to start with, so as to build-up a comprehensive dataset and conceptual understanding of process interactions between the building scale to the city scale and meso-scale.

Consensus from the workshop suggest benefits from:

- An integrated approach across all aspects of urban areas and not isolated individual studies is required.
- An urban ‘laboratory’ at a fixed site to bring together different communities and measurements/modelling efforts. This would enable short term Intensive Observation Periods (IOP) to be embedded into well-understood long-term datasets. Historically, the difficulty of long-term funding to facilitate such an initiative has meant many missed opportunities of well-bounded IOP studies. To address questions of change (e.g. technology, understanding, behaviour, land cover, climate) ensuring that quality controlled data sets, with extensive data storage (i.e. raw, processed data sets) with extensive urban metadata (biophysical, behavioural, etc.) are available allows for numerous and repeated solutions to be considered.
- Four dimensional observations are needed of multiple variables. Theoretical understanding and frameworks to address MOST at neighbourhood scales and heterogeneity at short scales is critical. We need to understand the transfers of heat,

mass and momentum through from the urban canopy-layer (UCL), roughness sub-layer (RSL), inertial sub-layer (ISL) and beyond to develop new model parametrisations

- Essential to development and deployment of appropriate measurement and modelling techniques/parametrisations is to cover scales ranging from within the UCL through the RSL, ISL to city-scale, boundary layer-scale, and meso-scale interactions
- Development of turbulence schemes and urban surface exchange parametrisations for Wyngaard's *Terra Incognita*
- 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 focussed 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 pixel scale and land cover variability to be addressed.
- With extensive non-traditional data sources in cities (e.g. mobile phones, social media, vehicle usage characteristics (windscreen wipers, speed) etc.), there are opportunities through data-mining to significantly enrich urban environmental system modelling (e.g. DA, assessment, etc).
- Linking with end users, with particular applications needs or concerns, is critical to ensure 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 and inhabitants of cities. 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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