Theme 4 Numerical Prediction of the Earth system: putting it all together

1. Urban scale environmental prediction systems

Conveners: Greg Carmichael (U. of Iowa, USA), Sue Grimmond (U. of Reading, United Kingdom) and Humphrey Lean (Met Office, United Kingdom)

The majority of the world's population now live and work in cities and towns, and in the next three decades, particularly in Africa and Asia, this is where most population growth is expected to occur. Thus it is essential that we can predict the environmental conditions and hazards urban centres and their occupants will experience, with as long a lead time as possible.

Areas of high population density are particularly sensitive to weather, air quality, climatic conditions and their variability. Each impacts activities within a city (e.g. transportation, energy demand, construction, school access, tourism etc.), with implications that extend well beyond the urban centre, particularly when it is a strategic part of a region or country. The impacts may also relate directly to acute (e.g. epidemic breakouts) and chronic (e.g. respiratory) human health and well-being.

While urban areas range from extensive conurbations (e.g. the Pearl River Delta, Tianjin-Beijing, Yangtze River Delta, New York-Boston) to megacities (e.g. Tokyo, Sao Paulo, Jakarta, Manila, Los Angles), to large cities (e.g. London, Hanoi, Bangalore) to small urban areas, these settings have important features in common (Table 1). However, atmospheric conditions and driving factors vary significantly, within as well as between cities, and the needs of various stakeholders, in terms of information and tools, differ considerably too. These factors need to be recognised in the development of understanding and services of meteorological and climatological data in cities.

A number of recent reports have considered what is needed to enhance predictive capabilities for urban areas (Table 2). This document while informed by these recommendations does not include all of the same material. Broadly, the research recommendations can be clustered in terms of needs for: (1) the development of high resolution coupled environmental prediction models that include realistic city specific processes, boundary conditions, and fluxes of energy and physical properties; (2) enhanced urban observational systems to force these models to provide high quality forecasts to be used in new urban climate services; (3) new, targeted and customized delivery platforms using an array of modern communication techniques developed in close consultation with users to ensure that services, advice and warnings result in appropriate action and in return inform how best to improve the services; and (4) the development of new skill and capacity to make best use of technologies to produce and deliver new services in complex, challenging and evolving city environments.

Here we outline briefly particular investment needs to improve model development and predictive capability. Note all the back ground material to support these statements are not presented here but much of it can be found in references such as included in Table 2.

Observations

To evaluate model performance, improve model algorithms, and provide data for forcing or assimilation, observational data are needed. Operational urban meteorological networks (within and around a city) need to be installed with attention to the optimum balance between resolution and practicability. Such observational networks will need surface-based instrumentation (soil moisture and air/soil/surface temperature), and vertical profiles (from within the deep urban canopy layer to the top of the boundary layer) of temperature, humidity, wind, turbulence, radiation, rainfall, air quality (gases and particles, precursors and secondary), reflectivity and refractivity.

Often as urban areas become larger, buildings become taller. This is particularly the case in rapidly urbanising Asia. In Shanghai, for example, in 2012 there were >100 buildings taller than 30 stories, with one building (the second tallest building in the world) > 630 m tall (Tan et al. 2014). This has implications both for measurements of atmospheric variables and for the contexts for which data are needed (e.g. the ability to predict conditions at a range of heights (e.g. a fire at floor 15 of at 30+ storied building disperses differently to a fire on the 2nd floor of a 3 storey building). New technologies are needed to gather observations in places where currently measurements are challenging or not possible. Investments are needed in conventional instrumentation, alongside high density sensor networks, mobile platforms, new remote sensing techniques, and other data sources (e.g. real-time information from windscreen wipers on cars etc.), and encourage improvement of technology to observe places and processes that remain difficult.). This includes a need to continue to design and better integrate the satellite and urban-centric observing systems.

Given the potential range of new measurement approaches and siting, appropriate metadata and protocols must be developed and reported, so that data are used appropriately for the breadth of applications (e.g. the needs of those interested in wind loading on a building is markedly different to data to force operational weather models). Smart protocols, to address data quality control, siting, metadata and to ensure all users are served well with the potential wealth of urban data.

Characterization of the urban surface/area is needed both to provide site metadata for observations and to model the urban area. Improved methods are needed to determine key urban surface characteristics; for example, material radiative (e.g. emissivity) and thermal (e.g. heat capacity) properties. Remote sensing techniques need to be developed so that additional data sets needed for modelling urban areas are available (e.g. leaf area index). In addition, enhanced spatial resolution and/or improved algorithms to deal with the challenges of the range of urban materials found over small areas combined with the complex geometries (e.g. creating shadows, mixed pixels) are needed. Due to the rapid changes that occur in many urban settings, techniques to facilitate timely updates also are important.

Methods need to be developed and evaluated to enhance the suite of variables that are directly modelled and directly observed (e.g. surface "temperatures", structure function parameters). This requires advances in both modelling and observations. These variables would be measured over large spatial domains (e.g. remotely sensed) and not require assumptions to yield the "observed" or 'modelled' data, given the challenges and complexity of the urban surface.

The impact of the patchwork of changing densities and heights of buildings (and trees) across the city needs to be much better understood. This requires advances in measurements of the mean and turbulent characteristics of the urban atmosphere in such settings (e.g. Doppler LiDAR misses the lowest 90- 100 m; SODAR is too noisy in urban area); how to model the processes occurring within and above tall urban surfaces (e.g. direct numerical simulation (DNS) and large eddy simulation (LES) currently require too much computational resource to undertake realistic simulations for extensive areas, i.e. to yield realistic surface temperature forcing, stabilities, and there are minimal data for evaluation of model results (e.g. extensive measurements of radiation, temperature, wind, chemical concentrations, horizontally and vertically within tall urban canyons (atmospheric and surfaces)). There is a need to develop and deploy measurements instrumentation that can sample this environment at rates that are compatible with the modelling. DNS and LES type modelling are needed to improve our understanding of exchange processes so we can develop appropriate parameterizations.

Observations are needed for a larger range of urban land uses (morphologies) to establish universal flow and flux characteristics. The existing long-term measurement stations need to be preserved, but more long-term datasets (rather than short-term campaigns) that have wide spatial representativeness are needed. These need to include simultaneous measurements of flow properties at various sites and levels to better study coherent structures and intermittent ventilation processes within the Roughness Sub-Layer (RSL).

To improve the understanding of air quality and greenhouse gases: Measurements of fluxes of greenhouse and other gases and particles (e.g. CO_2 using the eddy covariance approach) need to be undertaken combined with isotopic and chemical fingerprint analysis to determine not only the sizes of these fluxes, but also to identify emission sources (for example, background concentration, gasoline combustion, natural gas combustion and respiration).

For urban populations, exposure to poor air quality (e.g. high level of O_3, NO_2, SO_2, and aerosols) is a major concern. Improved spatial (horizontal and vertical) and temporal sampling will aid model development and applications. To support expanded and improved air quality-related services, there is a need to provide air pollution observations in near real time.

Anthropogenic heat and moisture emissions need to be better quantified by improved measurement and estimation techniques at a range of scales. This needs to include measurements of individual building measurements to close the energy budget of a control volume.

People spend a large amount of their daily lives indoors, yet the interaction of conditions indoors and outdoors in cities is poorly understood. This is important both for the design of buildings and their external environment, and also for building operations. The ingested air impacts the comfort, health and operations of the buildings. Greater knowledge of actual *in situ* conditions can reduce energy usage and CO_2 emissions. Consideration of external emissions with building openings and air-intakes also is important and if better known can reduce resource use while improving the health of those internally and outside.

In addition to enhanced observations of the physical and chemical properties and processes in the atmosphere, we also need more understanding of how human behaviours (individually and collectively) impact emissions of atmospheric pollutants, energy and water, etc.

Consideration needs to be given to design of observation networks. Data are needed at multiple-scales, both for specific areas of interest and for the larger region in which it is nested in. Nested networks should help to improve model prediction and provide longer prediction times for extreme events. A broader ring of information with successively more detailed focus around the city will support improved prediction. Research is needed on appropriate densities for such networks, including appropriate provisions for redundant information. Both the physical and chemical characteristics of the atmosphere need to be considered. For air quality related services, further exploration of network design is needed to optimize for prediction, in addition to the current focus on providing estimates of air pollution exposure.

Understanding

Advances are needed to develop methods and frameworks to analyse atmospheric data measured above complex urban surfaces. This includes attention to measurement source areas to ensure both representative results and also meaningful comparisons between observed data at specific sites and with models. Much more needs to be known about the outer layer of the urban boundary layer (UBL), the atmosphere above the ISL (inertial sub-layer). There is also need for further research on the relation between urban morphology and the flow (and exchanges) within the canopy, directly above, and the UBL. Research is also needed to better understand the coupling of surface and air temperatures. Similarly, there is a need to improve our understanding of ventilation and pollutant removal mechanisms (upward and sideward) for three-dimensional street canyons.

The needs of the wide range of stakeholders and end-users, who require information on current and predicted urban atmospheric conditions need to be more fully understood. In particular, the applications of interest to them and the scale of interventions needed. Such needs assessments need to inform what research developments have the greatest demand and potential benefit. The breadth of these stake-holders and end-users, and how they vary across cities, also needs to be recognised.

Modelling

To meet the needs for expanding urban-related services, NWP and air quality forecast (AQF) models are being run at finer resolutions, with a tendency towards closer integration of these efforts. Operational meso-scale NWP models in many national meteorological services are now being run at grid lengths of the order few km, where urban effects in larger cities can be seen, albeit crudely. These models make use of a wide range of urban land surface schemes that have been developed, although to date with very minimal, systematic evaluation. These schemes are undergoing rapid development and the testing that has been done so far suggests that systematic evaluation does result in improvements (Grimmond et al. 2010). However, there is large scope for additional improvements (Grimmond et al. 2011) and evaluation needs to be both offline and online (i.e. integrated into the larger forcing including the feedbacks in the full model) to ensure that the models are fit for purpose.

Current research involves meso-scale models being run at greater spatial resolution (Loridan and Grimmond 2013, Lean 2014). As one example, the UK Met Office is experimenting with a routinely running 333 m model for the greater London area. A fundamental issue is the need to better understand the behaviour of these models as they start to resolve turbulence. In this regard, many lessons can be learnt from the LES community. An example of the issues that may be encountered is the serious spin up effects often observed as air enters the domain of order 100m models and spins up turbulence. Higher resolution models will also require a great deal of work on the representation of the urban surface. On current projections of computer power, it will still be many (~40?) years before such models can resolve buildings (i.e. be equivalent in resolution to current street scale CFD/LES/DNS modelling) for any reasonable sized city. This means that a key problem moving forward will be "building grey zone" (analogous to the often discussed convection grey zone) where buildings are not resolved but the assumption, in lower resolution models, that there are many in each grid-point also breaks down. To improve model evaluations and understanding, a wider range of laboratory and CFD/LES/DNS studies are needed with structures that more closely resemble cities than earlier, idealized homogenous arrays to inform model development for urban RSL turbulence. Higher resolution models will also mean that the vertical extent of buildings will have to be considered with schemes correctly distributing effects of buildings on heat fluxes, drag etc over the lower parts of the boundary layer (e.g. Martilli 2007, Chen et al. 2012, Santiago et al. 2013) in conjunction with a number of other processes. An overall challenge moving to higher resolution and taking into account the considerations highlighted here, is to ensure that a balanced amount of effort is put into all the above aspects. It will not be worth (either in terms of research effort or in CPU required to run the model) striving for huge accuracy in one part of the model when there are still gross errors in others.

There is a need to improve short-range, high-resolution numerical prediction not only for weather but also for coupling to other sub-models. The most important examples are air quality and chemical dispersion, urban hydrology and inundation and, for cities close to the coast, ocean models.

Modelling air quality and chemical dispersion modelling in the urban zone will require improved modelling of the biogeophysical features of the land surface and consequent exchange of heat, moisture, momentum and radiation (the surface energy balance) with the UBL. Research with CFD/LES/DNS codes will allow improved understanding of wind and pollutant transport in regimes other than skimming flow and with combined effects of wind and buoyancy. Research is needed so more realistic air pollution chemistry mechanisms can be incorporated into the models. Of particular importance is the need to better represent pollutant emissions. There are currently large uncertainties in urban scale emissions and they increase finer grid resolution. Advances are needed in developing better emission models to support urban air quality forecasts.

Research is required, in which the coupled models will be an important tool, to enhance our understanding of the feedback between human activities (e.g. energy use in building, traffic) and the urban environmental conditions (e.g. air quality, anthropogenic heat fluxes). Often multi-scale modelling would allow more thorough investigations into the effects of large-scale atmospheric turbulence on the neighbourhood or micro-scale turbulence below the canopy levels. These tools need to be more thoroughly developed for a wide range of applications (e.g. the interaction between natural and built areas, human comfort; building energy consumption; and urban design). Furthermore, research is needed to better understand the air quality weather feedbacks at urban scales, and how sensitive predictability is to the complexity of the representations of these feedbacks. Research is also needed to further develop and evaluate data assimilation methods to support coupled prediction systems.

There is a need to improve understanding of dynamic (spatially and temporally) land cover and land use information for model parameters. Cities are dynamic, new structures are built and there is also continuous repair and regeneration of older building (e.g. new roofs, painting or resurfacing of walls, roads, green infrastructure) and growth and maintenance of vegetation etc. These all change the micro-scale features of the surface. Methods need to be developed to gather this information in a routine manner, ingesting the spatially explicit parameters to appropriate models.

<u>Tools</u>
Given the wide range of applications that are used, and required, within urban areas that would benefit from improved numerical predication of atmospheric processes within urban areas, there are a number of closely linked tools/applications that also could benefit from focused attention.

With increasing data availability, tools need to be developed to allow models to be able to accommodate wide differences in data availability depending on the application, from research to operational situation. For example, in field research studies, extensive wind observations may be available (and detailed building morphology), but for emergency response situations only minimal inputs may be available (for example, winds from the nearest airport, no three-dimensional building data).

More and more tools are becoming available, facilitating access to these tools so that development and research efforts go to improving these rather than re-developing the similar tools is what is important. Additionally, making these tools openly available would allow community expertise to be actively harnessed. In some cases developing web-based interfaces to run the models may greatly enhance usage, as would simple tools to improve provision of data to the models.

Many policy-makers, in different governance structures, along with community groups are actively engaged in proposals and discussions to enhance urban sustainability and resilience. These may involve changes to the local buildings/infrastructure in terms of urban greening through tree planting; repaving/replacing roads/pavements with high(er) albedo or low-emissivity materials; investing in multi-function solutions (e.g. green roofs). Tools are needed that allow such stakeholders to consider competing and unintended impacts of suggested changes. For example, the introduction of green infrastructure with intent of reducing air temperatures will increase humidity and change the air quality. Stakeholders need to be able to consider the net benefits to health and comfort. Different considerations will come into play if the concern is with day to day management versus extreme events.

<u>Communication</u>

By better informing the meteorological community of the needs for planning and managing cities of all sizes in an as sustainable manner, the needs of cities residents can be better served. Thus developing and encouraging communication that crosses traditional scientific disciplines and networks is important. This is also learning about who needs what information, in what form, with what appropriate lead times. For example, there are a number of public health warnings that could be improved by providing better tailored forecasts (e.g. heat waves, cold, air quality, pollen, flooding). Attention needs to be given to determine what would make the greatest improvement to the end-users of weather products. This would be aided by developing collaborations with stakeholders and end-users in the widespread development of early warning systems. In addition, research is needed into what are the most appropriate and effective ways to communicate data and warnings, both through conventional means and current (and evolving) electronic media, to maximise access and depth of content that is up-to-date.

Table 1: Common issues identified to enhance the predictive capabilities for urban areas (based on Grimmond et al. 2014)

1	Initiation of an Integrated Urban Weather, Climate, Water and Related Environmental Services
2	Databases and data sharing
3	Observations
4	Modelling and prediction
5	Applications
6	Communications and outreach
7	Evaluation
8	Research and Development
9	Capacity Development

Table 2: Recent reports with recommendations for urban prediction

Dabberdt WF, A Baklanov, GR Carmichael, V Chandrasekar, CSB Grimmond, P Nurmi, K Petty, V Wulfmeyer, L Jalkanen 2013: WMO GURME Workshop on Urban Meteorological Observation Design, WMO GAW Report No. 208, http://www.wmo.int/pages/prog/arep/gaw/documents/GAW_208_web.pdf
Grimmond CSB, M Roth, TR Oke, YC Au, M Best, R Betts, G Carmichael, H Cleugh, W Dabberdt, R Emmanuel, E Freitas, K Fortuniak, S Hanna, P Klein, LS Kalkstein, CH Liu, A Nickson, D Pearlmutter, D Sailor, J Voogt 2010: Climate & More Sustainable Cities: Climate Information for Improved Planning & Management of Cities (Producers/Capabilities Perspective) *Procedia Environmental Sciences*, 1, 247-274.

Grimmond S, G Beig, B Brown, G Carmichael, Chen B, Fang Z, G Fleming, A Garcia, L Jalkanen, H Kootval, Li H, K Longo, Mu H, Peng L, Shi J, Tan J, Tang X, D Terblanche, Woo W-C, Zhang J 2014: Establishing integrated weather, climate, water and related environmental services for m Megacities and large urban complexes – Initial guidance. WMO Expert Workshop Shanghai, China 20-21 August 2013 http://www.gfcs-climate.org/sites/default/files/events/Expert%20Workshop//WMO_Megacity_IMP_Plan.pdf
Martilli A 2007: Current research and future challenges in urban mesoscale modelling. Int. J. Climatol., 27: 1909–1918. doi: 10.1002/joc.1620
National Research Council 2010: *When Weather Matters: Science and Service to Meet Critical Societal Needs*. Washington, DC: The National Academies Press http://www.nap.edu/openbook.php?record_id=12888
National Research Council 2012: *Urban Meteorology: Forecasting, Monitoring, and Meeting Users' Needs.* Washington, DC: The National Academies Press, http://www.nap.edu/openbook.php?record_id=13328
Zhu T, M Melamed, D Parrish, M Gauss, L Gallardo Klenner, M Lawrence, A Konare, C Liousse 2012/2013: WMO/IGAC Impacts of Megacities on Air Pollution and Climate GAW Report No. 205, http://www.wmo.int/pages/prog/arep/gaw/documents/Final_GAW_205_web_31_January.pdf

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Grimmond CSB, M Blackett, M Best, J Barlow, JJ Baik, S Belcher, SI Bohnenstengel, I Calmet, F Chen, A Dandou, K Fortuniak, ML Gouvea, R Hamdi, M Hendry, T Kawai, Y Kawamoto, H Kondo, ES Krayenhoff, SH Lee, T Loridan, A Martilli, V Masson, S Miao, K Oleson, G Pigeon, A Porson, YH Ryu, F Salamanca, GJ Steeneveld, M Tombrou, J Voogt, D Young, N Zhang 2010: The International Urban Energy Balance Models Comparison Project: First results from Phase 1 J. of Applied Meteorology & Climatology, **49**, 1268-92, doi: 10.1175/2010JAMC2354.1

Grimmond CSB, M Blackett, MJ Best, J-J Baik, SE Belcher, J Beringer, SI Bohnenstengel, I Calmet, F Chen, A Coutts, A Dandou, K Fortuniak, ML Gouvea, R Hamdi, M Hendry, M Kanda, T Kawai, Y Kawamoto, H Kondo, ES Krayenhoff, S-H Lee, T Loridan, A Martilli, V Masson, S Miao, K Oleson, R Ooka, G Pigeon, A Porson, Y-H Ryu, F Salamanca, G-J Steeneveld, M Tombrou, JA Voogt, D Young, N Zhang 2011: Initial Results from Phase 2 of the International Urban Energy Balance Comparison Project, International J. of Climatology 31, 244-272 doi: 10.1002/joc.2227

Grimmond S, G Beig, B Brown, G Carmichael, Chen B, Fang Z, G Fleming, A Garcia, L Jalkanen, H Kootval, Li H, K Longo, Mu H, Peng L, Shi J, Tan J, Tang X, D Terblanche, Woo W-C, Zhang J 2014: Establishing integrated weather, climate, water and related environmental services for m Megacities and large urban complexes – Initial guidance. WMO Expert Workshop Shanghai, China 20-21 August 2013 http://www.gfcs-climate.org/sites/default/files/events/Expert%20Workshop//WMO_Megacity_IMP_Plan.pdf

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