From Urban Meteorology, Climate and Environment Research to Urban Integrated Services

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1. Introduction

Over the past few hundred years the human population has clustered increasingly in large settlements, to the point where the urban population now exceeds the rural population. They are concentrated in 1-3% of the Earth's land surface in cities of a wide range of sizes. Cities that exceed 5 million have had rapid worldwide growth from four such conurbations in the 1950s to 59 in 2015. Many of these cities are situated in developing countries and are characterized by high/elevated air pollution levels. In 2009 16% of the world's population was living in cities with more than 5 million inhabitants (UN, 2012). Such large entities are heavily dependent on the underlying infrastructure, including all transport systems (road, rail, pedestrian, bicycle etc), water and power supply, sanitation and drainage systems, communication networks etc. The complexity of this infrastructure, together with its vulnerability, increases in a non-linear fashion with size, e.g., doubling the size of a city may increase several times the complexity and therefore vulnerability. Fast growing large cities are major drivers of economic growth, but they often result in rapid and unbalanced growth with new urban populations that are often poor.

The dramatic demographic shifts associated with the growth of cities have wide-ranging implications. Few are felt more by residents than deterioration of air quality. The cities in poor, developing countries often are not subjected to restrictions on emissions of the sort more common in North America and Europe. Cities like London and Los Angeles have implemented policies and strategies to attempt to curb air pollution. Until recently, changes in air quality resulting from increasingly dense urban centres have not been quantified in detail, and the effects on regional climates and the impact on global warming remained undocumented systematically.

The need to examine the effect of the rising number of cities on air pollution, local climate and their effects on global warming is important. Cities share common characteristics, notably a high density of population which makes them more sensitive and vulnerable to weather/air quality/climate variations inducing/enhancing health impacts (e.g. epidemic breakouts, respiratory chronic diseases in vulnerable groups, heat stress, flooding etc.) and affecting economic activities (transportation, tourism, construction, school access, etc.).

The World Meteorological Organization (WMO) on the recent World Meteorological Congress (https://sites.google.com/a/wmo.int/cg-17/) emphasized that the rapid urbanization that is currently taking place will require new types of services making best use of science and technology and considered this problem as one of the main priorities. Such Integrated Urban Weather, Environment and Climate Services (Grimmond et al., 2014) should assist cities in facing hazards such as storm surge, flooding, heat waves, and air pollution episodes, especially in changing climates.

2. Urban weather/climate and their footprint

There are two main mechanisms by which cities will further affect local, regional and global climates. Firstly, urban features such as the morphology and heat emissions will continue to influence, local temperatures, air circulation and alter the formation of precipitation and the frequency and intensity of thunderstorms. Secondly, changing chemical emissions and feedbacks with atmospheric pollutants will alter the subsequent effects on weather and climate, both locally and further afield.

Many features in cities can influence atmospheric flow, its turbulence regime, and the microclimate, and thus can modify the transport, dispersion, and deposition of atmospheric pollutants both within and downstream of urban areas (one form of which is acid rain). Key examples include: (i) The distribution of buildings, and other obstacles (or more generally of all roughness elements), affects the turbulence regime, speed and direction of the flow; (ii) The extensive use of impervious materials and the often reduction of vegetation in urban areas affects the hydro–meteorological regime and pollutant deposition; (iii) The release of anthropogenic heat by human activities (transportation; building heating/cooling) affects the thermal regime; (iv) The release of pollutants (including aerosols) affects the transfer of radiation the formation of clouds and precipitation; (v) Street geometry ('street canyons') affects the flow regime and the exchanges of heat between different surfaces (e.g., roads and walls).

The net result may be strong urban heat islands – areas of warmer temperatures - which mean cities may be several degrees warmer than nearby rural areas. Such temperature differences can disturb regional air circulation. Wind patterns may be disrupted even further because of numerous and increasing high rise buildings. The disturbances can in turn lead to altered levels of precipitation, air pollution and thunderstorm frequencies.

The contribution of cities to global warming through greenhouse gas (GHG) emissions is probably substantial, mostly due to plumes of CO_2 emissions from urban areas or supporting areas nearby, with the intensity possibly slightly less on a per capita basis. However, due to the long-life and well mixing of the long-lived greenhouse gases in the atmosphere, the climate effect of them from urban areas is similar to what would be expected if the populations lived elsewhere (e.g. rural areas). The global and regional effects of short-lived climate forcers from megacities are even more uncertain. Folberth et al. (2012) showed that on the global scale effects of non-CO_2 emissions could be nearly neutral, with a very small net cooling calculated from the climate-chemistry models (from ozone, methane and aerosol products).

3. Megacities air quality and larger scale effects

Recent international projects initiated to study the issue include: MILAGRO (http://www.mce2.org), MEGAPOLI (http://megapoli.info), CityZen (https://wiki.met.no/cityzen/start), ClearfLo (www.clearflo.ac.uk), WISE (Seoul), SUIMON (Shanghai) (see comprehensive worldwide overview of impacts of megacities on air pollution and climate and corresponding projects in WMO/IGAC, 2012). In particular, the MEGAPOLI studies aimed to assess the impacts of megacities and large air-pollution hotspots on local, regional and global air quality; to quantify feedback mechanisms linking megacity air quality, local and regional climates, and global climate change; and to develop improved tools for predicting air pollution levels in megacities (Baklanov et al., 2010). The European project FUMAPEX (http://fumapex.dmi.dk/) developed for the first time an integrated system encompassing emissions, urban meteorology and population exposure for urban air pollution episode forecasting, the assessment of urban air quality and health effects, and for emergency preparedness issues for urban areas (Baklanov et al., 2007). Such Urban Air Quality Information and Forecasting Systems (UAQIFSs) were realized and demonstrated in 6 European cities: Bologna, Castellon/Valencia, Copenhagen, Helsinki, Oslo, Torino.

While important advances have been made, new interdisciplinary research studies are needed to increase our understanding of the interactions between emissions, air quality, and regional and global climates. Studies need to address both basic and applied research and bridge the spatial and temporal scales connecting local emissions, air quality and weather with climate and global atmospheric chemistry. WMO has established the Global Atmosphere Watch (GAW) Urban Research Meteorology and Environment (GURME) project (http://mce2.org/wmogurme/) which provides an important research contribution to the integrated urban services. GURME pilot projects serve as examples for development of air quality capacity in cities moving from research to operational activities and further to products and services and their dissemination. One example is the SAFAR project (Beig et al., 2015) where air quality services were developed for New Delhi for the Commonwealth Games 2010, and consequently implemented for continuous use. Subsequently this system has been implemented in Pune, and will be implemented in 4 other Indian cities. In the SAFAR project (http://safar.tropmet.res.in), air quality monitoring was put in place, an emission inventory was developed, forecasting models were implemented and products were developed for the public and decision-makers, that are available through different services (Fig. 1).

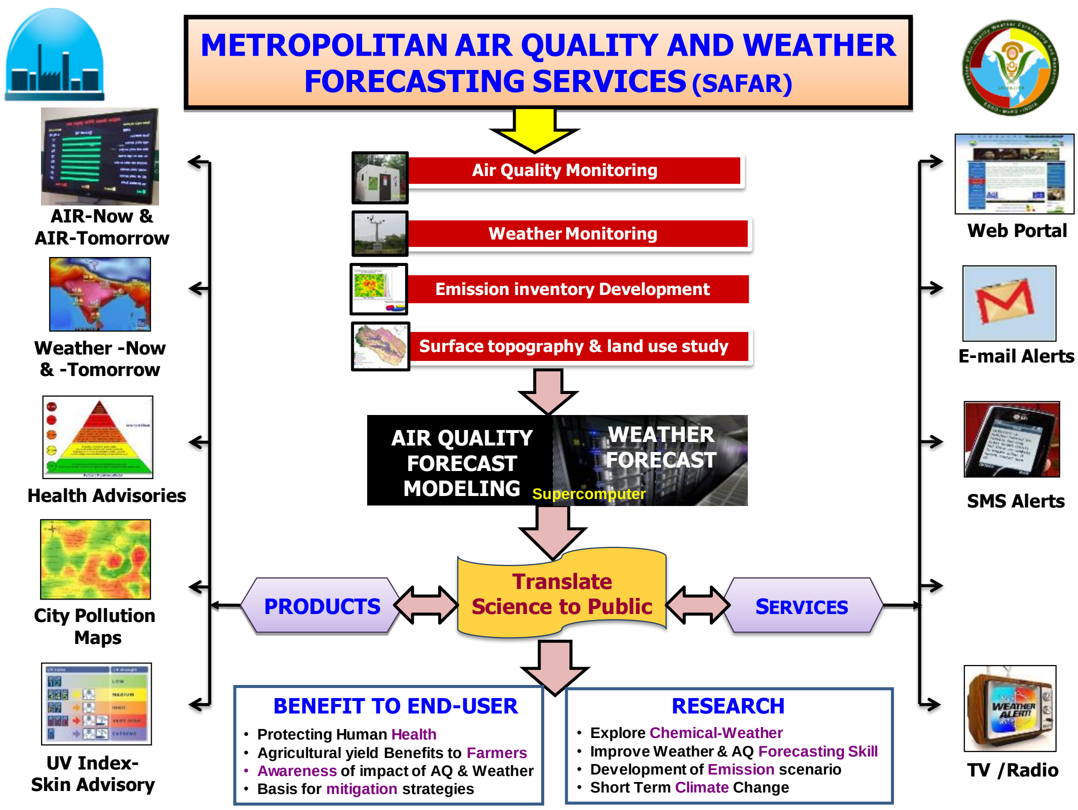

Figure 1: The SAFAR system developed in India as a WMO GURME project (Beig et al., 2015)

Megacities and other densely populated regions emit significant amounts of pollution into the atmosphere, and the local effects are especially evident within the boundaries of well-known polluted megacities, such as Beijing and Delhi. Large quantities of pollutants are derived from urban transport, energy production, and other types of industry. These have effects on the environment and are harmful to health. However, pollution is not confined to within the boundaries of the (mega)cities, it can be transported large distances contributing to overall hemispheric background pollution. The impacts of (mega)cities are quite variable and can extend in all directions. The average transport distance for black carbon and other primary fine particulate matter (PM) components is up to 200 km for most megacities. Maximum transport distances are significantly higher, with 25% transported more than 2000 km (Butler and Lawrence, 2009). Secondary organic aerosols are a very important part of PM2.5 concentrations (Freney et al., 2014; Beekmann et al., 2015).

The sources and processes leading to high concentrations of main pollutants such as ozone, nitrogen dioxide and particulate matter in complex urban areas, however, are not fully understood, limiting our ability to forecast air quality accurately. The comparison of three major global emissions inventories, alongside two city level inventories, examined in MEGAPOLI (Denier van der Gon et al., 2011) showed that there is huge variation in the sources and degree of emissions between megacities, in particular, by geographical region. For example, much of the megacity emissions in Europe and the Americas are associated with road use, whereas in Asia and Africa the output largely stems from residential natural/ biofuel consumption.

4. Cities in changing climate/global change

Global climate variability and change substantially affect cities, whose citizens are more vulnerable than other territories. The impact spans entire urban environments; ranging human and environmental health, safety, food security, water resources, infrastructure and beyond. Thus they need to be equipped to adapt to global change. Given the large number of activities within a city and its surroundings impacted by climate, many wide ranging agencies have the responsibility to provide climate sensitive services. In particular for those major cities in coastal zones, more reliable information should be provided for water resourcing, extreme storm events and climate trend predictions, to support local decisions about investments and town planning. The key for providing information and services for climate in need for cities are well researched climate information and prediction products. This requires studying the large scale and long-term processes, such as ocean temperature and current, changes in land cover, and slow changing variables in the atmosphere. Ocean and land surface changes can produce fluctuations that are potentially predictable for climate at seasonal and inter-annual time scales.

The World Climate Research Programme (WCRP; http://www.wcrp-climate.org/), jointly sponsored by WMO, ICSU and UNESCO/IOC, has been coordinating the Coupled Model Intercomparison Project (CMIP) since 1995. Its objective is to better understand past, present and future climate changes arising from either natural, unforced variability or in response to changes in radiative forcing in a multi-model context. This understanding includes assessments of model performance during the historical period and quantifications of the causes of the spread in future projections. Idealized experiments are also used to increase understanding of the model responses. In addition to these long time scale responses, experiments are performed to investigate the predictability of the climate system on various time and space scales as well as making predictions from observed climate states. An important part of CMIP is to make the multi-model output publically available in a standardized format. A specific CMIP project related to urban issues is the Aerosol Comparisons between Observations and Models (AEROCOM; http://aerocom.met.no). It is an open international initiative of scientists interested in the advancement of the understanding of the global aerosol and its impact on climate. A large number of observations, surface concentrations, other observations of relevance and results from more than 14 global models have been assembled to document and compare state of the art modeling of the global aerosol. The range of model results documented with AEROCOM shall help to reduce the uncertainty in aerosol climate forcing estimates.

To meet the special need of cities, integrated climate-chemistry or Earth System models need to be regionally downscaled to produce refined climate change products. The WCRP-sponsored Coordinated Regional Climate Downscaling Experiment (CORDEX; http://www.cordex.org/) provides a framework for evaluating and comparing various Regional Climate Downscaling (RCD) techniques, enhancing regional capabilities for climate prediction. Recent efforts have been made for multi-disciplinary approach among physical science and risk assessment, with a view to improved use of regional climate prediction for impact and adaptation planning. Also, the Working Group on Regional Climate (WGRC) has been working to serve as conduit for two-way information between WCRP and the various institutions and coordinating bodies that provide climate service. With increased demand on the climate information in megacities, it is anticipated that the Group would extend its efforts to address climate information for the urban community.

While the information need from urban decision support systems are focused on specific spatial extents in all time scales – from a very short range for emergency response to a decadal scale and climate factors for responses to slow-onset disasters as well as planning for adaptation/mitigation – currently available forecasting and analyses systems are often fragmented by temporal scale, and tend to focus on general overview of larger spatial extents. Especially, greater attention should be paid to the weather and climate extremes that have enormous impacts on society and their environment, as the occurrence, intensity and character of many types of extremes are already changing and will very likely change in the future, as the climate continues to change due to human influences (IPCC, 2013). To provide targeted climate information and prediction products, prediction models for temperature and rainfall as well as extreme events with high impact (e.g. heat wave, floods, onset and offset of Meiyu in Shanghai) need to be developed.

Three-quarter of the world`s cities are located in coastal regions. Sea level change is expected to have a severe impact on these coastal cities. The change in sea level and its impacts differ among regions, therefore it is required to make well-researched predictions reaching from the global to the regional and local scales. Most coastal cities in the world operate emergency response systems against fast-onset hydro-meteo-oceanic and geological hazards and associated risks. Their efficiency and effectiveness can be improved only when the systems are designed and operated through the holistic approach for long-term climate context, especially to be able to provide sound analyses on impacts in all time and special scales. WCRP`s Grand Challenge on sea level change and coastal impacts is the community effort for an integrative interdisciplinary research with the main goal to establish a quantitative understanding of the natural and anthropogenic mechanisms of regional to local sea level variability. The necessary analyses on global and regional climate change data and simulations are considered. It also aims for close interaction with coastal communities to assure that results of the proposed scientific research are incorporated into practices of coastal zone management, impacts and adaptation efforts. Future commitment should follow, to ensure seamless operation for weather and climate information service for disaster management and city planning, to improve resilience of coastal cities to weather and climate extremes especially associated with the sea level rise.

Facing all these challenges for future improvement in climate information for cities, an integrated and seamless approach will significantly improve our knowledge on climate change, its environmental consequences as well as the impacts to human dimensions; for example, simulation and prediction of climate and weather phenomena in all time scales, integrated analysis for climate and urban environments for impact assessments, interdisciplinary and long-term environmental data collection and processing systems. In this context, there is an emerging voice for the need for WCRP and WWRP to together address urban populations and environments – where hourly-to-decadal time scales, regional geographic scales and seamless coupled weather-climate modeling capabilities become more urgent and more challenging - in a prompt, effective and coordinated manner. Aiming to improved climate services for urban communities, the core contribution of research programmes should include the continuous review of technologies / prediction skills that respond to the user requirements, identifying and answering to the science gaps, and ensure usability of available climate information/knowledge – to be carried out in parallel with user interaction.

5. Research needs and strategy for the future

People are central to a city and its functioning. They require new services that make the best use of new science and technology (Xu, 2006; Kootval, 2013; Grimmond et al., 2014). Each city faces an unique set of hazards and risks that require tailored priorities when designing services. Cities also provide unique opportunities to capitalize on the co-benefits that can be achieved by optimizing energy use, improving air quality and minimizing GHG emissions that drive global climate change through the integrated use of urban weather, climate, water and related environmental services. However, to deliver these services and realize their benefits a seamless approach - coalescing weather and climate - lays at the core of providing information and prediction products for these services. This requires a strong and wide-reaching institutional cooperation.

The needs and requirements of each city needs to be informed by holistic impact and hazard identification in order to map the city’s specific vulnerabilities and identify the services that would be most beneficial. Coastal cities have different concerns to land-locked cities; similarly requirements of an urban area in the Tropics differ to one often impacted by severe winter weather. Climate change could severely change the hydrologic cycle creating great challenges for water recourses, water availability and water management in cities and its surroundings. Besides there is an urgent need to look for strategies that deal with waste disposal and analyze the impact on cities. Data sharing arrangements between city institutions is a fundamental building block for authorities to identify the priority services and also to design and establish urban observational networks that capture the phenomena of interest at the spatial and temporal resolution required.

City services are also heavily reliant on high resolution coupled environmental prediction models that include realistic city specific process, boundary conditions and fluxes of energy and physical properties. The models need to be regionally downscaled and improvements need to be made in the context of decadal to seasonal predictions. New urban-focused observational systems are needed to drive these models and to provide high quality forecasts used in these new services (Tan et al., 2015). There is an urgent need for an integrated approach to climate and weather information products in urban areas. Seamless predictions are at the core of providing high-quality climate sensitive services. The use of new, targeted and customized means to communicate with users is required to ensure that services, advice and warnings result in appropriate action and feedback to improve the services. New skill and capacity will be required to make best use of new technologies to produce and deliver new services in a challenging and evolving city environment.

WMO encourages National Meteorological Services (NMSs) to establish sound working relationships with municipal authorities and jointly identify and agree the priorities for joint services and the resources required for sustained service delivery and improvement. Considering the global importance of urbanization, the growing number of megacities and large urban complexes, NMSs would do well to include this phenomenon as a high-level priority and consider how best to also include the unique climate service requirements of the urban environment in the Global Framework for Climate Services. NMSs should showcase their urban experiences, share their experiences and establish best practices as to how to best serve the urban dweller who now is rapidly becoming a majority stakeholder in urban weather, climate, water and related environmental services.

6. Towards Integrated Urban Weather, Environment and Climate Service (IUWECS)

A broad set of concepts defines the development of IUWECS. These concepts relate to the conditions faced by urban populations and the impacts of environmental conditions on the megacity and urban society, the need for a legal framework and clearly defined government agency interactions to enable creation and maintenance of such a system, and the advances of science and technology required to develop and implement such a system.

Development of an IUWECS requires scientific and technological development in many areas, including (Grimmond et al., 2014b): (a) understanding and knowledge regarding enhanced observational needs to meet the requirements of integrated services in megacity and other urban environments, and identification of observational source locations in complex environment; (b) concepts, scientific capabilities and technology for seamless services; (c) the science and technology required for provision of service applications to society; (d) smart delivery approaches, including the application of new technology to create an “intelligent and wise” city; (e) methods for efficiently making use of large, complex databases (i.e., “Big Data”); and (f) implementation of user-relevant approaches for evaluating the quality and benefits of products and services.

Accomplishing these activities will require an acceleration of the transition of research capabilities and knowledge to operational systems. The scientific effort is also heavily reliant on extensive sharing of capabilities and knowledge among participating organizations in an IUWECS. Research on basic physical and chemical processes and development of numerical models and tools are an integral and central component of a reliable and accurate forecast products and services. Ultimately then, as an ever-increasing number of (mega)cities loom on the horizon, a new generation of multi-scale integrated models are needed for helping to ensure that we can adapt to the responsibilities associated with (mega)cities. Connections between megacities, air quality and climate include (Fig. 2): (i) Nonlinear interactions and feedbacks between urban land cover, emissions, chemistry, meteorology and climate; (ii) Multiple temporal scales from seconds to decades and spatial scales from buildings to global; (iii) Complex mixture of pollutants from large sources.

The numerical models most suitable for an integrated urban weather, air quality and climate forecasting operational system are the new generation limited area models with coupled dynamic and chemistry modules (so called Integrated Meteorology-Chemistry Models (IMCM)). These have benefited from rapid advances in computing resources plus extensive basic science research (see Zhang, 2008, Baklanov et al., 2014 for reviews). Current state-of-the-art IMCMs encompass interactive chemical and physical processes, such as aerosols-clouds-radiation, coupled to a non-hydrostatic and fully compressible dynamic core including monotonic transport for scalars, allowing feedbacks between the chemical composition and physical properties of the atmosphere. However, simulations using fine resolutions, large domains and detailed chemistry over long time duration for the aerosol and gas/aqueous phase are still too computationally demanding due to the huge model complexity. Therefore, IMCMs weather and climate applications still must make compromises between the spatial resolution, the domain size, the simulation length and the degree of complexity for the chemical and aerosol mechanisms. A typical model run on the weather scale for an urban domain uses a reduced number of chemical species and reactions because of its fine horizontal and vertical resolutions, while climate runs generally use coarse horizontal and vertical resolutions with reasonably detailed chemical mechanisms (Barth et al., 2007). There are initiatives to expand the related services of large forecast centers. For example the MACC project (Monitoring Atmospheric Composition and Climate, http://copernicus-atmosphere.eu) is the current pre-operational Copernicus Atmosphere Service on the global and European scale, providing data which can be downscaled to urban agglomerations.

The representation of the urban land surface and urban sublayer has undergone extensive developments but no scheme is capable of dealing with all the surface exchanges (Grimmond et al. 2010, 2011). To complicate this further, as the resolution of models becomes greater, combined with the large size of urban buildings in many cities, the limits of current understanding are being challenged. Key questions include: should buildings be directly resolved? what can be simplified to make the computations tractable in realistic modelling time? at what scale can the current land surface schemes and model physics be applied?

Research needs also relate to secondary organic aerosols and its interaction with clouds and radiation, data assimilation including chemical and aerosol species, dynamic cores with multi-tracer transport efficiency capability and the general effects of aerosols on weather/climate evolution. All of these areas are concerned with an efficient use of models on massively parallel computer systems.

Operational centres that base their products and services on IMCMs not only need to follow closely the evolution of the research and development of these coupled models, but interactively engage with these activities. Research on basic physical and chemical process and development of numerical models and tools are an integral and central component of a reliable and accurate forecast products and services. Nevertheless, operational personnel will not be fully responsible for these research and development activities, so strong and long-term partnerships should be established between researchers and operational groups (internal and external). These partnerships should promote the development of methods of evaluation to measure improvements in forecast skills and benefits.

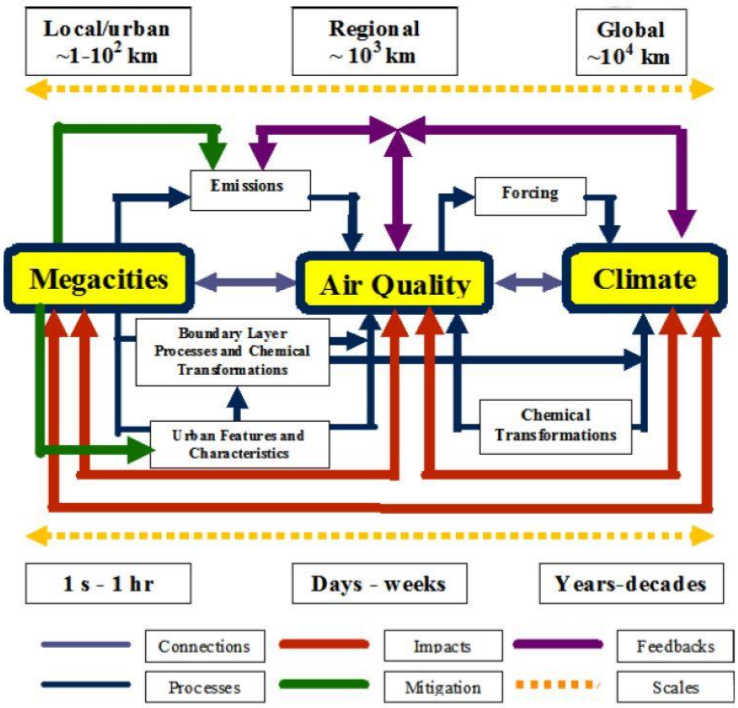

Figure 2: MEGAPOLI schematic showing the main linkages between megacities, air quality and climate (Baklanov et al., 2010). In addition to the overall connections between megacities, air quality and climate, the figure shows the main feedbacks, ecosystem, health and weather impact pathways, and mitigation routes which need to be included in the Integrated Urban Weather, Environment and Climate Service (IUWECS) . The relevant temporal and spatial scales are also included.

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