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From urban meteorology, climate and environment research to integrated city services

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ABSTRACT

Accelerating growth of urban populations, especially in developing countries, has become a driving force of human development. Crowded cities are centres of creativity and economic progress, but polluted air, flooding and other climate impacts, means they also face major weather, climate and environment-related challenges. Increasingly dense, complex and interdependent urban systems leave cities vulnerable: a single extreme event can lead to a widespread breakdown of a city's infrastructure often through domino effects. The World Meteorological Organization (WMO) recognizes that rapid urbanization necessitates new types of services which make the best use of science and technology and considers the challenge of delivering these as one of the main priorities for the meteorological community. Such Integrated Urban Weather, Environment and Climate Services should assist cities in facing hazards such as storm surges, flooding, heat waves, and air pollution episodes, especially in changing climates. The aim is to build urban services that meet the special needs of cities through a combination of dense observation networks, high-resolution forecasts, multi-hazard early warning systems, and climate services for reducing emissions, that will enable the building of resilient, thriving sustainable cities that promote the Sustainable Development Goals. A number of recent international studies have been initiated to explore these issues. The paper provides a brief overview of recent WMO and collaborators research programs and activities in urban hydrometeorology, climate and air pollution; describes the novel concept of urban integrated weather, climate

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and environment related services; and highlights research needs for their realisation.

1. Introduction

Over the past few hundred years humans have clustered increasingly in large settlements, to the point where the urban population now exceeds the rural population. Concentrated on less than 3% of the Earth's land surface, this population is in settlements of greatly varying size. In 2009, 16% of the world's population lived in cities with more than 5 million inhabitants (UN, 2012). Cities depend heavily on infrastructure (e.g. transport systems - road, rail, pedestrian, bicycle, etc.), water and power supply, sanitation and drainage systems, communication networks, etc.), the complexity of which may add to the settlements' vulnerability in a non-linear manner with size (e.g., doubling city size may more (or less) than double the complexity and vulnerability).

Cities share many common characteristics, notably high population densities, making them more sensitive and vulnerable to weather/air quality/climate variations inducing/enhancing health impacts (e.g. epidemics, chronic respiratory diseases, heat stress, flooding etc.) and affecting economic activities (transportation, tourism, construction, school access, etc.). A single extreme event can through a domino of effects lead to a broad breakdown of a city's infrastructure (e.g., hurricanes Sandy in New York, Katrina in New Orleans; recent examples of air pollution in Beijing, Delhi, London, Paris etc.).

Increasingly is it recognised that current rapid urbanization necessitates new types of services to make the best use of science and technology. The New UN Urban Agenda, adopted by the 3rd UN Conference on Housing and Sustainable Urban Development in October 2016 (Habitat-III, 2016) considers urban resilience, climate and environment sustainability and disaster risk management (DRM) as key issues for urban sustainable development for the next 20 years. At the 17th World Meteorological Congress in June 2015 (Resolution 68, see WMC-17, 2015), the WMO emphasized such Integrated Urban Weather, Environment and Climate Services (Grimmond et al., 2014a, 2014b; Baklanov et al., 2016) should assist cities in facing hazards such as storm surges, flooding, heat waves, and air pollution episodes, especially in changing climates.

The objective of this paper is to provide a brief overview of recent WMO and collaborators research programs and activities in urban hydrometeorology, climate and air pollution, presenting the emerging concept of urban integrated weather, climate and environment related services, and research needs for their realisation at scales both within and beyond the city.

2. Urban Research Meteorology & Environment (GURME) and High Impact Weather (HIW) projects

Cities affect weather and climate at local, regional and global scales through two main mechanisms. Firstly, urban features such as the morphology of buildings and heat emissions 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 affect 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). As described by Baklanov et al. (2007) and Cleugh and Grimmond (2012), key examples include: (i) distribution of buildings, and other obstacles (or more generally of all roughness elements), affects the turbulence regime, speed and direction of the flow; (ii) extensive use of impervious materials and the common reduction of vegetation in urban areas affects the hydrometeorological regime and pollutant deposition; (iii) release of anthropogenic heat by human activities (transportation; building heating/cooling) affects the thermal

regime; (iv) release of pollutants (including aerosols) affecting the radiative transfer, and formation of clouds and precipitation; (v) street geometry ('street canyons') affects the flow regime and heat exchange between different surfaces (e.g., roads and walls).

The net result may be strong urban heat islands and disturbed regional flows. Wind patterns may be further disrupted by numerous (and increasing) high rise buildings. The disturbances can modify precipitation, air pollution and thunderstorm frequencies and their spatial distributions.

WMO has had a long-term commitment to studies of urban meteorology and environment (WMO, 1996); for example, WMO Commission for Climatology (CCl) Expert team(s) of Urban and Building Climatology (established in the 1970′s through to 2010) and WMO Global Atmosphere Watch (GAW) Urban Research Meteorology and Environment (GURME) project (initiated 20 years ago).

National Meteorological and Hydrological Services (NMHS) have an important role in the management and study of urban meteorology and environment. In addition to collecting information they have essential urban weather and air pollution forecasting capabilities, and can aid emission control strategies. The WMO established GURME to help enhance the capabilities of NMHS to handle meteorological and related aspects of urban pollution (Dabberdt et al., 2013). This is through co-ordination, focussing on current activities, and initiation of new ones (Section 3, http://www.wmo.int/gaw/gurme and http://mce2.org/wmogurme/).

The WMO World Weather Research Programme (WWRP) High Impact Weather Project (HIW), launched in 2016, is to promote cooperative international research to achieve a dramatic increase in resilience to high impact weather worldwide. This involves both improving forecasts for timescales of minutes to two weeks and enhancing their communication and utility in social, economic and environmental applications. Five general research pillars underpin HIW (Jones and Golding, 2014):

1. Understanding the processes and predictability of weather systems that generate hazards;
2. Multi-scale forecasting of hazards using coupled numerical weather, ocean, land surface, ice and air quality modelling, nowcasting, data assimilation and post-processing systems;
3. Forecasting the human impacts, exposure, vulnerability and risk of hazards to people, buildings, businesses, infrastructure and the environment using a variety of tools;
4. Communicating hazard forecasts and warnings to reach vulnerable communities and achieve responses from risk managers and the public that increases resilience;
5. Evaluating hazardous weather, impact and risk forecasts, alerts and warnings and the resulting responses with user-relevant metrics.

Several research and development projects to enhance HIW prediction for large cities around the world are underway; for example, SURF for Beijing (Barlage et al., 2016; Liang et al., 2017); Pan Am for Toronto (Environment Canada, 2016); TOMACS for Tokyo (Nakatani et al., 2015); WISE for Seoul (Choi et al., 2013; WISE, 2015).

The objectives of the recently completed WWRP TOMACS (Tokyo Metropolitan Area Convection Study for Extreme Weather Resilient Cities, Nakatani et al., 2015), were to 1) elucidate the mechanism of local high-impact weather in urban areas (e.g., local torrential rain, flash flood, strong wind, lightning), 2) improve nowcasting and forecasting techniques of local HIW, and 3) provide high resolution weather information to end-users through social experiments.

The 2014–2018 SURF (Study of Urban Impacts on Rainfall and Fog/Haze) project, initiated by the Institute of Urban Meteorology, China Meteorological Administration (Barlage et al., 2016; Jingjing et al., 2015; Liang et al., 2017), aims to better understand urban, terrain, convection, and aerosol interactions to improve weather forecast accuracy. Beijing is a test case, but it is anticipated the enhanced understanding will be transferable to many large cities globally. Specific objectives include: (i) promotion of cooperative international-research to improve understanding of urban weather-systems via summer thunderstorm-rainfall and winter aerosol field studies; (ii) improved high-resolution (~1 km grid) urban weather and air quality forecast-models; (iii) enhanced urban weather forecasts for societal applications (e.g., health, energy, hydrologic, climate change, air quality, urban planning, and emergency-response management).

The ambitious goal of WISE (Weather Information Service Engine, for the Seoul metropolitan area, 2012–2019, web: http://wise2020.org) is to resolve urban environmental issues; recent advances in high-resolution numerical weather modelling, urban flood prediction, road meteorology, and new

urban service systems to reduce the impacts of natural disaster and climate change on urban areas. The main objectives are to: (i) improve technology and infrastructure implementation for urban and rural meteorology information services; (ii) mitigate and adapt to the climate change and urbanization by developing applied models; (iii) develop decision support for disaster relief; (iv) provide information to support the national agenda; and (v) build a mashup service platform for easy customized services.

Environment and Climate Change Canada (ECCC) with partners, increased weather and composition measurements and forecasts during the 2015 Pan and Parapan American Games held in Toronto, Canada to provide essential services for enhanced weather monitoring and forecasting and for local-level preparedness activities. As a result, a high spatial and temporal resolution dataset was assembled for Greater Toronto Area. Additional new automated land- and marine-based weather stations, experimental monitoring platforms, six Automated Weather Observing System (AWOS) stations (higher frequency), four ground-based radiometers (ultraviolet radiation sensors), air quality stations for O_3, PM2.5 and NO_2, multiple mobile observations of weather and air quality variables supplemented pre-existing ECCC stations. The network monitored weather at the venues, extreme heat, air pollutant concentrations, and southern Ontario lake breezes (as these can be associated with severe weather initiation). Data are posted on the Government of Canada Open Government Portal (http://open.canada.ca/en/open-data keyword TO2015) as they become available.

The urban chapter of the WWOSC book on Seamless Prediction of the Earth System (WMO, 2015) highlighted the following key areas where research investment is important (Grimmond et al., 2015):

(1) 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 determine unknown processes and to force these models to provide high quality forecasts to be used in new urban climate services;
(3) understanding of the critical limit values for meteorological and atmospheric composition variables with respect to human health and environmental protection;
(4) 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 turn inform how best to improve the services;
(5) 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.

3. Megacities air quality and larger scale effects

Airborne emissions from major urban and industrial areas influence both air quality and climate change on scales ranging from local to regional and up to global (Molina and Molina, 2004). International projects concerned with megacities include: MILAGRO (http://www.mce2.org), MEGAPOLI (http://megapoli.info), CityZen (https://wiki.met.no/cityzen/start), ClearfLo (www.clearflo.ac.uk), SAFAR (Delhi), SUIMON (Shanghai, Tan et al., 2015) and others (see comprehensive worldwide overview of impacts of megacities on air pollution and climate and corresponding projects in WMO/IGAC, 2012).

MEGAPOLI aimed to assess the impacts of megacities and large urban agglomerations on local, regional and global environment; to quantify feedback mechanisms linking megacity air quality, local and regional climates, and global climate change; and to develop integrated tools for assessments and mitigations (Baklanov et al., 2010). 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, assessment of urban air quality and health effects, and for emergency preparedness issues for urban areas (Baklanov et al., 2007). Such improved Urban Air Quality Information and Forecasting Systems (UAQIFSs) were undertaken in six 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. GURME provides a

mechanism to integrated urban services and research, notably by encouraging pilot studies move from research to operational activities with enhanced products, services and dissemination.

WMO recommends that city governments consider adopting Multi-Hazard Early Warning Systems (MHEWS) to minimize losses from hazards (Tang, 2006). This approach allows a single cost-effective system to deliver warnings on a wide range of hazards, including storms, temperature extremes and air pollution. By employing impacts-based warnings, which describe the physical impacts of a hazard, rather than just meteorological parameters or air pollution concentrations, these systems can communicate more clearly to people about what actions they should take.

One of the first cities to successfully implement a MHEWS (Tang, 2006; Dabberdt et al., 2013) is Shanghai, which was a WMO GURME project that prepared for the safety of the Shanghai World Expo 2010. Developing a MHEWS requires analyzing and mapping city-specific information on population patterns, hospitals and other infrastructure, evacuation routes, and other relevant factors. It also requires political commitment, clear authority and roles, and standardized procedures.

Another GURME example, SAFAR (http://safar.tropmet.res.in, Beig et al., 2015) developed ongoing air quality services for New Delhi prompted by the Commonwealth Games 2010. Subsequently this system has been implemented in Pune, and will be expanded to four other Indian cities. Air quality monitoring is established, an emission inventory developed, forecasting models implemented and products developed for the public and decision-makers (Fig. 1), these are made available through different services.

Densely populated regions emit significant amounts of pollution into the atmosphere. The local effects are especially evident within megacities, such as Beijing and Delhi. Large quantities of pollutants are derived from urban transport, energy production, and other types of industry. These impact the environment and are harmful to health. However, pollution is not confined to the boundaries of the megacities and can be transported large distances contributing to overall hemispheric background pollution. The impacts of megacities 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,
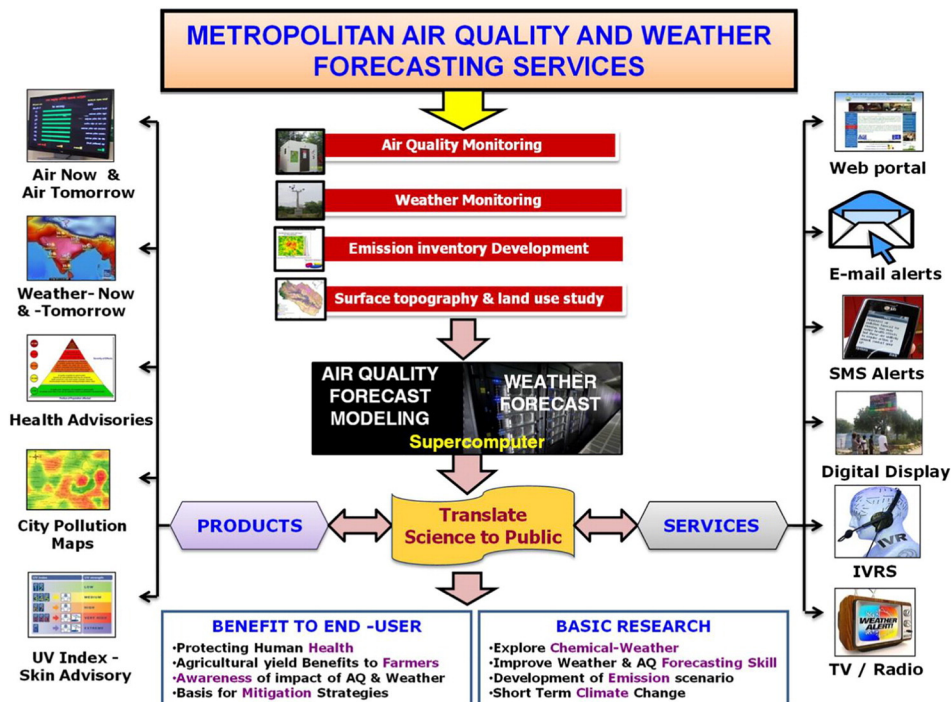

Fig. 1. System of Air quality Forecasting And Research (SAFAR) developed in India as a WMO GURME project (Beig et al., 2015).

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 and Beevers, 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. WMO research programmes for climate smart, sustainable and resilient cities

Changes in climate substantially affect cities. The entire urban environment - ranging from human and environmental health, safety, food security, water resources, infrastructure and beyond – is highly susceptible not only to the locally specific phenomena (e.g. floods, heat/cold waves and other extreme weather events), but also to larger scale changes affecting broad ranges of territories (e.g. droughts, sea level rise). Therefore it is essential to study large scale and long-term processes in parallel with local long- and short-term phenomena; for example, ocean temperature, ocean currents, changes in land cover and slow changing variables in the atmosphere are directly linked to regional climate variability, regional sea-level change, local water and energy cycles and extreme weather events of high impact to society. Moreover, these phenomena at all scales are directly attributed for environmental and societal changes in cities (e.g., the urban heat island effect, changes in water quantity and quality, air quality) and require planning for natural disaster mitigation.

This calls for a seamless and integrated approach, bridging the gaps between weather and climate, to improve understanding and projections of weather and climate extremes as well as their socioeconomic impacts (WMO, 2015). While the information needed from urban decision support systems have specific spatial extents for all the time scales – from 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. There is an emerging voice in the communities of weather and climate research, namely, the World Climate Research Programme (WCRP) and the World Weather Research Programme (WWRP), to address hourly-to-decadal time scales, regional geographic scales and seamless coupled weather-climate modelling capabilities.

Three-quarter of the world's cities are located in coastal regions. Paired with the ongoing rapid urbanization coastal areas are facing substantial risks specifically associated with ocean variability and change. Sea level rise might be the most recognized threat to coastal areas, however the various impacts are of a broader nature. The increase in the ocean heat content, caused by climate change influences the emergence, frequency and intensity of extreme weather events such as storms. Long-term sea level rise and enhanced ocean swelling is expected to severely impact coastal cities by intensifying coastal degradation, increasing tidal waves, inundating lagoons and seaside wetlands, damaging coastal ecosystems, changing the water availability and affecting coastal activities and livelihoods. An urgent need exists to equip the urban stakeholders with high-quality reliable climate information to enable adequate city planning and governance, therefore it is required to make well-researched predictions reaching from the global to the regional and local scales. WCRP's Grand Challenge on sea level change and coastal impacts (http://www.wcrp-climate.org/grand-challenges/gc-sea-level) 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. Future commitments should follow, to ensure seamless operation for weather and climate information service for disaster management and city planning, to improve resilience of coastal cities.

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). The WCRP's Grand Challenge on Weather and Climate Extremes (http://wcrp-climate.org/grand-challenges/gc-extreme-events) aims to mobilize and harmonize research efforts to advance the understanding and predictability of weather and climate extremes, including droughts, heavy precipitation and associated events, heat waves, as well as tropical and extratropical

storms. These advanced information and predictions products should enable targeted climate information and prediction services, and underpin the development of accurate early-warning systems and integrated urban services for cities.

From the other side the contribution of cities to global warming through greenhouse gas (GHG) emissions is 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. To support the success of post-COP21 actions to reduce climate-disrupting GHG emissions through a sound scientific, measurement-based approach, the 17th World Meteorological Congress (2015) requested a plan for an Integrated Global Greenhouse Gas Information System (IG3IS). Given ca. 75% of global CO_2 emissions are from urban areas, a large part of this system will be focusing on observations and detecting mitigation of urban area CO_2 (IG3IS, 2016).

The emerging need for urban climate services calls for the development of high-quality, science-based climate information tailored to city requirements to improve urban resiliency and to support the sustainable development of the cities in the world. To comprehensively address the crucial urban climate challenges, strong coordination and cooperation within the climate research community is required. The World Climate Research Programme (WCRP, http://www.wcrp-climate.org/), jointly sponsored by WMO, ICSU and UNESCO/IOC, has been coordinating climate research internationally over the past decades and could play a valuable role in urban climate. Considering the complexity of urban issues, WCRP aims to encourage and support credible research leading towards reliable climate and environmental services for the urban community, providing direct linkage among climate research communities, city networks and all other relevant urban stakeholders, and the frameworks for urban-focussed activities in the UN system. As it recognizes both the breadth and merit of city's needs that arise from multiple and combined impacts of various climate factors, WCRP serves as a helpful research information resource for urban issues.

Several scientific advances have been providing the basis for integrated urban climate services for the cities of tomorrow, meanwhile a strategic approach for further development and applications remain challenges of tomorrow. At present, a large number of global and regional climate models operate on spatial and temporal scales unsuitable for urban environments, and specific applications for urban-specific questions are yet to further develop. For example, the Coordinated Regional Climate Downscaling Experiment (CORDEX; http://www.cordex.org/) of WCRP provides a framework for evaluating and comparing various regional climate downscaling techniques, enhancing regional capabilities for climate prediction. Further challenges arise with the improvement in integrated very high-resolution modelling, taking into account the spatial and temporal scales and relevant physical processes, tailored to urban environments. Furthermore, the all-scale output should be made available to urban stakeholders to extract prediction products and information for decision-making processes in cities.

5. Society request and strategic approach for integrated urban services

People are central to a city and its functioning. They require new services that make the best use of new science and technology (Tang, 2006; Kootval, 2013; Grimmond et al., 2014a, 2014b). Each city faces a 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, environment and climate - lies 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 need 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 resources, water availability and water management in cities and its surroundings. Similarly, there is an urgent need to develop strategies to deal with waste disposal and understand its impact on cities. Data sharing arrangements between city institutions is a fundamental building block for authorities to identify the priority services. These include the design installation and

operation of urban observational networks that capture the phenomena of interest at appropriate spatial (3D) and temporal resolutions.

City services are heavily reliant on high resolution coupled environmental prediction models that include realistic city specific processes, 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 (e.g. data assimilation) 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 (WMO, 2015). 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 NMHS to establish sound working relationships with municipal authorities, to establish jointly identified and agreed priorities for joint services, and at the resources required for sustained service delivery and improvement. Considering the global importance of urbanization, the growing number of megacities, large urban complexes and medium size cities, NMHSs 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. NMHSs should showcase their urban experiences, share their experiences and establish best practices as to how to best serve the urban dweller who is now a majority stakeholder in urban weather, climate, water and related environmental services.

6. Research needs towards integrated urban weather, environment and climate service

A broad set of concepts defines the development of Integrated Urban Weather, Environment and Climate Service. These concepts relate to the conditions faced by urban populations and the impacts of environmental conditions on 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 (Fig. 2).

Development of urban integrated services 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 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 urban integrated system. 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 cities exist, a new generation of multi-scale integrated models are needed for helping to ensure that we can adapt to the responsibilities associated with them. Seamless connections between megacities, air quality and climate include (Fig. 3): (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.
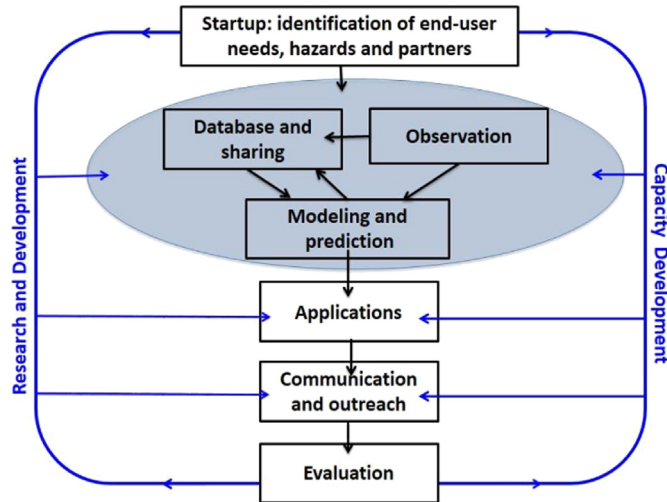
Fig. 2. Components of to the development an Integrated Urban Weather, Environment and Climate Service (IUWECS) (Grimmond et al., 2014b).

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 Coupled Chemistry-Meteorology Models (CCMM)). 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 CCMMs, recently published as a joint effort of the WMO GAW, WWRP, WCRP and EuMetChem COST Action (CCMM, 2016), 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, CCMMs 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 Copernicus Atmosphere Monitoring Service (CAMS, http://copernicus-atmosphere.eu) provides global and European scale data which can be downscaled to urban agglomerations (and smaller).

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.

Urban hydrology and flood-management systems are an important part of urban integrated services. The Flood Forecasting Initiative (WMO-IFMTS, 2012) aims at promoting the End-to-End Flood Forecasting and Early Warning (E2E FFEW) Strategy and serves as an umbrella for finding and coordinating synergies between different WMO activities sharing a common disaster risk reduction objective (Fig. 4). Seamless coupling of
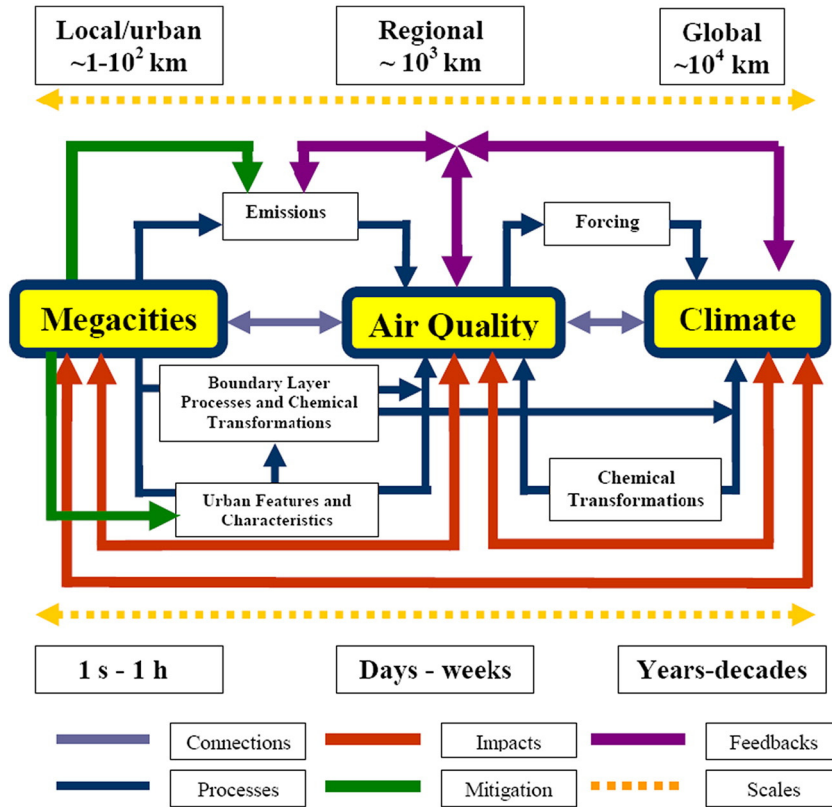
Fig. 3. Main linkages between megacities, air quality and climate (the MEGAPOLI perspective, Baklanov et al., 2010) and the ecosystem, health and weather impact pathways, and mitigation routes which need to be included in the Integrated Urban Weather, Environment and Climate Service (IUWECS). The relevant temporal and spatial scales are indicated.

urban weather and climate observation and modelling systems with urban hydrology systems is one of urgent and challenging tasks for research and service communities.

New and emerging technologies can be used to harmonize, integrate and densify meteorological, hydrological and environmental observations in urban areas. Crowdsourced data collection and networks of mobile sensors embedded, for example, in mobile phones or cars, can provide low-cost and flexible solutions that complement more traditional sources of observations.

Operational centres that base their products and services on CCMMs 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.

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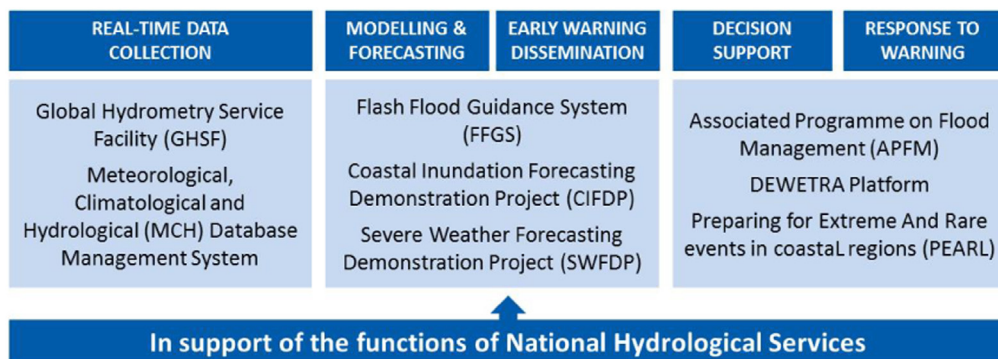**Fig. 4.** Key components of the urban hydrology and flood-management systems of the Flood Forecasting Initiative (WMO-APFM, 2016).

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