Guidance on integrated urban hydro-meteorological, climate and environmental services: challenges and the way forward

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Guidance on Integrated Urban Hydro-meteorological, Climate and Environmental Services: Challenges and the Way Forward

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Abstract

This chapter describes a new World Meteorological Organisation (WMO) approach to the provision of science-based services to assist the planning of safe, healthy, resilient and climate-friendly cities. The approach is outlined in full in the WMO *Guidance on Integrated Urban Hydrometeorological, Climate and Environmental Services (Volume I)* publication (WMO 2019), which has been approved for promotion and communication to WMO Members. Highlighted here are the underlying concepts and methods that underpin the services to help manage cities on a day-to-day basis, responding to short-term hazards but also to prepare for climate change are described. Heterogeneous dense observation networks, high-resolution forecasts, multi-hazard early warning systems, long-term climate prediction and service applications all working in combination, are at the heart of such services, the implementation of which will support mitigation and adaptation strategies for achieving thriving climate resilient cities and promotion of the United Nations Sustainable Development Goals (WMO, 2021). To meet the needs of urban areas, the concept of **I**ntegrated **U**rban Hydrometeorological, Climate and Environmental **S**ervices (IUS) is bedded in a multidisciplinary approach that identifies the requisite partnerships, including research agencies, city governments, international organizations, and private sector stakeholders, to establish and sustain urban services. As this is an emerging and diverse service, the requirements are broad with considerable research, development, capacity building and cross-service integrations yet to be done. In addition to providing an overview of the concept, we set out the challenges and recommended path forward to develop and implement IUS.

Keywords Integrated urban services; Multi-hazard early warning systems; Weather; Climate; Environment; Air Quality; Hydrology; World Meteorological Organization; Challenges and the way forward; Research and development; Seamless earth system prediction; Scales

Key Messages

- WMO's participation in the UN New Urban Agenda includes developing both the concept and guidance for the provision of multi-hazard early warning to long term urban planning services for cities.
- Integration of weather, hydrology, environment and climate urban services (IUS) will lead to accurate, efficient and consistent services.
- National Hydrometeorological Services are positioned to lead the promotion and development of Integrated Urban Services (IUS).
- Understanding capabilities, capacities and roles and responsibilities amongst different levels of government, universities, agencies and decision-makers is the first challenge followed closely by data access and the co-design of the IUS.
- Research and science will play a significant role to develop multi-disciplinary scientists to bridge the scientific gaps and to demonstrate the effectiveness of IUS.

14.1 Introduction

The United Nations' (UN) New Urban Agenda (UN, 2016) and the UN Sustainable Development Goal SDG11: Sustainable Cities and Communities (UN, 2019) amongst others, focus attention on cities and human settlements as places where equitable opportunities for human development are needed. The novel concept and approach of Integrated Urban Hydrometeorological, Climate and Environmental Services (or Integrated Urban Services, IUS) serves this agenda through promoting the idea of services for: (i) sustainable development, and (ii) multi-hazard early-warning systems for cities. Allied with these international agendas is the Sendai Framework for Disaster Reduction 2015–2030, a core aim of which is to substantially reduce the mortality, economic losses and damages and disruption of basic services arising from extreme climate events as well as the mitigation of technological and security risks. Given this, the ideal is for services to be impact/risk based (WMO 2016) and include hazard prediction as well as hazard exposure, vulnerability and other effects, to inform governments, business sectors and the public about how hydro-meteorological hazards may impact lives, livelihoods, property and economic activity so that appropriate actions and plans can be formulated. Because defining disaster risk and forecasting hydro-meteorological impacts is generally beyond the remit of meteorologists and hydrologists (WMO, 2015), engaging with disaster management officials and other relevant experts will yield benefits for disaster risk reduction (DRR). As argued by Rogers and Tsirkunov (2013), National Hydrological and Meteorological Services

(NMHS) may be well placed to meet such challenges, given their capacity to understand the dynamic relations between extreme weather events and impacts, their record of engagement with the DRR community and burgeoning expertise in integrated risk communication across a range of stakeholders and affected public and private services. Moreover, atmospheric processes and associated hydrometerological and climate extremes know no national boundaries and are interrelated. Accordingly, global scale collaboration and integration is essential for the development and beneficial application of cognate services for reducing the impacts arising from meteorological, climate, environmental and hydrological extremes. WMO Members, often represented by NMHS, provide a framework for such international cooperation. Here, we articulate the IUS concept which numerous types of agencies (e.g. government institutes, universities and private companies) may be providers of the requisite components for created integrated services at the urban scale (WMO, 2019).

To move towards development of IUS, WMO formed an interdisciplinary Urban Expert Team, with scientists representing the different WMO research and service development Programs. From within the Global Atmospheric Watch (GAW) program, the Urban Meteorology Science Advisory Group (GURME SAG) led the development of the Guidance for Integrated Urban Hydro-Meteorological, Climate and Environmental Services. Eventually the guidance will comprise three volumes. Here we discuss Volume I, which addresses the concept, methods, gaps, challenges and the path forward for the development of an operational IUS (WMO 2019). The second volume contains examples and case studies (WMO 2021). Volume III will address implementation guidelines. As with other WMO documentation, these will be updated as needed. While Volume I addresses lessons learned from examples of IUS, these are discussed in detail elsewhere (Grimmond et al. 2020). In this chapter we, as the original authors of the WMO publication provide a summary of the *Guidance on Integrated Urban Hydrometeorological, Climate and Environmental Services (Volume I)* (WMO 2019), describe the need for IUS (Sect.14.2), present the IUS concepts, methods and challenges (Sect. 14.3), discuss implementation of IUS (Sect. 14.4), briefly summarize gaps and the path forward (Sect. 14.5) and draw conclusions (Sect. 14.6).

14.2 The Need

14.2.1 Growth of Cities

A driving change in people's daily lives has been the accelerating growth of cities. Urban populations, especially in developing countries, have created crowded cities that are centres of creativity and economic transformation. However, air pollution, extreme weather conditions, flooding and other hazards create substantial challenges in urban environments (Bulkeley, 2021; Grimmond et al., 2020; Pelling, 2003; World Bank, 2010). As a response to the challenges posed by rapid city growth and the advent of megacities, the United Nations (UN) HABITAT-III conference in October 2016 adopted the New UN Urban Agenda (UN 2016) which makes urban resilience, climate and environment sustainability as well as disaster risk management key foci (Grimmond et al. 2020).

Because of their dense, complex and interdependent urban infrastructure and the reliability of urban populations on these, cities are becoming increasingly vulnerable to the impacts of extreme hydrometeorological events. Through cascading downstream or "domino" effects, spatially widespread and far-reaching breakdown of critical city infrastructure can arise from a single extreme event (Grimmond et al. 2020, WMO 2021), wreaking havoc on services and people's lives. As noted by Grimmond et al. (2020), as the components of urban systems are tightly intertwined, the availability of good predictions, tailored and refreshed at appropriate spatial and temporal scales, will facilitate effective and efficient urban operations, an imperative made even more critical when extreme events occur. As what constitutes an extreme varies for different elements of urban infrastructure (across and between cities), understanding what "all" the critical thresholds are, is essential. Figure 14.1 illustrates the cascading effects from a typhoon event. There may be immediate impacts requiring multiple services followed by potential structural changes to the city fabric leading to health impacts for example caused by the proliferation of vector-borne disease catalyzed by standing water that offers mosquito breeding sites.

If exposure units (e.g. vulnerable communities/neighbourhoods, sectors, critical assets) are to optimise their response, small area forecasts are needed that identify which parts of the city are most likely at risk to any given hazard. Combining forecasts with detailed community and infrastructure information facilitates resources to be used most appropriately. Services drawing on new communication methods and technologies will not only ensure rapid assimilation of data by short-term prediction systems to enhance forecasts but also facilitate rapid communication of tailored products to targeted end users. Given this, IUS should include impact predictions that consider the interplay between hazard, exposure and vulnerability in the generation of risks. Further, IUS can provide tools to support appropriate long term planning of cities, a case made in many chapters of this book. Importantly ensuring sustainable approaches to the development of cities will benefit not only the urban populace but also the global environment as cities are the largest sources of greenhouse gases (GFCS, 2018).

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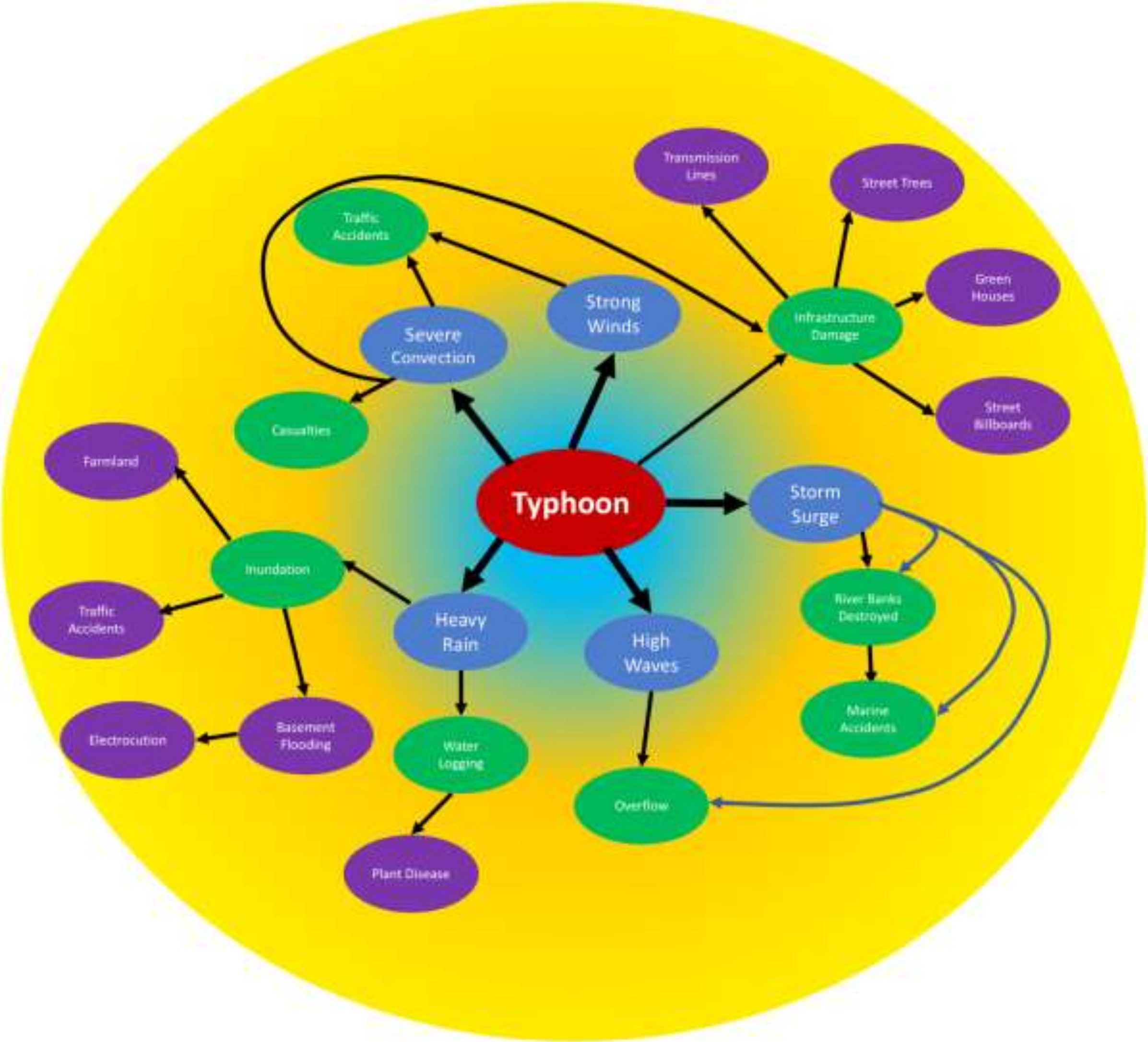

Fig. 14.1 Schematic showing the domino effect using a typhoon (or hurricane) event as an example. The event (red) creates several hydro-meteorological hazards (blue), that generate immediate impacts (green) with related effects (purple) requiring different services. (Source: WMO (2019) Guidance for Urban Integrated Hydrometeorological, Climate and Environmental Services. Volume I: Concept and Methodology. WMO-No: 1234, ISBN 978-92-63-11234-7. https://library.wmo.int/doc_num.php?explnum_id=9903

14.2.2 Resilient Cities

In response to climate change and sustainable development concerns over the last two decades, a range of cities have formed networks for developing strategies for achieving climate resilient cities (e.g. Local Governments for Sustainability (ICLEI 2020); C40 Cities Climate Leadership Group (C40, 2020), 100ResilientCities (100ResilientCities, 2019) and its replacement Resilient Cities Catalyst - https://www.rcc.city/)). The resolutions and statements arising from these networks provide additional motivation for the development of the IUS, including:

- "*A resilient city is prepared to absorb and recover from any shock or stress while maintaining its essential functions, structures, and identity, adapting and thriving in the face of continual change*" (100ResilientCities 2019)
- "*A smart city has embedded 'smartness' into its operations, […]. It analyzes, monitors and optimizes its urban systems, be they physical (e.g. energy, water, waste, transportation and polluting emissions) or social (e.g. social and economic inclusion, governance, citizen participation)*." (ICLEI 2020)
- "*An EcoMobile city fulfills its objective of creating a more livable and accessible city by utilizing Sustainable Urban Mobility principles to achieve significant reductions in greenhouse gas emissions and energy consumption, improvements to air quality, and increased mobility opportunities for all citizens*." (ICLEI 2020)
- "*A view of resilience that includes not just the shocks - earthquakes, fires, floods, etc. — but also the stresses that weaken the fabric of a city on a day to day or cyclical basis. Building urban resilience requires looking at a city*

> *holistically: understanding the systems that make up the city and the interdependencies and risks they may face*." (100ResilientCities 2019)

A large number of cities subscribe to these objectives irrespective of size or level of socio-economic development. Ensuring population safety and resilience to extreme weather and climate events are central reasons for many cities' calls for action, with societal expectations of good living standards, sustainable economic development, cities as places with a competitive edge to invest in and do business and politically supported to do so, increasingly important.

14.2.3 Urban Service Requirements

The underlying aspiration of IUS is to provide support for policymaking (at all time scales) from regulations to emergency services to the public, businesses, institutions and responsible authorities on a day-to-day and long term planning basis at the city level (WMO, 2019). For urban management services to evolve and be fit for a rapidly changing set of climate and broader environmental circumstances, new knowledge is required. Added to this is a capability to deliver and cut across many entities, scientific disciplines and time scales (WMO, 2019). A compound event such as a heatwave embedded in a moderate yet prolonged dry spell serves to demonstrate the type of approach required. For example, an affected city may need to address concurrently, enhanced energy demands, increased pressure on healthcare systems, water quality and supply issues and wildfires at the urban-rural interface, while a global pandemic occurs where building ventilation regulations are critical. Critical in relation to the potential magnitude of the impact will be understanding the nature of the pre-existing drought conditions, preparatory lead-time and the ability to anticipate how the heatwave may evolve and affect services and the integrity of urban systems at large. Being able to integrate all the requisite information would enhance coping capacity, assist identification of vulnerable infrastructure and foretell cascading effects arising from infrastructure failure (WMO, 2019).

The nature of first order meteorological/climatological information required by cities for managing climate related risk is very much determined by a city's climate, geographical and geophysical settings as well as its form (three-dimensional structure) and function (social, cultural, economic and other activities). First order needs include all year round monitoring and prediction of conditions so extremes (e.g. severe weather and climate events) and typical conditions that might pose a threat to the functioning of a city. These might include: typhoons/hurricanes, extra-tropical storms, convective storms, tornadoes, droughts, extreme heat and cold stress, typical winds, temperatures and humidities by season[1], sand and dust storms, wild fires, flash floods, landslides, river and lake flooding, storm surges or swell, long-term sea level rise, coastal inundation, air and water pollution, chemical and other harmful matter dispersion events, harmful UV radiation, pollen and other aerobiological allergens, factors related to food-, water- and vector-borne disease, and changes in soils[2] (WMO, 2019). Longer term needs encompass high-resolution climate services for building codes, zoning, planning and design. A central tenet of IUS is working across systems. For example, an eco-system's urban design and planning approach, such as "Blue-Green Solutions", which incorporates green (vegetation) and blue (water) elements is very dependent on the micro-climate and water resource availability and timing. If the design scale is the city-block, then urban processes need to be linked with meteorological, climatological, hydrological, air pollution processes (e.g. understanding the science for model predictions) to develop a good design that makes an area more resilient rather than a design that increases vulnerability[3]. To achieve what is necessary, existing solutions and scientific tools are fundamental as well as academic multi-discipline curricula and capacity building, which will provide a starting point for bringing together different professionals (e.g. architects, engineers, urbanists, policy makers, meteorologists) concerned about the resilience of cities. Shared knowledge of data repositories, models, examples of application needs and how to provide direct access between the components of information systems all need to be established. Cities need to be furnished with warnings, including climate watch advisories, to ensure appropriate urban system design and operations and the appropriate location of critical assets such as hospitals, schools, power stations, commercial centres and other key land use types.

14.2.4 Benefits of Integration

Integration (weather, climate, hydrology and the environment) is an efficient and effective evidenced based practice in seamless prediction (from urban and nowcasting scales, short and medium term forecasting, sub-seasonal and seasonal spatio-temporal scales) of the Earth System (Brunet et al. 2015, Grimmond et al. 2015) and for the provision of multi-hazard early warning services (WMO 2016). The challenges and problems are co-dependent and hence, multi-disciplinary science approaches are required to resolve gaps and inconsistencies (WMO, 2019).

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[1] Critical for building design, landscape planning, outdoor workers, etc

[2] Note extremely dry soils compared to typical conditions can result in the collapse of buildings or cracking of external facades making them vulnerable to even light rainfall or wind events.

[3] Water needs to be available to sustain vegetation or maintain water features. For example, if energy is needed to supply the water (e.g. to roof top gardens) the environmental costs may outweigh the benefits. Some vegetation can have detrimental influence son air quality through impacts to chemistry and/or flow.

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IUS are developing within the WMO concept of the seamless Global Data-Processing and Forecasting System (GDPFS) that include issues related to heterogeneous observations, their processing and management, high-resolution prediction systems, product generation, services and their verification (WMO 2013a). As stated by the WMO, the GDPFS aims to enable Member states and partners to support decision-makers and risk-based warnings (WMO, 2004). The seamless GDPFS builds upon the existing systems with the additional goal to be more agile and adaptable to support local, regional or national needs, different application programs including non-weather related predictions with co-designed products for impact-based and risk-based forecast and warning services to support decision-making, taking into account vulnerability and exposure information (e.g. for urban emergency preparedness and sustainable development) (WMO, 2004).

14.3 The Integrated Urban Services (IUS) Concept and Challenges

14.3.1 The Concept

IUS can be provided at a range of spatial scales from the large metropolitan area to smaller neighbourhood to city block scales. However, the nature of IUS is highly dependent on the application, requirements, and local and regional factors. The urban domain, often defined by local governments, can include contiguous cities, the area and roads in-between, rural watersheds (or catchments) and the location of industries as all are critical to the city functioning (WMO, 2021).

The generic components of IUS are set out in Figure 14.2. This provides a framework for discussing the concept as expanded on below. It is worth noting that Integration of Urban Services can be delivered at the technical, product or service levels, or in all permutations and combinations.

14.3.2 City Requirements/Local Tailoring

Cities can amplify or mitigate hazards. For example, impervious surfaces can amplify flooding at many scales up to the regional scale, flooded subways or underpasses create microscale problems, dense tall buildings can trap air pollution, and greenspace can mitigate large scale heatwaves for some wards (WMO, 2019). Accordingly, the needs and objectives of IUS will be city-specific, necessarily diverse at the intra-urban scale and need to be "fit for purpose" (Figure 14.2, #1). Thus, well-designed IUS will be sensitive to local needs even if developed at the national scale. Meaningful dialogue on requirements and initial steps may be the greatest challenge in developing an IUS. A mutual understanding between service providers and city authorities of capability, vision, roles and responsibilities is a prerequisite for success. Communication of science to city authorities who have vastly different expertise, cultures, skills and knowledge may pose a potential barrier to the process to form partnerships. Therefore, a common trust and language must be developed with leadership, experience and vision crucial.

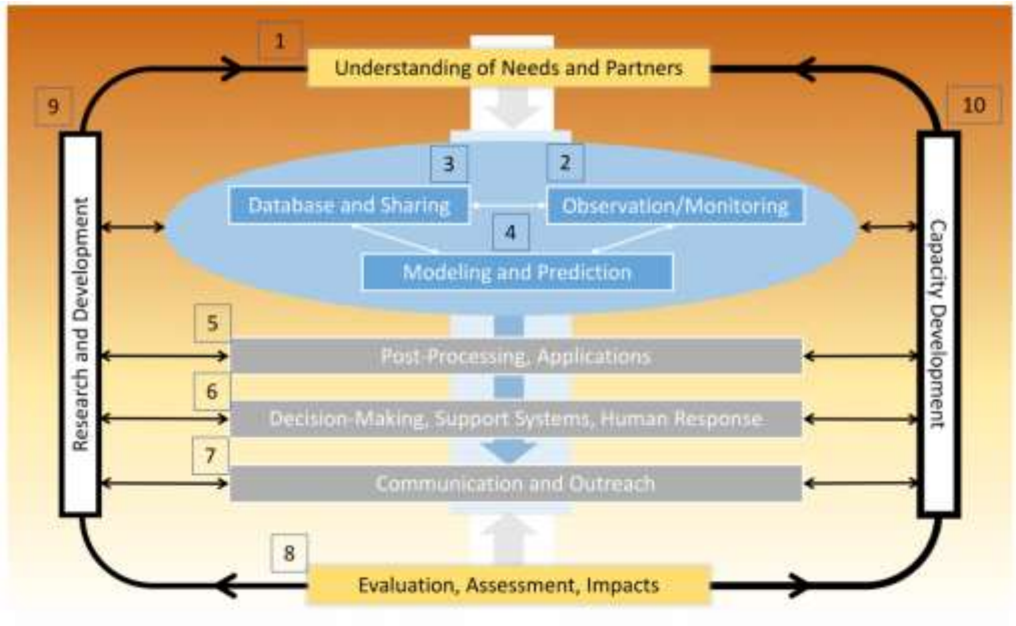

Fig. 14.2 Schematic of the components of an Integrated Urban Service (IUS) System. The numbers (#) are referred to in the text (Source: WMO 2019 Guidance for Urban Integrated Hydrometeorological, Climate and Environmental Services. Volume I: Concept and Methodology. WMO-No: 1234, ISBN 978-92-63-11234-7. https://library.wmo.int/doc_num.php?explnum_id=9903)

14.3.3 Observations

Generally, urban areas are observation sparse, a result of challenges associated with the appropriate siting of meteorological instruments (e.g. rain gauges, wind, air quality sensors) for representative measures needed across the IUS domains. Typically, IUS observation networks are not dense enough to detect intra-urban variations in IUS fields. Further, urban observations are not always utilised in current operational numerical weather prediction (NWP), air quality modelling and/or assimilation systems, as urban atmospheric and other key processes change rapidly (vertically and horizontally), so are either not represented or are coarsely parameterized. In contrast urban hydrological networks are better developed, with water level and flow gauges located in sewers, natural streams and engineered urban watercourses (WMO 2008; WMO 2010a). Resource limitations can also be a significant limiting factor, especially in low and middle-income countries.

For urban observations, four ideal requirements exist: (i) real time monitoring and scientific understanding; (ii) data assimilation for numerical weather forecasting; (iii) climatology for model evaluation and verification; and (iv) evaluation and verification of services (including information on human perception and response) (WMO, 2019).

Although urban siting requirements are clearly prescribed by the WMO (2006), they may not serve the requirements of the current/next generation of urban models capable of resolving processes at the street canyon and building scales. Perhaps the best way forward is to apply guiding principles rather than rules, and to retain a flexible approach for siting urban stations. Without doubt, a comprehensive review is required as part of any discussions related to the siting of urban meteorological instruments to serve the purposes of model evaluation and verification. For example, the type of observation required may be numerical model dependent and thus determine such things as instrument type, its siting and sampling frequency (Grimmond and Ward 2021). One can imagine in the case of a numerical model that only assimilates vertical profiles of above surface layer wind versus surface layer (i.e. inertial sub layer – roughness sub layer – canopy layer) winds, the configuration of observations will be quite different.

The complex three dimensional nature of urban environments places heavy demands on measurements and sensor locations, as these need to be representative of the area under consideration. This will vary between high and low building density area having many variations including land cover (e.g. green space, roads, buildings) and emissions (e.g. heat, water, chemical) between differing land uses (e.g. central business district, and residential/suburban). Added to this is determining the appropriate temporal and spatial sampling that includes the vertical dimension, both within and above the urban canopy, and through the boundary layer. Complete watersheds, upwind areas, and a range of urban densities may need enhanced observations. The appropriate mix of observations, scale and frequency of sampling is a challenge and will evolve over time.

Non-homogeneity of data also poses a challenge as urban development and regeneration regularly alters the environment around observation sites. Like all observation sites, instruments undergo regular evaluation, re-calibration and replacement. Consequently station metadata, with frequent updates (especially because of the changing urban evironement), is as important as the data, because it provides the foundations for homogeneity testing and establishing the link between sensors, measurements and the surrounding area and for use in applications (WMO 2017a).

Technological developments have opened up a range of exciting possibilities for real-time monitoring of IUS processes (e.g. surface exchanges, air quality, water flow) via atmospheric profiling using ground based measurement networks. Instrumentation such as ceilometers, Doppler lidars, microwave radiometers, small radars, wind profilers, and Doppler sodars (latter is usually restricted to airports because of noise constraints), can provide information on the nature of urban boundary layer processes (e.g. thermal structure, momentum flux) as well as cloud, thermal, moisture and precipitation fields (Grimmond and Ward 2021). Complementing ground-based measures are those made from satellite platforms that provide a bird's eye view of the urban surface. Encouragingly the accuracy of ultra high resolution (scale of metres) satellite thermal and other monitoring of the urban surface (including building density and urban fabric roughness) has improved over the recent years because of the emergence of high resolution, multi-sensor systems, and new processing techniques, facilitating the assimilation of associated measurement into integrated urban prediction models. The development of the field of satellite-based urban meteorology and climatology continues at pace, with space-borne thermal radiometers and hyperspectral infrared imagers either in operation or planned for the near future (Guanter et al. 2015), with advances in vertical profiling measurements also expected (e.g. Meteosat Third Generation). Understanding and managing the uncertainty of measurements from new observation platforms and exercising scientific judgement and flexibility will be an ongoing priority as the research and applications community strive to use such novel and innovative techniques to improve short-term forecasts and high-impact predictions. Another potential source of urban data is that from small mobile sensors (e.g. phones, cars) and citizen science networks. However, the quality and uncertainties associated with this type of data needs to be fully tested and quantified.

In addition to knowing about the nature of IUS fields, information on the physical and socio-economic make-up of urban environments is required (Grimmond and Souch 1994; Ching et al. 2018). This is because the urban surface in its widest sense, including both indoor and outdoor built environments, interacts with the overlying atmosphere. Accordingly, information on urban form, comprised of the three-dimensional structure of cities, the nature of the urban fabric (natural and built materials) and land cover type, and anthropogenic heat emissions are critical as input into urban meteorological models. Allied data such as environmental, geomorphological, socio-economic, population and economic activity are also essential for providing important contextual information to support analyses, for model applications and for reflection upon how the outcomes of measurement, monitoring, modelling and evaluation campaigns are relevant to policy development, urban planning, emergency response and public health.

14.3.4 Databases and Data Sharing

The data required to manage IUS risks is typified by its diversity and magnitude. Accordingly, knowing about existing databases and data sharing and getting people on board are critical to the notion of IUS. Different institutions within a city play key roles in information gathering, processing. It is essential to the success of IUS that the appropriate people in city authorities, related agencies, companies, research institutes, are identified, a common language established so that work cane be undertaken collaboratively to build integrated urban information systems, that have meaningful communication of what will be ‘big data’. To facilitate this, legislation or memoranda of understanding, may engender co-operative partnerships. Data exchange is not only an important enabler of IUS, but creates a vehicle and opportunity to communicate, interact and exchange knowledge and to understand the needs as highlighted in Figure 14.2 – #3. Indeed, data exchange can serve as a catalyst for the creation of IUS (WMO 2019, WMO 2021). Notwithstanding the challenges associated with making observations open for operational use, it cannot be emphasized enough how data sharing and is critical to fostering IUS developments and collaboration.

It is also critical to make data (observation, model outputs etc.) accessible in formats that are usable amongst partners. The goal should be for open data and easy access to information (WMO, n.d.). Essential is agreement amongst different network-members about metadata definitions, data storage protocols and clear usage policies. For example, Muller et al. (2013) provide useful guidance materials for urban observing systems and metadata.

14.3.5 Modelling and Prediction

Models (Figure 14.2 - #4), whether numerical (e.g. hydrological, chemistry-atmosphere forecast model), physical (e.g. hardware models within wind tunnels or climate chambers), statistical (e.g. probabilities, empirical relations between components, machine learning/artificial intelligence (AI)), and/or conceptual (e.g. schematics showing relations between components), are an integral part of IUS (WMO 2019). In the IUS context, the overall purpose of models is to shed light on the response of urban surface and atmospheric processes, to urban form (structure, fabric and land cover) and urban function (human activities) and changing weather, climate, hydrological and environmental conditions, at a range of time scales. The corollary of this is the modelling chain should serve the purposes of urban services and impact prediction, assessment and risk quantification, to assist decision-makers and related stakeholders, with a programme of sustained research in place focused on model capability, consistency and improvement.

Amongst a range of modelling possibilities are Regional/Seamless Earth modelling systems. These attempt to model land-atmosphere, atmosphere-hydrological and ocean-atmosphere feedbacks and processes at very high resolutions – hundreds of metres or less – in order to describe urban to intra-urban scale processes. Such modelling systems are valuable tools and crucial for some IUS requirements. As noted by Brunet et al. (2015), integration at the appropriate level requires collaboration amongst diverse and highly technical disciplines. That said, although the full integration of earth or urban system processes may be a logical step and a long-term strategic goal, challenges exist (Grimmond et al. 2015). Some of these derive from the fact that the requisite disciplines ‘speak’ different languages, work with contrasting prediction and modelling paradigms, set objectives that are not wholly compatible and link with a variety of end users in different ways. To address such challenges, the formation of multi- and inter-disciplinary partnerships with a commonality of purpose and protocols is critically important (WMO 2019). For effective operational deployment of IUS models, management is necessary. For example, extending to high resolution NWP or to coupled Numerical Environmental Prediction models is complex and no management rules are generally in place (WMO 2019). As outlined by the US National Research Council, the normal practice in meteorology and air quality modelling is to move to a model upgrade when there are compelling scientific grounds, with clear modelling system performance gains and no major degradation of key variables, hence making model inter-comparisons an integral part of the governance process (NRC, 2012).

In the case of the application of Earth-system models to cities, as full a set of physical, biogeochemical, and socio-economic processes as possible need to be represented, with their relative importance in many ways determined by the nature of the intended modelling applications. For example, for heatwave alerts or urban planning directed to the mitigation of urban thermal effects, the focus will be external and indoor temperature and atmospheric and surface heating processes. This is because as external temperatures rise so will those inside buildings. Where air conditioning (AC) is ubiquitous, as in some high-density high-income cities such as Osaka or New York, this will result in an elevation of energy demand for building cooling, resulting in an increase in the emission of waste (anthropogenic) heat into the environment and possible further

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elevation of urban air temperatures (Takane et al. 2019). Nearby districts without AC may become exposed to this 'extra' heat via advection processes (Huang et al. 2019). Accordingly, knowing, via mapping, the heat vulnerability characteristics of 'down-wind' urban populations as part of the information contained in heat action plans may assist with managing the unintended consequences of AC-related heat emissions (Takane et al. 2020). For the situation of modelling environmental hazards for coastal cities to determine exposure and vulnerability, it will be essential to account for ocean-atmosphere-wave interactions, ocean-wave-riverine interactions, and their interplay with land cover (WMO, 2019). For urban flooding, changes in coastal or river flood plains, surface changes due to building or infrastructure construction will be crucial.

Urban green space, whether in the form of tree-lined streets, gardens, parks and green roofs, can modify urban temperatures at a range of scales depending on its scale of application as a heat mitigation strategy. Green space also provides benefits for flood management. Despite its potential attractiveness as an urban planning approach to IUS risk management, the conscious large-scale implementation of green infrastructure for climate-specific sensitive planning in cities remains confined to only a few examples. Integration of green infrastructure related atmospheric, environment and water processes into urban systems models has active research requiring coupling models across scales that simulate soil-vegetation-atmosphere interactions (WMO 2019). Integration of the assessment of the benefits and costs of these actions on a broader range of urban activities is also possible within an IUS community, hopefully preventing unintended consequences. For example, to understand the impact of climate risk management adaptation and mitigation strategies at the intra-urban to urban scales, urban planners and designers require fields of relevant IUS variables at high spatial resolutions for current and future city configurations and climate scenarios. Developers of IUS therefore need to be cognizant of this requirement.

14.3.6 Applications

IUS have the potential to contribute to the long-term sustainability and resilience aspirations of cities via a wide range of potential applications (Figure 14.2 - #5). Although not an exhaustive list these might include:

- urban specific disaster risk reduction as might be required for managing the outcomes of severe storms or periods of extreme heat
- CBNE response – from industrial accidents or terrorism that release of chemical, biological, radioactive nuclear and explosive
- better city operations through forewarnings of IUS related risk for critical infrastructure
- acute and chronic human health problems
- sustainable city economic development and planning at scales from months to seasons
- managing weather/climate risks in business, commercial and outdoor recreation sectors
- managing urban flooding
- managing environmental and health
- climate change adaptation
- climate sensitive design and planning at the urban (~10-15km) to neighbourhood (<1 km) scales,
- short-term renewable energy forecasts and infrastructure management
- fire risk and responses
- snow-clearance and road-icing

Applications should not be developed independently of potential end-users; the so-called 'loading dock' approach, whereby a product is developed without end user engagement then delivered with little consultation (figuratively dropped on the loading dock) must be avoided (section 14.3.8). Accordingly, application developers and IUS governance models need to engage actively and meaningfully with the target sectors or stakeholders in a specific IUS risk problem such as the energy, water supply and sanitation, environmental, agricultural, transport and tourism sectors (WMO, 2019).

14.3.7 Decision Support

Arising from the applications component of IUS is information for decision-making in a wide variety of services (Figure 14.2 - #6). Over the past couple of decades, there has been a move away from single hazard focused systems to Multi-Hazard Decision Support Systems. These are designed to present consistent (integrated and seamless), relevant and often uncertain and conflicting information, to both technical experts (e.g. severe weather or flood forecaster) and users (e.g. emergency managers) for assessment, to support alert and warning related decision-making. Considerations often include societal impacts, action statements (e.g. issuance of severe weather warnings for typhoon tracks with uncertainty information, river level predictions nearing flood thresholds, heat health alert) and human behavior especially how recent events may have influenced population response to warnings and advice (WMO, 2019). In order to assess the quality of the impact-based products, predictions are presented alongside observations and their historical performance taken into account. Assessments of whether appropriate messages (including probabilistic information about uncertainty) for the location and whether these landed with the target audience are also acted upon. In making informed decisions based on application products, the history of false positives and false negatives is important as over/under-warning of previous events may engender a lack of trust in forecasts and predictions and thus influence end user or stakeholder response to warnings. Over time, an iterative process will operate such that through developer and end user interaction, collaboration and critical reflection, feedbacks to the Decision Support System component or even beyond to the more fundamental observation, analysis and modelling components of the IUS system will occur so that IUS efficacy is enhanced (WMO, 2019).

14.3.8 Service Delivery, Communications and Outreach

The path from raw data to product and services development and eventual delivery to end users and stakeholders is complex and requires an understanding of and engagement with partners (Figure 14.2 - #7). Because of the wide range of potential end users and stakeholders (e.g. emergency management authorities, urban planners, health workers) the mode and form of information delivery is likely to be diverse. For example, emergency situations require the information/warnings to be disseminated with as long a lead time as possible to enable quick and timely implementation of preventive measures. In contrast, weather information in real-time is not necessary for longer term urban design and planning. Independent of delivery time scales, vital for any information presented to end users is ensuing it is comprehensible and tailored to their level of expertise with detailed and voluminous information often counter-productive. Crucial is the way information on uncertainty is presented and addressed, and how IUS stakeholders might respond and subsequently use the products. ‘Uncertainty’ training will be required. Thus, capacity and capability development will be important for all involved in IUS to understand the various constraints (WMO-GFCS 2019).

To ensure effective dissemination of information, a well-honed communication strategy, with supporting mechanisms, sensitive to end user and stakeholder needs is imperative (WMO, 2014; WMO, 2016). For wide and effective information dissemination, an integrated products/services delivery platform, providing access to all identified users as determined by their needs, represents the ideal with a programme of awareness raising and training in the application of IUS products complementing this. A range of possible dissemination technologies exist including dynamic web portals, Digital Display Board Systems, Integrated Voice Response Services, as well as communication through traditional avenues such as like TV, radio, E-mail alerts, press releases, media conferencing and short message service alerts (WMO, 2019). Leaflets, publications, workshops, conferences and symposiums form effective ways for awareness raising and wider public education. To ensure quality control, the avoidance of misinformation and the creation of confusion and panic amongst the wider public, the responsibility of dissemination of information via social media (e.g. Facebook, Twitter, WeChat) best lies with those trained in risk communication and the expert use of IUS products and developing the ‘trusted/authoritative voice” for warnings will be critical. Over time, and assuming IUS community members develop a ‘community of practice’ (COP) philosophy, ways of working and communication will develop and mature to a level that ensure seamless operation of IUS.

14.3.9 Evaluation and Methodologies

The true test of an IUS system is the extent it delivers its goals (e.g. reduced loss of life, improved livelihood, reduced societal and economic costs for regular city operations, improved preparedness) (Travis and Bates 2014). Accordingly, evaluation and assessment of performance is a critical aspect of the IUS framework (Fig. 14.2 - #8). “Before-After” event comparisons are possible for heat-health action plans as these can evaluate individual events or seasons (e.g. Benmarhnia et al. 2016). Tailoring evaluations of IUS delivery to the intended user-oriented outcomes is crucial. For example, Amorim et al. (2018) describe how collaboration with the health sector can lead to the development of indicators (e.g. heat-induced mortality, long-term mortality from combined exposure to NO_2 and $PM_{2.5}$) for evaluation and assessment of where service improvements are required.

As overall system performance is an outcome of all the parts, evaluation of individual IUS components (Figure 14.2) is crucial to understand their effect on overall results. To achieve this, diagnostic/process-oriented causal assessments as well as statistical evaluations complete with uncertainty analysis should be undertaken. Such an approach will inform the iterative co-design of the IUS. Further, dynamic evaluation techniques using the same IUS for very different urban services scenarios can be applied to impacts evaluation (WMO 2019). As new partners, stakeholders and users broaden the IUS scope new evaluation approaches will need to be developed. For model development and robust diagnostic evaluation and quantitative user evaluation, ‘Test Beds’ with data from all fields relevant for the target parameters and variables (e.g. flooded area, soil water content, population response) will be needed along with independent data sets for initialization and assimilation (WMO 2019).

14.3.10 Research and Development

Given the novelty of IUS as a multidisciplinary approach to IUS risk management, an iterative and continuous enhancement process will make a sustained programme of research and development (R&D) necessary (Figure 14.2 - #9), focusing not only on all IUS components but also on specific city systems, socio-economic impacts, population response and benefit accrual. Although practitioners are not responsible for R&D, their involvement as co-producers will have mutual co-benefits with participation R&D programmes. The potential array of players in R&D is vast with partnerships and Test Beds between research and operational bodies key, in order to foster the rapid conversion of research results to operational use and to train the next generation of multi-disciplinary scientists (WMO 2019).

14.3.11 Capacity Development

Once initiated, IUS will evolve rapidly, requiring capacity development efforts to be resilient (Figure 14.2 - #10) with the identification of strategies to facilitate a community of practice (COP, working together) approach to service development, evaluation and improvement key. Players are likely to include universities, public and private research institutions and agencies, NMHSs, international organizations, professional organizations, governmental and non-governmental organisations and community-based programmes (WMO 2019). Capacity development will necessarily encompass multi-disciplinary training in urban Earth system science, socio-behavioural and economic studies, urban planning and architecture, urban observations and network design, data sciences, user workshops for high resolution products, terminology and knowledge gaps, success metrics and impacts, decision-support system use, risk communication and knowledge management (WMO 2019).

14.4 Implementation

14.4.1 General Comments

Central to the success of an IUS will be seamless provision of services across a wide range of time scales including consistency and efficiency. As individual IUS will not be static, IUS developers, operators and managers need to be attuned to the necessity of an iterative dynamic process for continual IUS evolution and the provision of the requisite scientific knowledge and human resources for long-term sustainability. The ethos of IUS embodies a multi-disciplinary philosophy from the outset in order to facilitate an inclusive approach to partnership building. For example, urban planning legal documents addressing air quality and vegetation feedbacks, require innovative actions and partnerships involving social science and law research put into practice. A catalyst for instigation may be an extreme IUS event that engenders a government level response and call to action, or when a significant international event (e.g. Olympics, Expositions) is planned and staged requiring high resolution point warnings (Joe et al. 2018). Although usually funded independently of normal operating budgets, such events can be leveraged for the initiation of the development of IUS with international and national demonstration projects a proven vehicle for knowledge sharing, triggering inspiration and initial IUS implementation.

14.4.2 Role of the National Meteorological and Hydrological Services (NMHS)

As noted earlier IUS processes in general know no national bounds. Accordingly, cooperation at global, regional and local scales is essential for managing IUS related risks. The WMO, a United Nations Specialized Agency, is an intergovernmental organization with 193 national states and territories (called Members). Through its relevant programmes and technical commissions, it coordinates and guides its Members. Members of WMO are states and represent the disciplines of weather, climate, hydrology and the environment whether it is at the national, regional or local level or whether government, academia, research institutes or private sector (WMO 2013b). This is an important distinction as most IUS can not be delivered by a single organization. This highlights the important coordination role that WMO can play in IUS. Consequently, one key aspiration of IUS is to establish mandates for collaborations through either legislation or co-operative agreements. Generally, the focus of NMHS is at the national scale. At the urban scale, city authorities will play a significant role in the overall specification, scope, definition, implementation, delivery and utilization of IUS with the requisite services coming from a variety of different providers. In this regard and given the increasing recognition of cities as 'at risk' spaces, now is an opportune time for WMO members to consider generalizing and specializing their infrastructure (e.g. observations, models, products) for managing IUS related risk (WMO 2021). Notwithstanding the largely national focus of national agencies and a mandate to support but not necessarily provide services at the municipal level, NMHS possess specialized capabilities, products and warning communications that extend to more complex multi-hazard early warning systems delivering integrated services within urban settings (WMO 2019). In summary, NMHS are well-placed to play a central role in this because:

- '*NMHS operational systems and service delivery mechanisms are able to connect data, predictions, products and warnings with the type of applications related to city needs. However, important developments are needed to support these applications with an adequate scientific basis (e.g. urban areas need to be better represented in observations and in models).*
- *NMHS collect observations that are critical to IUS, but they need to be complemented by a wide range of observation types from other organisations. This requires a broadening of methods to integrate these data and data providers.*
- *NMHS can best harness the potential and results of specialized research now and in the future.*
- *NMHS already recognize themselves as key players in bringing that potential to fruition / operation in the provision of IUS*' (WMO 2019, p19).

As outlined in WMO (2019) first steps to achieving the pivotal role of NMHS in IUS delivery will necessarily include the following:

- Capacity building to introduce concepts but also to develop self-awareness, to educate and train meteorologists and potential partners (WMO 2010b, WMO 2017b, WMO 2017c).
- Critical reflection upon the suitability of existing predictions systems for urban settings and associated institutional, governance and partnership arrangements and capacities and capabilities
- Identification of the needs, capabilities and capacity of local governments, the private sector and other city-level stakeholders to better define IUS requirements (e.g. Grimmond et al. 2010, Mills et al. 2010).
- A willingness to shift to a service paradigm more suited to the notion of IUS, by going beyond traditional services and understanding the subtlety of urban system stressors, as well as cumulative/compounded impacts over different timescales.
- Build understandings of individual end-user needs through a process of mutual engagement, tailor products to fit the defined risk management problem and consider the utility of case studies for illustrating the links between hydrometeorological processes and impacts.
- Consider how existing legal frameworks may facilitate partnership development and where possible move to a National Framework for Climate Services (NFCS[4]) approach as espoused by the WMO
- Build narratives about the societal benefits of IUS that may arise from implementation related to specific events and the co-benefits (win-wins) for other urban services (WMO 2019).

14.5 The Path Forward

14.5.1 Resources for Implementation of Integrated Urban Services (IUS)

Fundamental to IUS are partnerships that span the producers of IUS products, stakeholders and end users. These are essential to mobilizing and optimizing resources (Figure 14.2 - #1). Significant efforts are required to begin the dialogue process, to understand roles and responsibilities, to appreciate mutual constraints, capabilities and capacities, and to develop mutual trust. Engagement is necessary to settle on a common strategic vision and avoid barriers to IUS development and implementation. Ideally, all relevant service institutes should collaborate in undertaking the achievement of IUS. Some fundamental requirements for IUS implementation, include:

a) Programme resources

Observations, whether provided by the scientific or end use community, are fundamental to IUS and underpin service development (e.g. forecasts) and evaluation. This makes access to observations and provision of metadata for quality assurance purposes by all partner agencies essential, given the likely diversity of measurement methods and sites. Given the much smaller scales for IUS products (cf. traditional NMHS operational scales) high (spatial) resolution modelling systems that simulate key urban processes are required. To enable smooth IUS creation and operation, early definition of partner mandates, interactions, roles and responsibilities is ideal, with this best facilitated via a well-designed partner governance/legal framework and a communication office so the multi-agency joint action can be coordinated (WMO 2019).

b) Technical expertise

The pool of technical expertise available for IUS instigation and development is potentially vast. For example, WMO members have access to a wide range of WMO programmes and activities, such as:

- World Weather Research Programme - https://community.wmo.int/activity-areas/wwrp
- World Climate Programme (WCP) - https://public.wmo.int/en/programmes/world-climate-programme
- Global Framework for Climate Services (GFCS) - https://gfcs.wmo.int/
- Hydrology and Water Resources Programme - https://public.wmo.int/en/programmes/hydrology-and-water-resources-programme
- Global Atmospheric Watch (GAW) - https://public.wmo.int/en/programmes/global-atmosphere-watch-programme
- Public Weather Service (PWS) - https://public.wmo.int/en/programmes/public-weather-services-programme
- Global Data Processing and Forecast Systems (GDPFS) - https://community.wmo.int/activity-areas/global-data-processing-and-forecasting-system-gdpfs
- Disaster Risk Reduction Programme - https://public.wmo.int/en/programmes/disaster-risk-reduction-programme
- WMO Integrated Global Observing Systems (WIGOS) - https://public.wmo.int/en/about-us/vision-and-mission/wmo-integrated-global-observing-system
- WMO Information Systems (WIS) - https://public.wmo.int/en/about-us/vision-mission-strategic-priorities/wmo-information-system-wis

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[4] Step-by-step Guidelines for Establishing a National Framework for Climate Services, https://library.wmo.int/opac/doc_num.php?explnum_id=4335

- Global Atmospheric Watch (GAW) Urban Research Meteorology and Environment (GURME) - https://community.wmo.int/activity-areas/gaw/science/gurme
- HiWeather Research Projects - https://public.wmo.int/en/resources/bulletin/hiweather-10-year-research-project
- WMO Technical Commissions - https://community.wmo.int/governance/commission-membership
- WMO Regional Climate Centres (RCCs) - https://public.wmo.int/en/our-mandate/climate/regional-climate-centres

City authorities or countries contemplating IUS can turn to WMO Members already experienced in IUS, the development of Multi-Hazard Early Warning Systems (MHEWS) projects, and/or cities engaged in IUS demonstration projects (WMO 2021). A vast range of knowledge related to urban processes and their interactions of relevance to IUS developers also resides in other international and national agencies, universities, and public and private research institutes.

c) Financial resources

Long-term commitment to urban safety and management of cities given their dynamic nature requires appropriate and sustained investment mechanisms to support all IUS components. In addition to national and local government funding, pay services for special users, especially businesses, may provide effective avenues for revenue generating opportunities to sustain IUS operations and improvements (UNDP 2016, WMO 2019).

d) Service resources

Key to the success of IUS will be its ability to deliver on its goals in an efficient and effective manner. Accordingly, rolling reviews of the efficacy of the underlying traditional and new services in the areas of meteorology, hydrology and air quality will be required.

e) Cost-benefit/social impact

The potential for IUS to produce substantial cost savings via assisting with the development and operation of more efficient, sustainable and resilient cities is immense. However, IUS value and its ability to make a difference will need to be proven by the conduct of systematic cost-benefit and social impact analyses similar to those that have been conducted for a range of NHMS (e.g. Barrett et al. 2021, Freebairn and Zillman 2002, Gray 2015). The demonstration of clear value will assist with raising the political appetite for IUS development.

14.5.2 Science/Knowledge Gaps

The nature of IUS will be unique to each individual city and reflect a city's distinct IUS risk profile as an outcome of the interaction between exposure, hazard type and vulnerability. With the implementation of IUS in a number of locations, it has become apparent that a range of scientific, technical and knowledge gaps exist examples include (see also WMO 2019, Grimmond et al. 2020):

- Making and utilizing representative high resolution observations
- Representation of urban form (three-dimensional structure, fabric, land cover) and metabolism in models.
- Data assimilation schemes suited to three-dimensional urban observations including representativeness assessment and uncertainty analysis.
- Identification of modelling systems (coupled) and approaches (e,g. ensemble) that capture urban environmental processes, are fit for probabilistic hazard prediction and facilitate the understanding of the origins of prediction uncertainty
- Balancing service/user relevant scales for prediction and generation of tailored products with what is possible via downscaling techniques
- Understanding and projecting the impact of a changing climate on cities for a range of possible IUS futures as portrayed by Representative Concentration Pathways (RCPs) and Shared Socio-Economic Pathways (SSP)
- Physical and socio-economic impact of cities on weather, climate, water and the environment now and in the future
- Physical and socio-economic consequences of non-hydrometeorological hazards (e.g. earthquakes/volcanic eruptions/space weather) and their interactions with IUS processes and drivers
- Understanding user and wider public response to IUS Decision Support Systems
- Consensus on IUS related common language
- Finding effective ways to narrate, communicate and manage risk
- Establishing IUS value for money
- Identifying critical threshold (meteorological, hydrological) values associated with step changes in human and infrastructure consequences arising from extreme hydrometeorological events
- Development of user relevant and friendly service delivery platforms that utilize advances in communication technologies (WMO 2019)

Although not exhaustive, this list indicates areas of research needed in the coming years - in many ways a next steps agenda - and serves as a pointer to the matters that will require serious consideration for those contemplating IUS development (WMO 2019).

14.6 Summary

Cities are densely populated and experience domino effects from extreme weather, flooding and air pollution hazards which can be extremely disruptive to societal and economic activities (e.g. industry, transportation), that adversely affect the environment and quality of life. The United Nations adoption of a 'New Urban Agenda' and with that the WMO's concept of IUS has been developed and articulated to meet the multi-hazard early warning weather, climate, air quality and hydrology warning needs for cities including long term planning and design. Integration of services requires multi-disciplinary science and multi-sector (levels of government and application sectors from, diverse decision-making) engagement and a basis for science-based consistent and efficient decision-making.

As weather, climate, water and environment pay no respect to political boundaries, the WMO is responsible for coordinating and guiding its Members and the scientific community. It has developed Guidance for IUS and identified National Hydrological and Meteorological Services (NHMS) as being in the best position to lead IUS development and delivery. However, an imperative for IUS development is deep engagement of key political players in cities and practitioners including IUS research providers, civil protection agencies, transportation managers, urban planners, legislators and regulators.

Cities have specific requirements arising from their diverse geography, climate, weather, economics, governance, amongst many other factors, making it necessary for services and products to be tailored for, and effectively communicated to, decision-makers and users. For example, IUS could help cities build resilience to climate related hazards. It is openly acknowledged that considerable gaps, and challenges including mutual understanding of capabilities, capacities, roles and responsibilities exist. These need attention, if IUS are to deliver on their aspirations.

Beyond describing the concept and components of IUS, some of the imperatives for taking IUS forward are outlined. We conclude some key starting points to creating IUS (WMO 2019):

- Waiting for a disaster to strike is not the reason to take action, a proactive approach to IUS development based on a vision for achieving resilient cities is best
- For cities contemplating development of IUS, well-functioning IUS in other cities different risk profiles (WMO 2021) exist already to provide some initial guidance
- At the outset – 'the conceptual design phase' – engagement with potential end users and relevant stakeholders will assist with socializing the idea of IUS, raise awareness and garner important feedback to inform development
- NHMS are well positioned to play a central role in the lead, promotion, development and coordination of IUS in addition to facilitating wider accessibility to data via influencing ownership issues and providing technical support (WMO 2019)
- Sustained multidisciplinary cross-cutting research programmes are fundamental for developing IUS as are well-honed protocols for evaluation
- Governance structures and legal frameworks that clearly articulate partner roles and responsibilities will benefit IUS development, implementation and operation.

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