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Integrated urban hydrometeorological, climate and environmental services: Concept, methodology and key messages

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ABSTRACT

Integrated Urban hydrometeorological, climate and environmental Services (IUS) is a World Meteorological Organization (WMO) initiative to aid development of science-based services to support safe, healthy, resilient and climate friendly cities. Guidance for Integrated Urban Hydrometeorological, Climate and Environmental Services (Volume I) has been developed with the intent to provide an overview of the concept, methods and good practices for producing and providing these services to respond to urban hazards across a range of time scales (weather to climate). This involves combining (dense) heterogeneous observation networks, high-resolution forecasts, multi-hazard early warning systems and climate services to assist cities in setting and implementing mitigation and adaptation strategies for the management and building of resilient and sustainable cities. IUS includes research, evaluation and delivery with a wide participation from city governments, national hydrometeorological services, international organizations, universities, research institutions and private sector stakeholders. An overview of the IUS concept with key messages, examples of good practice and recommendations are provided. The research community will play an important role to: identify critical research challenges; develop impact forecasts and warnings; promote and deliver IUS internationally, and; support national and local communities in the implementation of IUS thereby contributing to the United Nations' Sustainable Development Goals at all scales.

1. Introduction

The World Meteorological Organization's (WMO) cross-cutting urban focus initiative supports the implementation of the United

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Nations (UN) New Urban Agenda (UN, 2016a) and the Sustainable Development Goals (in particular, SDG11: Sustainable Cities and Communities; UN, 2016b) through the novel concept and approach of Integrated Urban Hydrometeorological, Climate and Environmental Services (*Integrated Urban Services or IUS*) for both (i) sustainable development and (ii) multi-hazard early-warning systems for cities. The Sendai Framework for Disaster Reduction 2015-2030 (UNDRR, 2015) aims to substantially reduce impacts of disaster in terms of mortality, economic loss and damages, and disruption of basic services, while contributing to the mitigation of technological and security risks, through the provision of impact-based services (WMO, 2016). These services consider hazards, vulnerability and exposure. Governments, businesses and the public need to understand how the hydrometeorological hazard may affect their lives, livelihoods, property and economic activity in order to take appropriate actions.

As weather, air quality, climate and the water cycle know no national boundaries, international cooperation at a global scale is essential to develop commensurate services and to reap the benefits from their application. The WMO, a United Nations Specialized Agency, provides the framework for such international cooperation. This intergovernmental organization's 193 member states and territories (called Members) are mainly concerned with issues at a national, regional and international level. WMO through its relevant programmes and technical commissions guides the Members and facilitates the generation of high quality, reliable information and services and its dissemination, communication to various stakeholders, governmental authorities, sectors in support of decision making. WMO commissions include relevant experts not only from government agencies (i.e. not only National Hydrometeorological Services, NMHS) but also universities, research institutes and private companies. Federal agencies, such as NMHSs, may support but not necessarily have a mandate to provide services at the municipal level (unless through agreement). Urban services, if they exist, may also come from a variety of different providers.

Defining disaster risk and forecasting hydrometeorological impacts are beyond the remit of many meteorological services and are a new challenge for most NMHS. However, an understanding of these impacts can be developed through collaborative engagement with disaster management officials and other relevant experts. The risks and impacts associated with extreme weather and climate events are dynamic, so it may be argued that NMHS, who have real-time dissemination capability, are best equipped to issue impact based warnings (World Bank, 2013). Integration or coordination amongst the services is also required to convey a consistent and accurate message as hazardous events could affect several services simultaneously or in sequence.

A WMO cross-programme group, formed by the Commissions for Atmospheric Sciences and for Basic Systems in consultation with other Technical Commissions, and led by the GURME (GAW [Global Atmosphere Watch] Urban Research Meteorology and Environment) Scientific Advisory Group developed the *Guidance on Integrated Urban Hydrometeorological, Climate and Environmental Services* in collaboration with globally relevant scientific services or disciplines. This guidance has three parts:

(i) Volume 1, addresses the concept and methods of an operational IUS (Grimmond et al., 2013; WMO, 2019a)
(ii) Volume 2 provides examples and case studies (WMO, 2019b)
(iii) Volume 3 will provide the IUS implementation guidelines.

As urban decision-making is embedded in different organizational or governance structures, partnership and cooperation relationships, this guidance will be relevant to all IUS practitioners, called sectors, herein. In the future, the guidance will be updated as needed.

The objective of the present paper is both to describe the IUS concept and to provide an overview of the Guidance (Vol. 1) for the broader scientific community and stakeholders. Following a background discussion (Section 2), the IUS concepts are outlined (Section 3). Results from surveys of urban experts and WMO members (Section 4) are used to articulate the science and knowledge gaps (Section 5) and to illustrate the lessons learnt and recommendations (Section 6). This is followed by concluding remarks (Section 7).

2. Background

Accelerating growth of urban populations, especially in developing countries, has become a driving force of human development. Crowded cities are centres of innovation and economic progress, but polluted air, extreme weather conditions, flooding and other hazards create substantial challenges. The October 2016 UN HABITAT-III conference adopted the New UN Urban Agenda (UN, 2016a) which makes urban resilience, climate and environment sustainability as well as disaster risk management foci.

Increasingly dense, complex and interdependent urban activities are rendering cities vulnerable: a single hazard event can lead to a widespread breakdown of a city's infrastructure through cascading downstream or “domino” effects (Fig. 1). As the components of urban systems are tightly intertwined, having good predictions that are tailored for the different systems, spatially explicit at the appropriate scale and refreshed at appropriate frequencies allows for the systems to be operated efficiently and effectively. This is especially important when extreme events occur. For example, tropical cyclones (typhoons or hurricanes) impact cities around the world annually, causing a cascade of effects (Fig. 1) including hazardous meteorological conditions (blue); first order impacts (green); and follow-on impacts (purple). The latter impacts may be immediate, as with traffic accidents associated with severe convection (e.g. road flooding) or take longer (days - weeks) to manifest themselves (e.g. plant disease). These impacts (Fig. 1) are not exhaustive, as there are also socio-economic impacts to individuals, neighbourhoods, the city, region and often beyond.

Being able to forecast/identify the area within a city most likely to be exposed to the hazards allows agencies to respond rapidly and optimally. Consequently, combining the forecast with detailed city information (e.g. demographics, infrastructure) is best. Using current communication technologies enables response systems to rapidly receive, assimilate, predict and enhance urban products and their delivery to end users. Neighbourhood scale weather, climate, air quality and water information is also needed to support long-

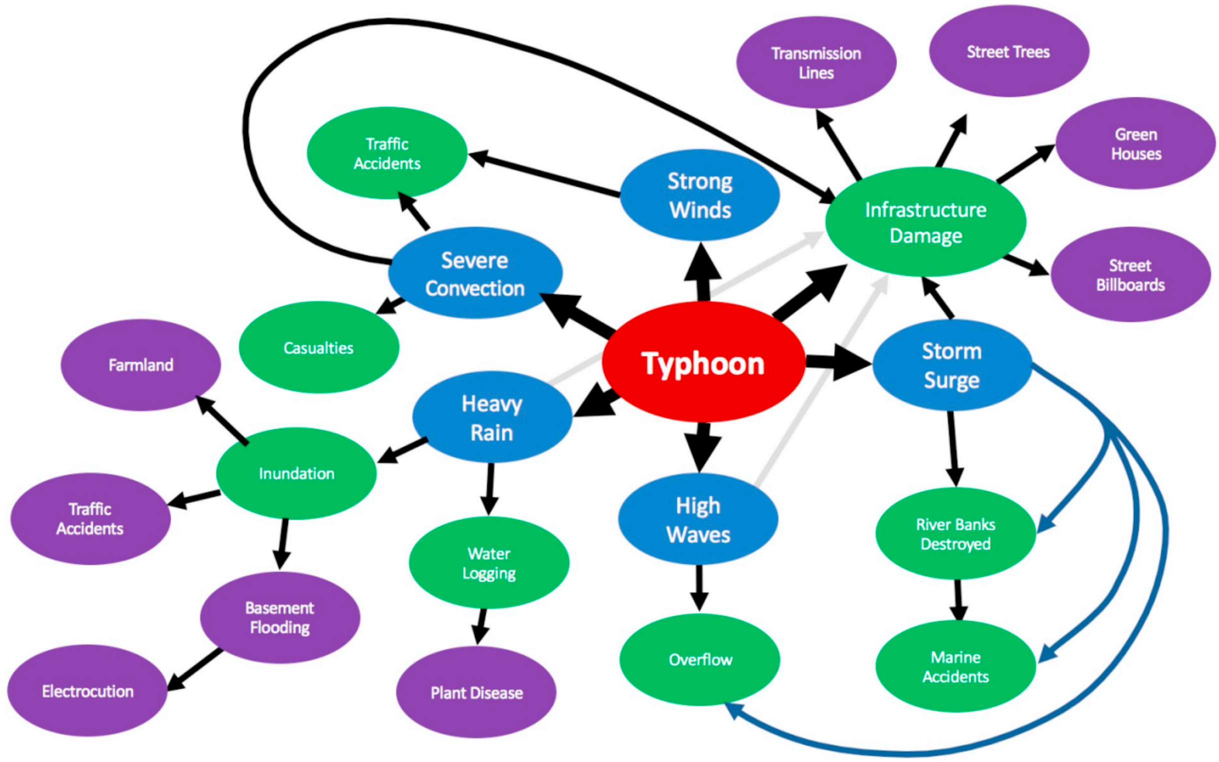

Fig. 1. Illustration of the domino effect for a typhoon event, which produces multiple hydro-meteorological hazards (blue) that have immediate effects (green) and follow-on impacts (purple) that can be both short- and long-term. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

term planning to ensure that cities evolve appropriately in the future. As cities impact their surroundings in numerous ways (e.g. as the largest sources of greenhouse gases; UN-HABITAT, 2011), creating sustainable cities is key to achieving global sustainability.

In the context of city management (by mayors and city agencies), urban services relate to transportation, infrastructure, housing, water and waste management, snow clearance and other city operations. In our context, IUS refers to the provision of weather, climate, hydrology and/or air quality infrastructure (data, observations, predictions) to support and integrate both traditional and other (new) urban services. They include hydro-meteorological forecasts for a range of phenomena (e.g. thunderstorms, tropical cyclones, coastal inundation, flooding) and conditions (e.g. air quality, health-related heat/cold stress) as well as climate services (e.g. carbon neutral cities, building codes, zoning, planning and design) at a variety of spatial (inter- and intra-urban) and temporal scales.

IUS have generally been developed from existing prediction systems, including:

- weather prediction designed for warnings (e.g. tropical cyclones, synoptic storms, thunderstorms) at global to local spatial scales and hourly/daily/weekly temporal scales
- climate services information systems (WMO, 2016) designed for products (e.g. climate extremes, sector specific climate indices, climate projections, climate risk management and adaptation) at global, national and regional scales, and from sub-seasonal to decadal and longer temporal scales
- hydrology and water hazard warnings (e.g. flash river floods, heavy precipitation, river water stage, storm tides, sea level rise, coastal inundation) at all scales including urban
- air quality hazards (e.g. smog, sand and dust storms, wildfires, regional haze, acid rain, volcanic ash plumes, accidental releases, etc.) at national, regional and local scales

3. Integrated urban services (IUS) concept

IUS inherently need to provide high resolution (~1 km or smaller) information compared to the regional scale (~10 km and larger). The goal is to provide urban to intra-urban spatial information. Urban domains encompass a wide range of physical and human geographical characteristics, including governance structures, with metropolitan areas often comprising multiple contiguous or neighbouring cities. Extensive commuter regions may create substantial infrastructure in rural areas (e.g. roads/trains between centres and industrial settings). Hence, the "urban" extent must consider the needs of planners to address housing, transportation and recreation in the metropolitan region.

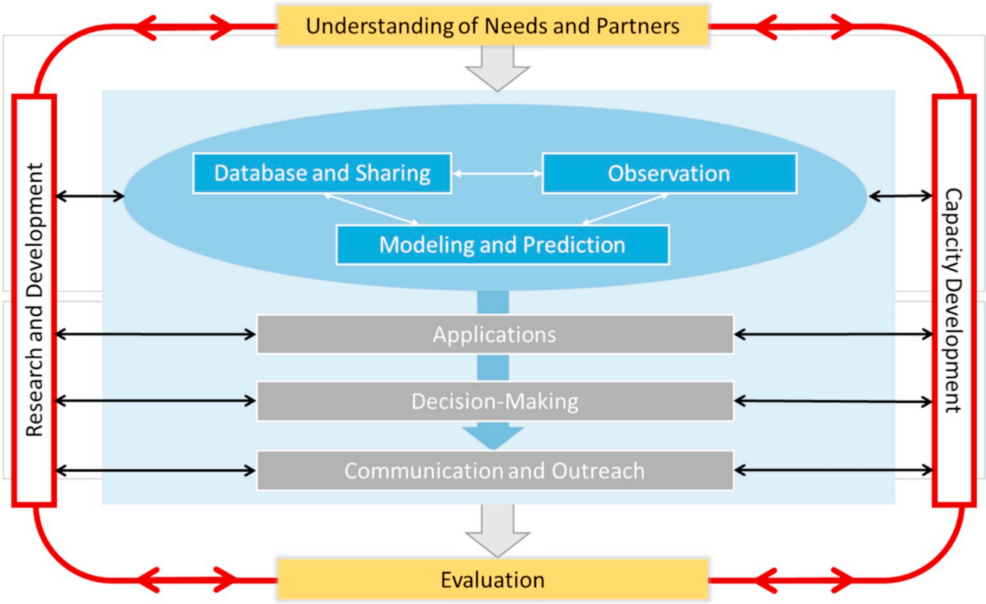

Fig. 2. Components of an Integrated Urban Hydrometeorological, Climate and Environmental Service (IUS) System. The generic framework shown is for impact based prediction systems, with boxes indicating where integration may occur. The mature IUS promotes integration in all components.

3.1. IUS components

To implement IUS may presents significant challenges, meanwhile it will make good use of already available, but perhaps not yet integrated, components (Fig. 2). The components are: dense observation networks and databases, high-resolution forecasts across different time scales, multi-hazard early warning systems, (improved) understanding of how to deliver and communicate the information, (improved) understanding of public perception, warning response, climate watch systems, and climate services for risk management and adaptation strategies (Baklanov et al., 2010; WMO-IGAC, 2012; Beig et al., 2015).

Fig. 2 generically describes the framework of a service providing information to an application sector. In the context of IUS, the weather, climate, air quality and hydrology are the focus for services for various sectorial stakeholders, partners or decision-makers (city authorities, planners, urban designers, behavioral experts). The components (boxes) in Fig. 2 indicate where integration may occur to create an IUS. Integration has three aspects:

(i) internal to a service (intra-service)
(ii) between one service and another (cross-service)
(iii) between sectors (cross-sector).

Integration may occur at the monitoring, data assimilation and/or urban system modeling level (e.g. including anthropogenic factors), or at the decision-making level where products and experts from the different services provide independent and perhaps sometimes even contradictory advice directly to decision-makers. The maturity of an IUS is defined by where the integration occurs and the depth of engagement with different sectors.

Integration has proven an effective practice in multi-hazard early warning systems and provides a holistic approach to enhance resilience. Evolution of comprehensive Earth system models, extension of forecasting both to longer (sub-seasonal, seasonal, S2S) and shorter (nowcasting) time-scales, and enhanced spatial (intra-urban) scales provide other levels of integration that are intrinsic to IUS information (Grimmond et al., 2015; WMO, 2015; Baklanov et al., 2016). As these issues are inter-dependent, multi-disciplinary approaches are required to resolve the gaps, identify inconsistencies and work towards solutions. The Guidance document (WMO, 2019a) promotes early cross-service and deep cross-sector integration.

Integration has significant challenges due to technical and decision-making complexity. Language to ensure mutual understanding of the intra-service, cross-service, cross-sector partners (Fig. 2, top yellow box) is essential and requires early engagement to establish roles/responsibilities, gain knowledge of capabilities, capacities, current and potential requirements. Frequently, the process may be instigated following a significant event with economic and/or societal impact (e.g. a heat- or cold wave, storm or flood event) or an opportunity for partners to come together with a shared vision of needs (e.g., major sports event or Expo or through socio-political will).

At the heart of the system are observations, data, monitoring and modeling to generate useful and usable information (post-processing) for the relevant partners (Fig. 2, blue ellipse). Effective city-specific impact-based warnings, their timely delivery and effective use in decision-support systems, can only be realized through co-design by decision-makers, service providers and various sectorial users (Fig. 2, grey boxes). These warnings must include effective communication and outreach to the urban population for effective action.

Tools to support longer term decisions (e.g. for urban design and planning towards resilience in a context of climate change; societal expectations for livability, health, workability and sustainability; urban actions to reduce greenhouse gas and other pollutants emissions) are being developed. The articulation of weather, climate, hydrological and environmental services within an urban context are required to address these new challenges. IUS should result in consistent cross-sector messages. It is critical that the end-users (e.g. public and specialists) understand the message especially when some form of warning is critical to successful mitigation. However, experience has shown that understanding of warning messages, risk profiles, human response and effective risk communication is a challenge and requires attention (WMO, 2018b).

The final step in a development cycle is the complete evaluation (i.e., scientific, functional, societal impact, etc.) and assessment of the IUS to build capacity, identify needs and areas requiring research and development (Fig. 2, bottom yellow box). The evaluations may require the collection of specialized data. The resources and skills in academia, research institutes (inside and outside government), private sectors and other agencies will be needed to meet the challenges. At each stage of the collaborative process, there is an on-going cross-service and cross-sector training, education, as well as a research and development process (Fig. 2, side white boxes). The process is not complete until the partnership itself is examined to ensure that the IUS is sufficiently resourced for the tasks at hand.

For the various partners to function most effectively and to find optimal solutions, information needs to be combined and shared, ideally using common infrastructure. The performance of all stakeholders, including providers, can be substantially enhanced if systems, infrastructure and operational activities are established and maintained within a multi-purpose framework. It is expected that the synergies developed as a result of IUS will yield gains due to efficiencies of the integration of a broad spectrum of urban environmental management systems and better functionality and reliability through more frequent activation of systems.

The innovation of the IUS concept, promulgated here, is that it allows the end-user to receive an appropriate product that considers two or more of weather, climate, hydrology and air quality scientific services. These individual services are often delivered through different programs or agencies and may also benefit from integration (e.g. flood with water quality warnings, meteorological warnings and disaster reduction activities) but the focus of IUS is the cross-service, cross-sector aspect. Some of the critical urban applications/services are inherently integrated (to various degrees) due to co-dependencies.

From the perspective of delivery, requirements, maturity and capacity, there will be a spectrum of approaches, from highly coupled (weather, climate, air quality, hydrology) probabilistic or deterministic modeling systems (numerical or statistical), with tailored products combined in multi-hazard, multi-scale decision-support platforms, to independent hazard predictions with interpretations by hazard specialists to support decision-makers. There are significant differences in requirements for IUS by cities from those generally currently available from national or regional service providers. So, depending on the specific requirements of a city, the capabilities and the resources available, the implementation of IUS can be significantly different in each instance.

3.2. Challenges

The many challenges to creating an effective IUS are described more fully elsewhere (WMO, 2019a). They include understanding the following: how to access and use observations in urban areas; representation of urban characteristics in models; urban scale and regional scale model integration requirements; impact of cities on weather, environment, water and climate; impact of changing climate on cities including mitigation and adaptation; feedback from the city activities to weather, water, air quality and climate (e.g. modification of energy use and greenhouse gas emissions feedbacks); role of other natural hazards (e.g. earthquakes, volcanic eruptions, space weather) on urban weather, air quality, hydrology and climate; development and use of integrated decision support systems; communication and multi-disciplinary risk management; evaluation of integrated systems and services; understanding of the critical limit thresholds, and; targeted and tailored delivery platforms and predictions of economic and social impact.

4. Demonstration cities

4.1. First order hazard and impact-forecast needs

The first order needs of cities are known. They are influenced by: location (e.g., coastal, river, mountainous, tropical, deserts), hazards (e.g., geological fault lines, volcanoes, dust storms, fire danger, space weather), climate conditions and the city itself (e.g. *major* industries, transport networks, technology, energy supply, construction styles).

The known need for services (WMO, 2019a) include monitoring and prediction of: severe weather, climate, hydrological and air quality events, such as, heat and cold waves, slippery roads, tropical cyclones and extra-tropical storms; droughts; flash floods; changes in soil stability and landslides; river and lake flooding; coastal inundation from storm surges or ocean waves; sea level rise due to climate change; sand and dust storms; wild fires; air and water pollution, including accidental releases and aero-allergens; harmful UV radiation; and disease vectors.

IUS should include societal impact predictions from natural and anthropogenic hazards (e.g. tropical cyclones, major storms, sand and dust storms, volcano eruptions) or extreme weather conditions (winds, rain, freezing rain, snow, ice, fog, hail, flooding and lightning) which may cause disruptions to key functions (e.g. transport, communications, energy distribution, renewable energy (e.g., solar power, wind energy)). As the societal impacts, may have long-term implications on people or ecosystems, they need to be included in urban planning.

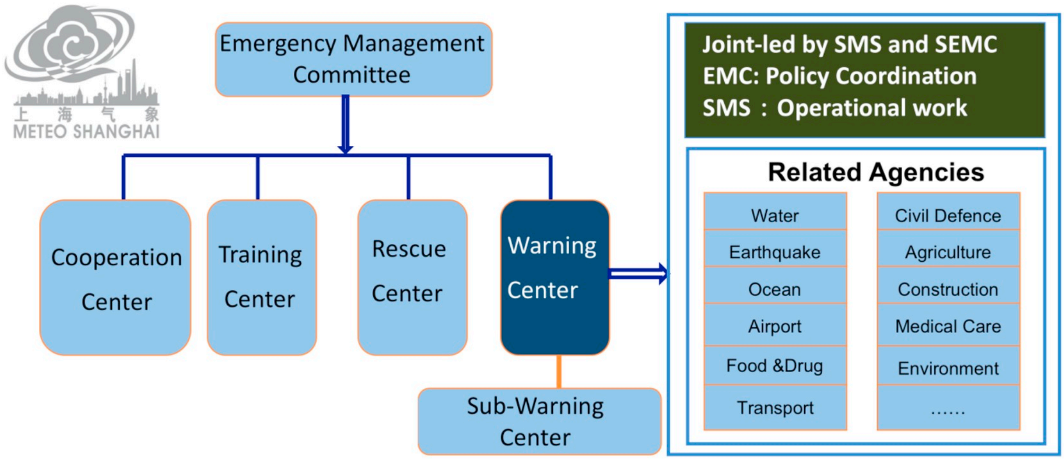

Fig. 3. Emergency Management Structure of Shanghai. Courtesy of Xu Tang.

4.2. Demonstration city surveys

Several cities have, are preparing, or are developing IUS for various reasons, with different levels of integration and providing different services. WMO has played a role in the development and/or demonstrations of some of these (e.g. Fig. 3, Tang, 2006; Grimmond et al., 2014; Baklanov et al., 2018, 2019; Amorim et al., 2018). To understand the state and development plans of IUS for good practice (WMO, 2019a), exploratory surveys were conducted with 31 urban experts representing 22 specific cities (Table 1). Some IUS were in demonstration or pre-operational mode but contributed key messages.

Table 1
Demonstration cities (identified by GURME experts). Not all respondents have IUS or IUS specific to a city (indicated by a blank).

City	Country
Amsterdam	Netherlands
Beijing	China
Copenhagen	Denmark
Dallas-Fort Worth	U.S.A.
Helsinki	Finland
Hong Kong	China
Jakarta	Indonesia
Johannesburg	South Africa
London	United Kingdom
Mexico City	Mexico
Moscow	Russia
Paris	France
Santiago	Chile
Sao Paolo	Brazil
Seattle	U.S.A.
Seoul	South Korea
Shanghai	China
Singapore	Singapore
St Petersburg	Russia
Stockholm	Sweden
Stuttgart	Germany
Toronto	Canada
	Kenya
	Italy
	Japan
	Malaysia
	Congo
	New Zealand
	Morocco
	Nigeria
	Argentina

4.3. Key messages

From the surveys, two key messages or general concepts arise, which are consistent with both the UN Sustainable Development Goals (UN, 2016b) and the Sendai Framework for Disaster Risk Reduction recommendations (UNDRR, 2015):

- *Governance*: The need to establish laws, regulations, standardized operating procedures and mechanisms for a multi-agency response – in which roles and responsibilities are clearly identified
- *Multi-Hazard Early Warning Systems (MHEWS)*: The need for operating procedures for early detection, prediction, briefing, and warning dissemination based on good observations and forecasts (World Bank, 2013).

Other key messages include the needs for: long term planning/design; bridging scientific disciplines (weather, climate, air quality, hydrology; cross-service integration); cross-jurisdictional (national, regional, urban) organizations and urban authorities (cross-sector) and; open data infrastructure and communication. In the following highlights from the survey are discussed briefly.

4.3.1. Governance example

The Shanghai Meteorological Service (SMS) of the China Meteorological Administration (CMA) has been evolving from a traditional weather forecast/warning service to include a multi-hazard disaster risk reduction service (Tang, 2006; Dabberdt et al., 2013; Tan et al., 2015). Initially, the focus was on air pollution episodes and high-impact weather during the Shanghai World Expo 2010. Subsequently, this has expanded to consider multiple weather hazards and to incorporate the vulnerability and exposure of various sites to enhance the resilience of the city infrastructure and capacity for risk management.

On 1 October 2006, the Shanghai People's Congress passed the “Shanghai Implementation Regulation of the Meteorological Law of the People's Republic of China”. This clarified the legal mandate of the SMS in disaster risk reduction (DRR). As a result, SMS was required to provide specialized weather hazard and disaster warning services in cooperation with other government departments such as agriculture, fisheries, flood control, traffic and transportation, fire control, police, environmental protection, civil administration, public health, tourism, harbour and maritime management (Tang, 2006). A 50-member Shanghai Emergency Management Response Committee (EMC, Fig. 3) was established and in February 2013, the Shanghai Emergency Warning Center was formed to enhance and improve the existing emergency procedures (Fig. 3). Thirty-six joint response mechanisms including co-operation agreements, warnings and action plans amongst 25 government agencies for Disaster Prevention and Mitigation were created. Action plans for weather disasters are issued by the General Office of SMS and each agency has defined responsibilities.

4.3.2. Urban multi-hazard early warning system (MHEWS) example

Sustainability and efficiency can be enhanced if systems and operational activities are established and maintained within a multi-purpose framework that considers all hazards and end users' needs. MHEWS are expected to be activated more often than a single-hazard warning system and, thus, should provide better functionality and reliability also for dangerous but rare high-intensity events (e.g. tsunami). Multi-hazard systems can help the public to better understand the range of risks of different hazards, reinforce desired preparedness actions and warning response behaviours. The Shanghai MHEWS is designed to cope with the threats from tropical cyclones, storm surges, rainstorms, heat and cold waves, thunderstorms, and air pollution as well as their cascading effects, such as floods, health impacts, accidents, and infrastructure damage.

A MHEWS should ideally incorporate all risks and vulnerabilities that are both natural and anthropogenic as many disasters are multi-dimensional. The warning system should be able to encompass all the potential consequences that may flow from a single extreme event. For example, an industrial fire may lead to widespread atmospheric contamination and to power outages causing the failure of heating or cooling for the entire city or parts of it. Given a MHEWS usually focuses on managing the potential cascade of disasters stemming from an initial hydro-meteorological hazard, the primary, secondary, and sometimes tertiary impacts (Fig. 1) require well-ordered coordination and cooperation to support highly sensitive users as well as the general public. Hence, the need for multi-agency coordination and multi-phase response requires standard operating procedures and action plans as well as early warnings (World Bank, 2013).

4.4. Other key messages

4.4.1. Multi-disciplinary initiatives

As Earth system modeling is complex and highly technical, one barrier to effective integration is a lack of mutual understanding of capabilities, capacity, responsibilities, roles within both services and sectors. Lack of a common language and terminology is identified as a key obstacle, but new generations of scientists with the necessary skills can be developed through multi-disciplinary conferences, training workshops and education programs.

4.4.2. Health initiatives

A cross-sectorial health-related hazard forecast, developed for the Shanghai World Expo 2010 (Fig. 4), combines meteorological, air quality and risk assessment monitoring for a variety of health products through modeling.

Another cross-sector collaboration on the reduction of impacts of weather, climate on public health has brought together the Hong Kong Observatory (HKO), local universities, sector-related social enterprises/ organizations (e.g. Senior Citizen Home Safety Association), and other government departments (Shun and Chan, 2017; WMO, 2018a) to develop the Hong Kong Heat Index (HKHI)

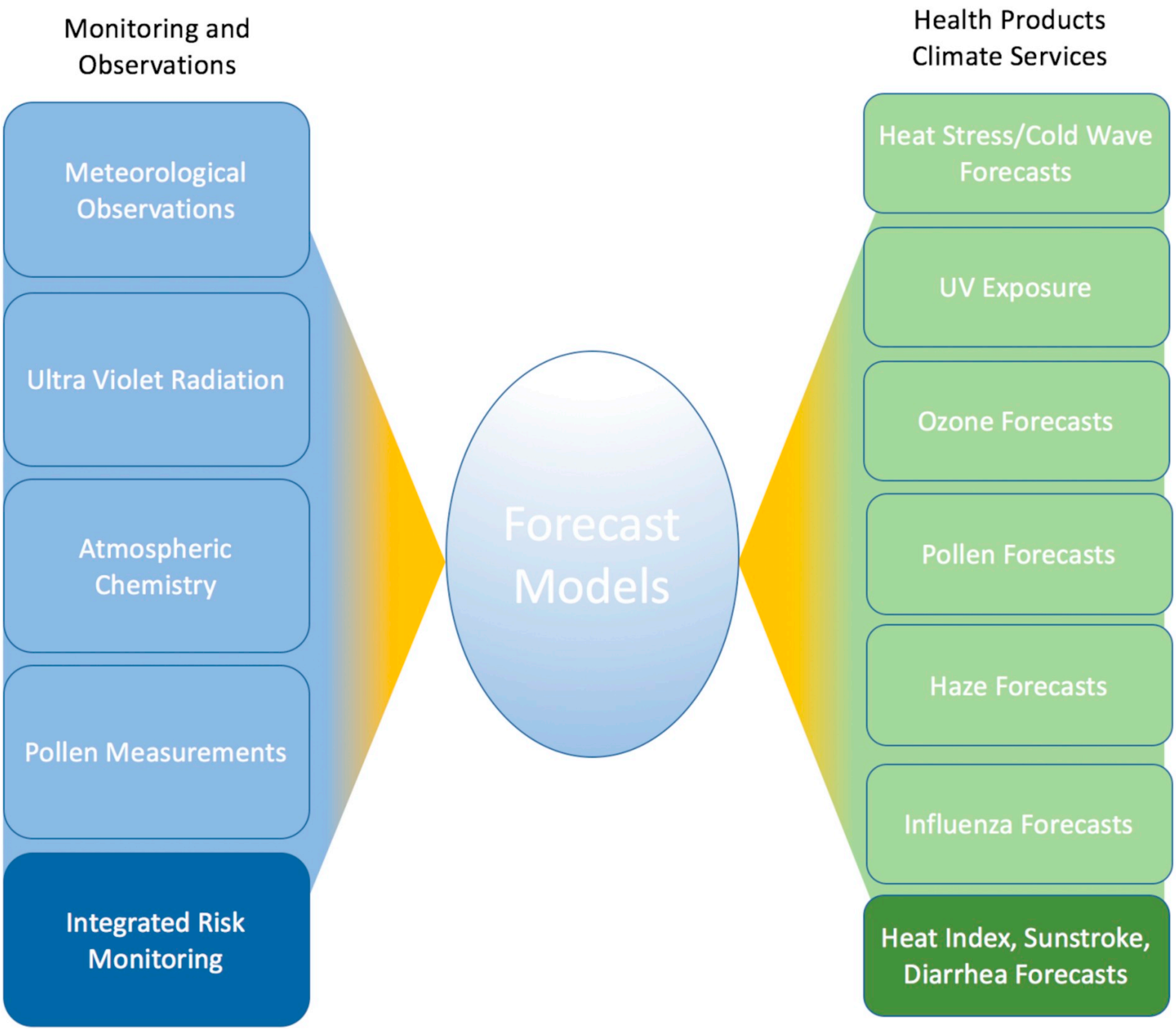

Fig. 4. Shanghai Meteorological Services for Public Health. Integrated Risk Monitoring takes into consideration bacterial food poisoning, diarrhea diagnostics, trauma, influenza and heatstroke in order to produce specialize heat index, sun stroke and diarrhea forecasts for the Shanghai World Expo 2010 (figure adapted after Xu Tang).

for the hot and humid sub-tropical climate (Lee et al., 2016) and to carry out health impacts studies of extreme hot weather events (Lau and Ren, 2018; Wang et al., 2018), seasonal variations of influenza (Chan et al., 2009), and weather - climate impacts on services for the elderly (Mok and Leung, 2009; Wong et al., 2015; Lee and Leung, 2016). Following the 2003 SARS (severe acute respiratory syndrome) event, local planning and development measures were implemented (Ng, 2009; Ren et al., 2011) that included weather considerations, and are now used elsewhere (Ren et al., 2018).

4.4.3. *Long-term urban planning*

Climate change should be considered in all urban planning because of the long times scales involved. Urban planners would like *urban system models* outputs at high spatial resolution. This can be achieved using high resolution weather models (~1 km) forced by multiple simulations of climate scenarios (e.g. carbon dioxide doubling) to provide climate and air quality at urban spatial and temporal scales (Amorim et al., 2018; Takane et al., 2019). These models can account for the urban fabric (Ching et al., 2018), physical (e.g., anthropogenic car emissions) and human behaviour processes (e.g. excess heat from use of air conditioners in heat waves; Lemonsu et al., 2012; Masson et al., 2013 Schoetter et al., 2017; Takane et al., 2019). As urban designers need both access to and understanding of the data/products, cross-sector (e.g., Earth system scientists to/from urban planners), training is necessary. For example, urban weather, climate, analysis and application can be linked from hazard to urban design considerations (Fig. 5).

4.4.4. *Open and accessible data*

Observations in cities are collected by many agencies/stakeholders. For consistent, efficient and effective use, these data must be

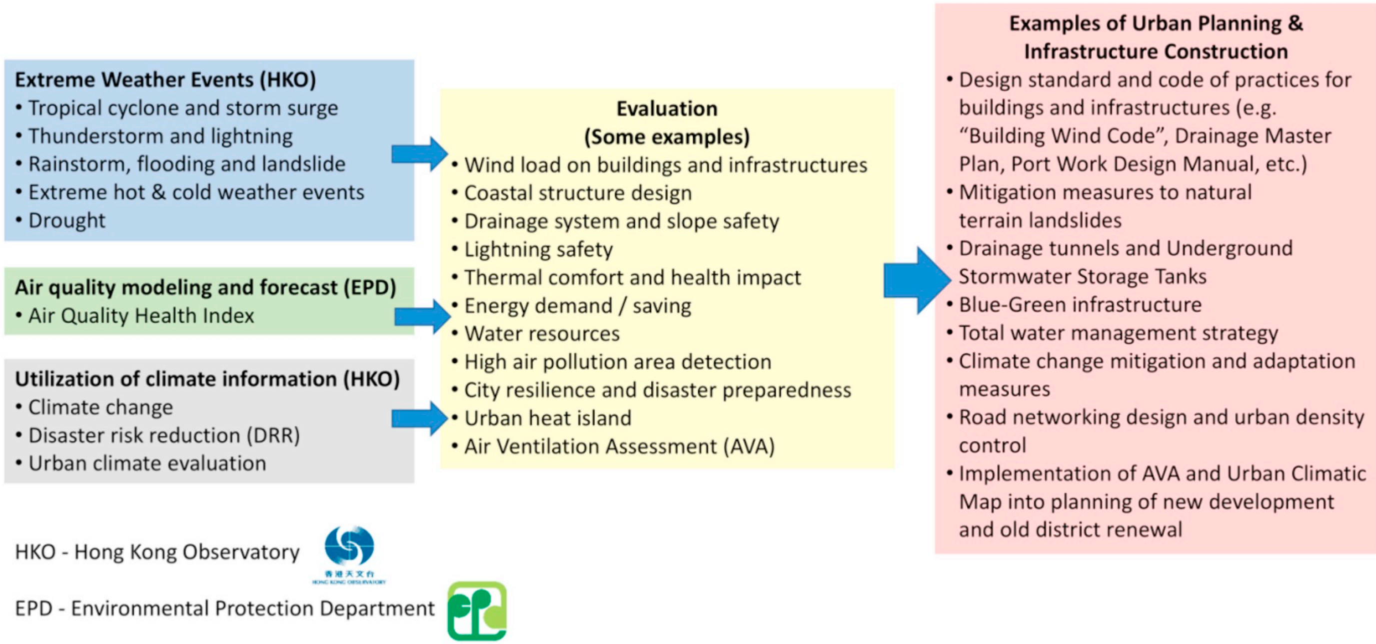

Fig. 5. IUS for urban planning, with an analysis sequence from hazardous event, evaluation of the impacts on long-term planning. Sources: Hong Kong Observatory used with permission.

open, accessible and preferably in a consistent format. As data come from different sensors, with different sampling strategies/ resolutions, collected for different purposes, of different quality and from different models, this means the data will be heterogeneous and that metadata are critical for appropriate use.

4.4.5. Communications/product dissemination

There are several aspects of risk communication and dissemination. The multi-hazard concept must address the issue of conveying the risk and impact of a variety of hazards (e.g. air pollution episode, tsunamis, river flooding, tornados) to a range of decision-makers, stakeholders and the public each with different knowledge base, expertise and requirements for levels for information (Golding et al., 2019).

Many IUS hazards will be highly tailored, have high spatial and temporal resolution (e.g. hourly for air quality and weather) and need to be targeted to at-risk individuals and not necessarily to the general population. This can vary from targeted emails, mobile applications, or text alerts, to public-display boards for extreme weather or air pollution conditions (Baklanov et al., 2018; CERC, 2019).

5. Science/knowledge gaps

Each city's priorities will vary with the hazards and risks that it faces, and it will need to consider these when designing an IUS. Extensive sharing of capabilities and knowledge amongst services and sectors is needed to undertake comprehensive development. Although progress has been made, many scientific and technological questions remain; these include:

- *Ensuring observations cover the range of spatial scale in cities.* For example, recognizing the difference between within street canyon, within a park, above roof level (within the roughness sub-layer), within the constant flux layer (or inertial sub-layer) and the varying depths of the boundary layer, is important. It is crucial to consider what different instruments measure, given their different assumptions or variables actually observed (e.g. mixed layer height, mixing height, temperature inversion, Kotthaus et al., 2018). The state and variations of the physical and chemical characteristics of the three-dimensional urban atmosphere needs to be observed (Grimmond et al., 2010).
- *Representation of urban form and function in models.* The urban material (e.g. surface type), form (e.g. building density, height and surface roughness), function (e.g. anthropogenic effects and building use), urban hydrology (e.g. irrigation and sewer system), and urban vegetation (e.g. leaf area index, phenology, extent and height) all need to be captured to model the hydro-meteorological and environmental processes and their influences at different temporal and spatial scales.
- *Data assimilation*: There is a need for development of schemes that can use 3D urban observations to improve model predictions in urban areas. These will require assessment and uncertainty analyses.
- *Ensembles and coupled models*: Evidence from a wide range of approaches to modeling the urban environment needs to be drawn on to select those that provide the most useful information on the probability of occurrence of hazards. Such modeling systems will certainly need to couple aspects of the urban surfaces (including walls) and its hydrology with the atmosphere and its pollutants; and in many cities IUS models will also need to incorporate the coastal ocean, lakes or (tidal) rivers. They will also need to include a means of assessing the sensitivity of the predictions to uncertain initial states and parameters, through use of model ensembles, for example.
- *Urban atmosphere scales requirements (to drive other models).* What scales are really required for useful forecasts or assessments? Understanding downscaling from global-regional models requires knowledge of the interactions of a range of scales and different approaches may be used depending on the characteristic time scales (Schlünzen et al., 2011) or on the application purpose (Hoffmann et al., 2016). This will drive the development of tailored products and services.
- *Understanding urban physical processes.* What is the impact of cities on weather/climate/ water/environment (e.g., air quality, water quantity and quality, ecosystem, thermal variability, disease transmission)? This will drive the complexity (feedback loop) of models.
- *Impact of changing climate on cities*. How will the urban environment (e.g., public health, economy and ecosystems) react to climate change (e.g., air quality, water quantity and quality, heatwaves, dust storms, wildfires and other high impact events).
- *Impact of changes to cities.* Cities constantly evolve, through demographic and population change, economic development, urban fabric changes (e.g., urbanization, land use, energy use, transport, pollutant and greenhouse gas emissions, densification and suburbanization) and driven by adaptation to climate and hydrological changes.
- *Other environmental hazards,* e.g. *earthquakes/volcanic eruptions/space weather, and their interactions with the atmosphere.* Social and environmental consequences of these high impact events may change the physical nature of the city (e.g. infrastructure including telecommunications, transport systems, housing, energy production, food/water supply, disease).
- *Development of integrated decision support systems* is needed to efficiently present relevant, often uncertain and conflicting information to technical experts, to support warning decision-making and should incorporate information about societal impacts, consequences and action statements. Understanding the impact on human response and behaviour is part of the decision-making process.
- *Communication and management of risk.* A common understanding and language is needed to bridge the services and sectors and to articulate a better understanding of the range of risk and impacts in order to take appropriate mitigation actions to protect the public (e.g. early warning systems or urban design/planning).
- *Evaluation of integrated services:* Cost-benefit studies are needed for both initiation and sustainability of IUS, e.g. socio-economic

evaluation of benefits, co-benefits (e.g. for climate), system operating costs and avoided losses.

- *Identifying and understanding critical limit values:* for meteorological and atmospheric composition variables with respect to human health and for environmental protection.
- *New, targeted and customized user interface and delivery platforms:* effective use of the many new communication techniques needs to be developed in close consultation with users to ensure that services, advisories and warnings result in appropriate action and, in turn, inform how best to improve the services.

6. Lessons learnt and recommendations

IUS will assist decision makers and end-users. It is important not to wait for a disaster before initiating the planning of an IUS as it takes time to develop. Various cities have, are preparing, or are developing IUS (Table 1) that can provide an initial template for development. From these a wide range of lessons have been learnt including:

- Initiation of integrated services is often opportunistic (e.g. following an extreme event or in preparation for a major event).
- It is essential to engage all relevant sectors (agencies, the public, city government, civil society, private businesses) from the beginning, so as to develop a mutual appreciation of the challenges, understanding of capabilities and requirements, a common language, and lines of communication.
- It is necessary to understand and/or establish regulatory and institutional frameworks that clearly define agency mandates, interactions, roles and responsibilities to enable creation and maintenance of IUS.
- Operational implementation should include cross-sector technology transfer mechanisms (co-design, research, development, test beds, capacity building) and cross-service provision (warnings, advisories, risk and impact communications, capacity building, evaluation).

The recommendations are:

- Encourage the scientific community and all levels of government to lead and contribute to the promotion, development and coordination of IUS, including knowledge transfer.
- Ensure that legal and institutional frameworks are in place for partnerships within cities that clearly define agency mandates, interactions, roles and responsibilities to enable creation and maintenance of IUS.
- Engage with relevant stakeholders and users (academia, agencies, non-government organizations, the public, city government, private sector, civil sector, businesses) from the beginning, to raise awareness, identify needs, co-design solutions and obtain feedback.
- Carry out further research, including multi-disciplinary cross cutting studies, to develop IUS.
- Encourage wide accessibility to data by influencing ownership issues and technical support.
- Encourage demonstration IUS projects to showcase the benefits and learning experiences to all.

7. Final remarks

Migration to cities creates densely populated environments and associated infrastructure which result in ever increasing vulnerabilities and exposure to natural and anthropogenic hazards. The UN has identified “*sustainable cities and communities*” as one of its Sustainable Development Goals (UN, 2016b).

The *Guidance on Integrated Urban Hydrometeorological, Climate and Environmental Services Volume I: Concept and Methodology* (WMO, 2019a) articulates a vision to support this goal. This paper highlights the concepts discussed more fully in WMO (2019a). Advances in high-resolution (space and time) observation and prediction are permitting development of integrated services to meet the needs and requirements of cities. From a disaster risk perspective, a cascade of impacts (“domino” effect) may occur in a city because of an initial hazardous event impacting a densely populated area as infrastructure fails. *Integrated Urban Services* include: multi-hazard early warnings (e.g. severe weather, climate, flooding, air quality, health), products supporting building design, urban design, planning and zoning that require micro- (building, street)) to local (neighbourhood) to regional (city) climate information.

Provision of urban services is within the mandate of city governments. Current provision and application of hydro-meteorological, climate and environment urban services are within the capability and capacity of many relevant institutions. Given co-dependencies, the delivery of effective and efficient urban services requires integration, co-operation and collaboration amongst different services and sectors (professions, levels of government).

Results from two targeted surveys indicate that *Integrated Urban Services* already exist or are in preparation/development with various stages of maturity in many cities. Urban service requirements will be city-specific, driven by many local factors including natural and human-made environment, science, applications, capacity, capability, infrastructure, organizational structures, mandates and socio-economic situations. Indeed, the surveys identified that capabilities already exist to deliver urban services but there is often a lack of mutual-awareness. There is a need for more interaction in order to understand the requirements and capabilities of both the service providers and the service users (sectors). The challenge of local versus national mandates of roles and responsibilities can only be solved through collaboration, and cross-service and cross-sector approaches are needed. One size does not fit all. There are still considerable knowledge gaps, scientific and implementation challenges. The implementation of IUS will be an evolving process.

Declaration of Competing Interest

None.

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