

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

Article

Accepted Version

Creative Commons: Attribution-Noncommercial-No Derivative Works 4.0

Grimmond, S. ORCID: <https://orcid.org/0000-0002-3166-9415>, Bouchet, V., Molina, L. T., Baklanov, A., Tan, J., Schluenzen, K. H., Mills, G., Golding, B., Masson, V., Ren, C., Voogt, J., Miao, S., Lean, H., Heusinkveld, B., Hovespyan, A., Teruggi, G., Parrish, P. and Joe, P. (2020) Integrated urban hydrometeorological, climate and environmental services: concept, methodology and key messages. *Urban Climate*, 33. 100623. ISSN 2212-0955 doi: <https://doi.org/10.1016/j.uclim.2020.100623> Available at <https://centaur.reading.ac.uk/90581/>

It is advisable to refer to the publisher's version if you intend to cite from the work. See [Guidance on citing](#).

To link to this article DOI: <http://dx.doi.org/10.1016/j.uclim.2020.100623>

Publisher: Elsevier

All outputs in CentAUR are protected by Intellectual Property Rights law, including copyright law. Copyright and IPR is retained by the creators or other copyright holders. Terms and conditions for use of this material are defined in the [End User Agreement](#).

www.reading.ac.uk/centaur

CentAUR

Central Archive at the University of Reading

Reading's research outputs online

Integrated Urban Hydrometeorological, Climate and Environmental Services: Concept, Methodology and Key Messages

Sue Grimmond¹, Veronique Bouchet², Luisa Molina³, Alexander Baklanov^{4*}, Jianguo Tan⁵, K. Heinke Schluenzen⁶, Gerald Mills⁷, Brian Golding⁸, Valery Masson⁹, Chao Ren¹⁰, James Voogt¹¹, Shiguang Miao¹², Humphrey Lean⁸, Bert Heusinkveld¹³, Anahit Hovespyan⁴, Giacomo Terrugi⁴, Patrick Parrish⁴ and Paul Joe¹⁴

¹University of Reading, Reading, United Kingdom, ²Environment and Climate Change Canada, ³Molina Center for Energy and the Environment, USA ⁴World Meteorological Organization, ⁵Shanghai Meteorological Service, ⁶U. of Hamburg, ⁷U. College Dublin, ⁸The Met Office, ⁹Meteo-France, ¹⁰Hong Kong U., ¹¹Western U., ¹²Institute of Urban Meteorology, ¹³Wageningen U., ¹⁴WMO Consultant *Corresponding author

Abstract

Integrated Urban hydrometeorological, climate and environmental Services (IUS) is a WMO initiative to aid development of science-based integrated urban services to support safe, healthy, resilient and climate friendly cities. As part of this initiative, Guidance for Integrated Urban Hydrometeorological, Climate and Environmental Services (Volume I) has been developed.

The intent of the guidance is to provide an overview of the concept, methods and good practices for producing and providing the services cities require to respond to the hazards across range of time scales (weather to climate). Such services involve combining (dense) observation networks, high-resolution forecasts, multi-hazard early warning systems, and climate services. These services should assist cities in setting and implementing mitigation and adaptation strategies that will enable the management and building of resilient and sustainable cities. A multidisciplinary approach helps to meet the social-economic needs. IUS include research, evaluation and delivery with a wide agency participation from city governments, national hydrometeorological services, international organizations, research institutions and private sector stakeholders. An overview of the IUS concept with a few examples of good practices is presented. Key messages and recommendations are provided.

Given research agencies globally expect research to provide “Impact” and the United Nations’ 17 Sustainable Development Goals the urban climate research community will play an important role in helping to deliver IUS internationally. Between us our contributions are needed at all scales: to support local and national communities to deliver IUS and to identify critical research challenges that become apparent as IUS

1. Introduction

The World Meteorological Organization’s (WMO) cross-cutting urban focus initiative supports the implementation of the United Nations (UN) New Urban Agenda (HABITAT-III, 2016) and the Sustainable Development Goals (e.g. SDG11: Sustainable Cities and Communities) (UN, 2016) 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, and implies that services should be impact-based (WMO, 2016). These services consider the hazard, its effect and the exposure relative to the city. Governments, economic sectors 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 meteorological, climate, environmental and hydrological services as well as to reap the benefits from their application. The WMO, a United Nation Agency, provides the framework for such international cooperation. This intergovernmental organization’s 197 member states and territories (called Members) are mainly concerned with issues at a national and international level. However, these services may be provided by various member government institutes, universities and private companies. National governments may not have a mandate to provide urban services (unless through agreement). So, there may be many different urban service providers, including city governments, universities or consulting companies.

Defining disaster risk and forecasting hydrometeorological impacts is generally beyond the remit of meteorologists and hydrologists. 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 events are dynamic, it may be argued that National Hydrometeorological Services (NMHS) who have real-time dissemination capability are best equipped to issue impact based warnings (World Bank, 2013). As the effects of a hazardous event could affect several services simultaneously or in

sequence, and to convey a consistent and accurate message, integration or coordination amongst the services is also required.

The GURME (GAW [Global Atmospheric Watch] Urban Research Meteorology and Environment) Scientific Advisory Group has led the development of the *Guidance on Integrated Urban Hydrometeorological, Climate and Environmental Services* with collaboration across WMO and globally with relevant scientific sectors. This guidance will consist of three volumes: (i) addresses the concept and methods of an operational IUS (Grimmond et al., 2013; WMO 2018b) and is the focus of this paper; (ii) will provide examples and case studies; and (iii) will provide the IUS implementation guidelines. As urban decision-making is embedded in different organizational structures, partnership and cooperation relationships, this guidance will be relevant, a perhaps of model, to all IUS practitioners. In the future, these will be updated as needed.

Following a background section, the IUS concepts are outlined (section 3). Results from surveys of urban experts are used to illustrate aspects of the IUS (section 4). The key messages and lessons learnt are identified (section 5) prior to the final comments (section 6).

2. Background

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

Increasingly dense, complex and interdependent urban activities are rendering cities vulnerable: a single extreme event can lead to a widespread breakdown of a city's infrastructure through cascading downstream or "domino" effects (e.g. Figure 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 effectively. This is especially important when extreme events occur. For example, typhoons (hurricanes) impact cities around the world annually. Their impact causes a cascade of effects (Figure 1) including hazardous meteorological conditions (blue); first order impacts (green); and follow-on impacts (purple). The latter impacts may be rapid, as with traffic accidents associated with severe convection or take longer (days -weeks) to manifest themselves (e.g. in the form of plant disease). Obviously, the impacts shown in Figure 1 are not exhaustive and most notably there are socio-economic impacts to individuals, neighbourhoods, the city, region and often beyond.

If the various groups that need to respond rapidly and effectively are going to optimise their response, small area forecasts are needed that identify which part of the city region are most likely to be exposed to the hazards. Combining the forecast with detailed information about the city, the people and the infrastructure, allows these resources to be used most efficiently and appropriately. Using new communication methods with the available technologies within the IUS will ensure that short term response systems can rapidly receive, assimilate, predict and be used in enhanced predictions to provide and communicate tailored urban products to end users. IUS are intended to provide tools and products to support long-term planning to ensure that cities evolve appropriately in the future. As cities impact their surroundings in numerous ways, such as the largest sources of greenhouse gases (UN-HABITAT, 2011), sustainable cities will benefit not only the majority of the global population but also the global environment.

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

Generally, IUS have been developed from existing systems (infrastructure, mechanisms), including:

- weather prediction designed for warnings (e.g. hurricanes, 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 decadal 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, etc.) at national and regional scales

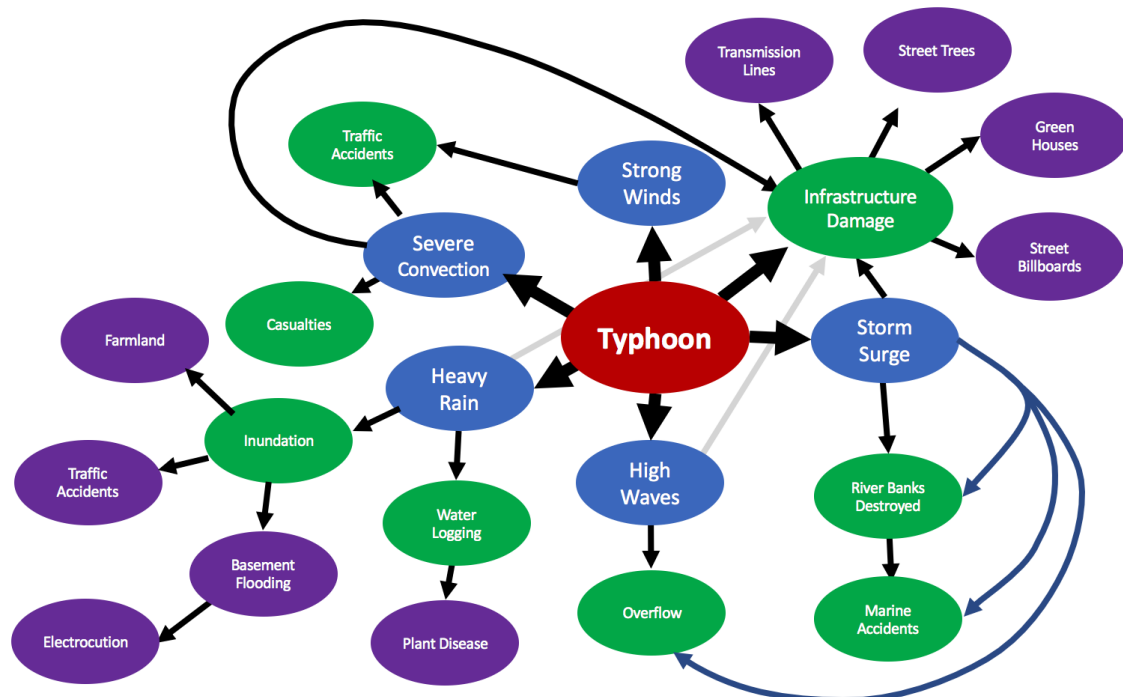


Figure 1: Demonstration of the domino effect for a typhoon event which produce multiple hydro-meteorological hazards (blue) which have immediate effects (green) with both short- and long-term impacts (purple).

3. Integrated Urban Services (IUS) Concept

IUS are inherently high resolution compared to the regional scale, with the goal to provide urban and intra-urban spatial information. Urban domains have a wide range of governance structures, with metropolitan areas often having contiguous or nearby cities. Extensive commuter regions may have created substantial infrastructure in rural areas (e.g. roads between centres, or transport routes to industrial settings). Hence, the urban areal extent must consider the regional context that (urban) planners need to address housing, transportation and recreation in the metropolitan region.

3.1 IUS Components

The implementation of IUS presents significant challenges but must make good use of already available (but not yet integrated) components (Figure 2), such as: 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; Beig et al., 2015).

Integration has three aspects: (i) internally to the NHMS, (ii) externally between NHMS and another agency, and (iii) multi-agencies. 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 to 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; Baklanov et al., 2010; WMO, 2015). As these issues to be addressed are inter-dependent, multi-disciplinary approaches are required to resolve the gaps, identify inconsistencies and work towards problem-solving.

Currently, the IUS concept for city and organization level activities remains un-formalised. Understanding of each other may create significant challenges Language to ensure mutual understanding of the needs and capabilities of the sectorial partners (Figure 2, top yellow box) is essential and requires early engagement to establish roles/responsibilities, gain knowledge of capabilities, current and potential requirements. Frequently, the process may be instigated following a significant event with economic and/or societal impact (e.g. a heatwave, storm or flood event) or an opportunity for partners to come together with a shared vision of needs (e.g., Olympics or through socio-political will).

At the heart of the system (from an NHMS or equivalent perspective) are observations, data, monitoring and modelling to generate useful information (post-processing) that can be used by the relevant partners (Figure 2, blue ellipse). Integration service providers and City Authorities create city-specific tailored products, transfer them in a timely and efficient manner to decision-makers and systems, so that impact-based warnings can be communicated effectively (Figure 2, grey boxes). Decisions may be for the short- or long-term.

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 emissions) are being developed. The articulation of weather, climate, hydrological and environmental services within an urban context are required to address these new challenges. It is critical that the end-users (e.g. public, specialists) understand the message especially when some form of warning is critical to successful mitigation. IUS should result in consistent cross-sector messages. However, experience has shown that understanding of warning messages, risk profiles, human response and effective risk communication is a challenge and requires attention (WMO, 2018c).

The final, but also the first, 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 (Figure 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, 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 (city authorities) training, education, as well as, a research and development process (Figure 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 task at hand.

For the various groups to function most effectively, they will need to combine and share information back and forth, ideally using common infrastructure. The performance of all stakeholders, including providers, can be substantially enhanced if systems, infrastructures and operational activities are established and maintained within a multi-purpose framework. Better functionality and reliability are achieved through more frequent activation of systems. It is expected that the synergies developed as a result of the integrated model will yield the same or more gains for the same costs due to efficiencies of the support of a broad spectrum of urban environmental management.

At the most basic level, an IUS should allow the end-user to receive an appropriate product that considers two or more of meteorology, climate, hydrology and air quality scientific services. These individual services are often delivered through different programs or even 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 of this endeavour is the multi-discipline, multi-service aspect. Some, if not all, of the critical urban applications are inherently integrated due to co-dependencies.

From the perspective of delivery, requirements, maturity and capacity, there will be a spectrum of approaches from highly coupled (weather, air quality, hydrology) probabilistic or deterministic modelling 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 urban weather, climate, hydrological and environmental services by cities and that are generally currently available by national or regional service providers. Depending on the specific requirements of a city, the capabilities and the resources available, the implementation of IUS is significantly different in each instance.

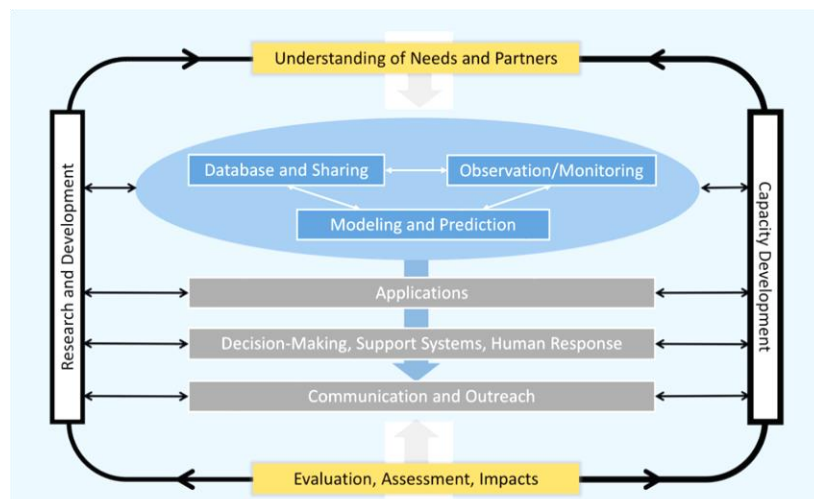


Figure 2: Components of an Integrated Urban Service (IUS) System

3.2 Challenges

The many challenges, described more fully elsewhere (WMO, 2018b), include:

- Understanding how to take and use observations in urban areas
- Representation of urban characteristics in models
- Urban scale and 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 geophysical hazards (e.g., dust storms, 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
- Targeted and tailored delivery platforms
- Impact based predictions (especially societal 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:

- geographical location (e.g., coastal, river, mountainous, polar, deserts and others) and
- geophysical factors (e.g., fault lines, volcanoes, dust storm, fire danger, space weather),
- climate conditions and the city environment itself.

Needs include monitoring and prediction for:

- severe weather – both summer and winter,
- heat and cold waves, extreme heat and cold,
- slippery roads,
- tropical cyclones and extra-tropical storms,
- droughts and water resources management to meet needs for food security,
- flash floods, changes in soil stability and landslides
- river and lake flooding from overflow,
- storm surges or swell, coastal inundation,
- sea level rise due to climate change,
- sand and dust storms,
- wild fires,
- air and water pollution,
- chemical and other harmful matter dispersion events and accidental releases,
- harmful UV radiation,
- pollen, other aerobiological allergens, disease

IUS should include societal **impact predictions** from natural and anthropogenic hazard (e.g. typhoons, major storms) or intense 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)) and have longer terms impact on humans and the ecology so need to be included planning.

4.2 Demonstration City Surveys /Examples

Different cities have or are preparing to develop IUS. IUS were initiated for various reasons and they have different levels of integration and provide different services. WMO has played a role in the development and/or demonstrations of some of these (e.g. Figure 3, Tang, 2006; Grimmond et al., 2014; Baklanov et al., 2018; Amorim et al., 2018). To understand the state and development plans of IUS for good practice (WMO, 2018b) exploratory surveys were conducted with 22 cities (Table 1). Not all respondents have IUS or IUS specific to a city (indicated by a blank) and some were in demonstration or pre-operational mode but contributed to the key messages.

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

Table 1: Demonstration cities (identified by GURME experts).

Key Messages

From the surveys, two core concepts were identified as key messages and are consistent with Disaster Risk Reduction recommendations (MHEWS; World Bank, 2013). They are related to:

- Governance: Establishing laws, regulations, and standardized operating procedures and mechanisms for a multiagency response – where roles and responsibilities are clearly identified, and
- Multi-Hazard Early Warning Systems (MHEWS): Providing operating procedures for early detection, briefing, and warning dissemination based on good observations and forecasts.

Other key messages include the needs of long term planning/design, of bridging scientific disciplines, of cross-jurisdictional (national, regional, urban) organizations, of open data infrastructures and communication. Highlights from the survey are briefly discussed.

Governance Example

The Shanghai Meteorological Service (SMS) of the China Meteorological Administration (CMA) has been changing from a traditional weather forecast/warning service to one with weather disaster risk forecasts integrated with a multi-hazard risk analyses (Tang, 2006; Dabberdt et al., 2013; Tan et al., 2015). Initially, the focus was on air

pollution episodes and high-impact weather at the World Expo 2010 site but was expanded to consider weather hazards that included the vulnerability and exposure of various sites enhancing 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”. It clarified the mandate of SMS in disaster risk reduction (DRR). SMS (weather) is now required to provide and receive support for specialized weather hazard and disaster warning services through 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 fifty member Shanghai Emergency Management Response Committee (EMC, Figure 3) was established. In February 2013, the Shanghai Emergency Warning Center was formed to improve the existing emergency responses (Figure 3). Thirty-six joint response mechanisms including co-operation agreements, warnings and action plans among 25 government agencies for Disaster Prevention and Mitigation were created. The action plans for weather disasters are issued by the General Office of SMS and each agency have defined responsibilities.

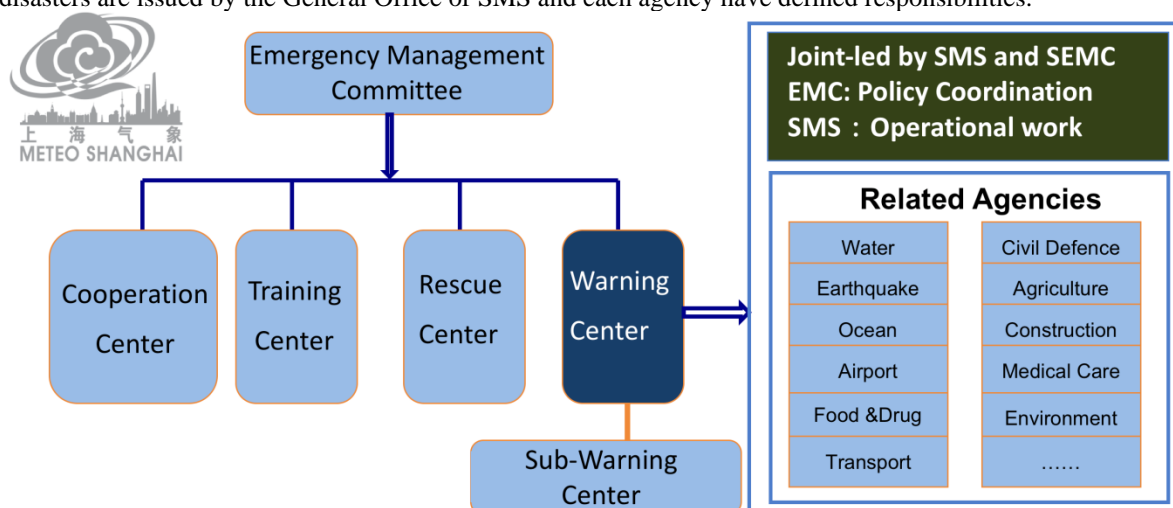


Figure 3: Emergency Management Structure of Shanghai. Courtesy of Xu Tang.

Urban Multi-Hazard Early Warning System 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 was 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. The case of health-related hazards, developed for Shanghai World Expo 2010, is depicted in Figure 4.

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

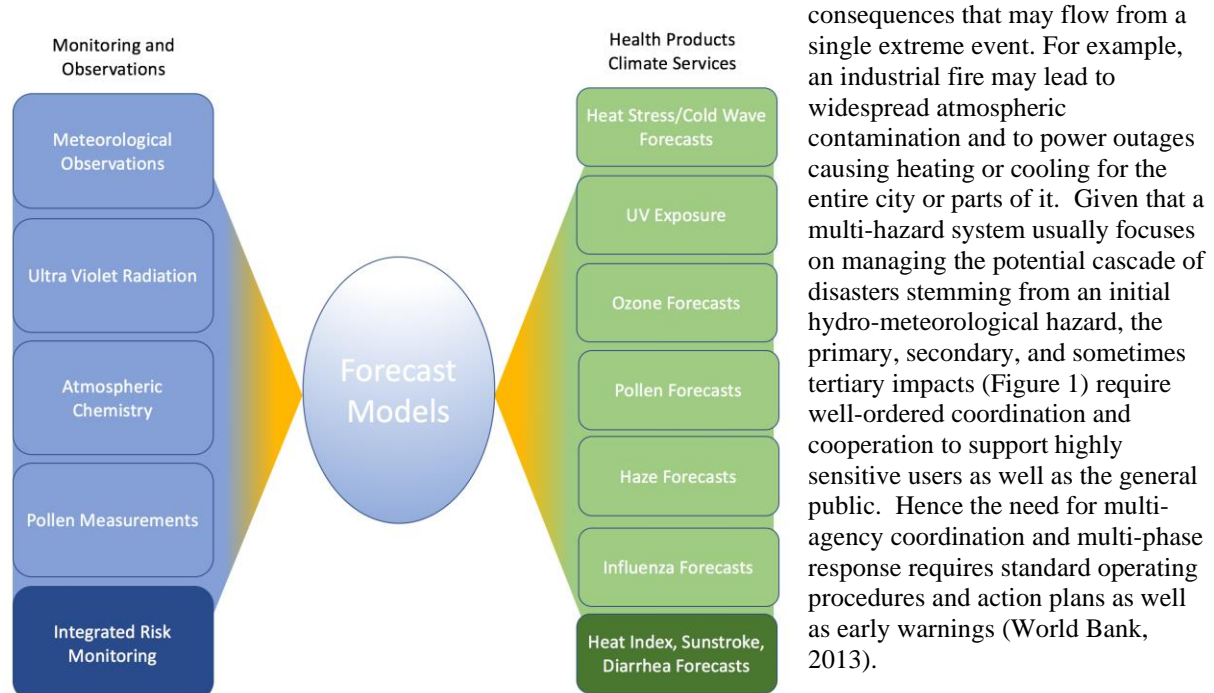


Figure 4: Shanghai Meteorological Services for Public Health. Integrated Risk Monitoring takes into consideration bacterial food poisoning, diarrhea diagnostics, trauma, influenza and heatstroke in order to produce specialize heat index, sun stroke and diarrhea forecasts for the Shanghai World Expo 2010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

Other Key Messages

Long Term Urban Planning: Urban designers need to know the effect of climate change at the urban scale for long term planning purposes. “Urban system models” are outputs and their interpretation are needed by urban planners at high spatial resolution (1 km or smaller; Amorim et al., 2018), that include representation of the urban fabric (Ching et al., 2018) and physical (both natural and anthropogenic) and human behaviour processes (Masson et al., 2013; Schoetter et al., 2017; Lemonsu et al., 2012). Cross-sector (e.g., from earth system scientists to urban planners) training is necessary to understand the complexity of the science. Figure 5 shows an example of the links from urban weather, climate, analysis and application.

Multi-disciplinary Initiatives: Earth system modeling is complex and highly technical. One of the barriers for effective integration is a lack of mutual understanding of capabilities, capacity, roles/responsibilities both within the services and the sectors. A common language and terminology were identified as key deterrents as well as new generation(s) of scientists need to be developed through multi-disciplinary conferences, training workshops and education programs.

Health Linkage: The Hong Kong Observatory (HKO) along with local universities and organizations (e.g. Senior Citizen Home Safety Association) collaborates with other government departments, tertiary institutions, and social enterprises in relation to the impact of weather on public health (WMO, 2018a; Shun and Chan, 2017) and include the development of the Hong Kong Heat Index (HKHI) for the hot and humid sub-tropical climate (Lee et al., 2016), studies of health impacts of extreme hot weather events (Lau and Ren, 2018; Wang et al, 2018), of seasonal variations of influenza (Chan et al., 2009), of the impact of weather and climate on and of the enhancement of services for the elderly (Mok and Leung, 2009; Wong et al., 2015; Lee and Leung, 2016).

After the severe acute respiratory syndrome (SARS) event in 2003, urban design measures were formulated and implemented into local planning and development (Ng, 2009; Ren et al., 2011) that included weather considerations and now used elsewhere (Ren et al., 2018).

Open and Accessible Data: Urban observations are collected by many agencies and stakeholders and for consistent, efficient and effective use, it must be open and accessible, with known quality, metadata and preferably the same format.

Communications/Product Dissemination: There are several aspects of communications: risk communication and dissemination. The multi-hazard concept must address the issue of issuing high impact warning of various hazards, their spatial and temporal scale, their risk and their impact to a variety of decision-makers, stakeholders and the public each with different expertise and requirements for levels for information (HIWeather, 2019).

Many forecasts have high spatial and temporal resolution (e.g. hourly for air quality and weather) and need to be targeted to at-risk individuals. Often email, text alerts and public-display boards are used for extreme weather conditions or air pollution event (Baklanov et al. 2018, CERC, 2019).

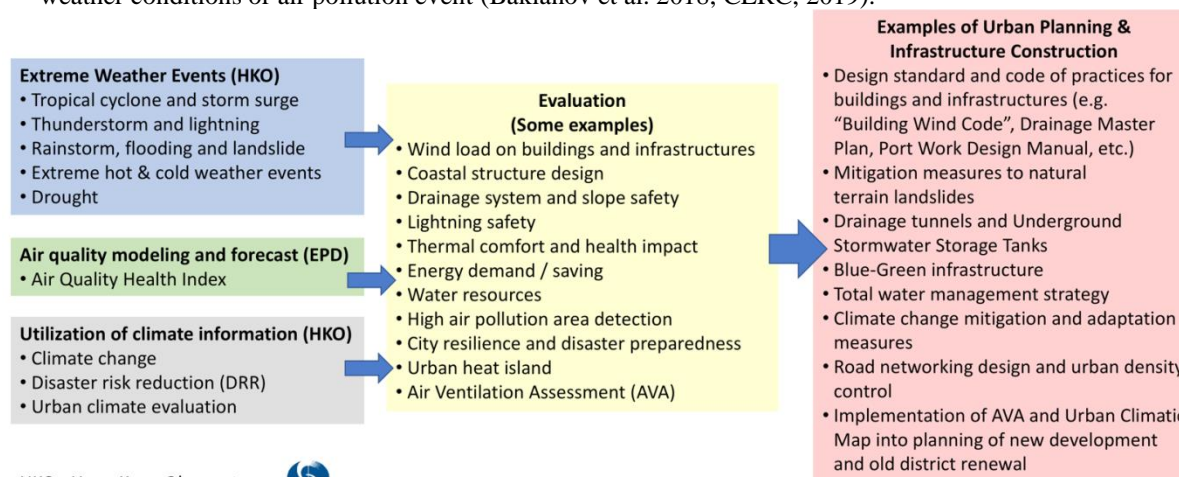


Figure 5: IUS for Urban Planning. This schematic shows the analysis sequence from hazardous event, evaluation within the urban context to impacts on long-term planning. Used with permission from Hong Kong Observatory.

5. Science/Knowledge Gaps

Each city has a unique set of hazards and risks that it faces and this will require tailored priorities when designing an IUS. The scientific effort is also heavily reliant on extensive sharing of capabilities and knowledge among city organizations that are undertaking comprehensive development. Although there is progress, there are open scientific and technological questions and include:

- **Understanding how to take and make use of observations in urban areas (for routine services or for research).** It is necessary to re-visit and address the issue of representativeness of high-resolution observations and siting in urban areas in street canyons, to above the city roofs and the whole three-dimensional urban boundary layer.
- **Representation of urban character in models.** The representation of the urban fabric/texture (e.g. surface type, building density, height, type, anthropogenic effects, surface roughness, sewer system) and the hydro-meteorological and environmental processes are dependent on the temporal and spatial scales of the model. This affects the data assimilation schemes, the uncertainty analysis, the approaches to ensemble and coupling of models.
- **Urban atmosphere scales requirements** (driving other sub-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. This will drive the development of tailored products and services.
- **Impact of cities on weather/climate/water/environment** e.g., air quality, water quality and quantity, ecosystem, urban heat island effect, disease transmission.
- **Impact of changing climate on cities** e.g., air quality, water quantity and quality, heatwaves, dust storms, wildfires and other high impact events that effect public health, economy and ecosystems.
- **Impact of changes to cities** (urbanization, land use, energy use, transport, GHG emission, densification, suburbanization, etc.) on urban and regional climate and hydrological patterns.
- **Major geophysical hazards – earthquakes/volcanic eruptions/space weather - interactions with meteorology.** Social and environmental consequences of these high impact events (e.g. on infrastructure including telecommunications, transport systems, housing, food/water supply, disease).

- **Development of Integrated Decision Support Systems** to efficiently present relevant, often uncertain and conflicting information, to technical experts to support warning decision-making taking into consideration, societal impacts, consequences and action statements. Understanding the impact on human response and behaviour is part of decision-making process.
- **Communication and management of risk.** Develop a common understanding and language is needed to bridge the disciplines; to articulate to decision makers 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;** e.g., user-oriented socio-economic evaluation of benefits and costs of system (avoided losses).
- **Understanding of the critical limit values** for meteorological and atmospheric composition variables with respect to human health and environmental protection.
- **New, targeted and customized delivery platforms** using an array of modern communication techniques, 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 can assist decision makers and end-user. It is important not to wait for a disaster to act. Various cities have or are preparing to develop IUS (Table 1) that can be used as an initial template for development. There are a wide range of lessons are 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 relevant stakeholders and users (agencies, the public, city government, private sector, businesses) from the beginning. Activities including developing mutual appreciation of the challenges, understanding capabilities and requirements, raising awareness, developing a common language and establishing lines of communications.
- It is necessary to understand and/or establish regulatory and institutional frameworks that clearly define government agency mandates, interactions, roles and responsibilities to enable creation and maintenance of IUS.
- Operational implementation should include cross-sector technology transfer mechanisms (research, development, test beds, capacity building) and cross sector service provision (warnings, advisories, risk and impact communications, capacity building, evaluation).

The recommendations are:

- Encouragement to lead and contribute in the promotion, development and coordination of IUS including knowledge transfer.
- Ensure that legal and institutional frameworks are in place in for partnerships within cities that clearly define government 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, businesses) from the beginning, including raising awareness and getting feedback.
- Further research, including multidisciplinary cross cutting studies, is needed to develop IUS
- Encouragement of wider accessibility of data via influencing ownership issues and technical support.
- Encouragement to showcase and demonstrate IUS projects for the benefit of all.

7. Concluding 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 United Nations has identified “*sustainable cities and communities*” as one of its Sustainable Development Goals (UN, 2016).

The *Guidance on Integrated Urban Hydrometeorological, Climate and Environmental Services Volume I: Concept and Methodology (WMO, 2018b)* articulates a vision to support this goal. This contribution provides only highlights of the concepts discussed in this document. Advances in high-resolution (space and time) observation and prediction are permitting these 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 extreme event impacting a densely populated area as infrastructure fails. *Integrated Urban Services* include multi-hazard early warnings (e.g., severe weather, flooding, air quality, health), to products supporting urban design, planning and zoning that require commensurate micro-climate information on the city-block scale. Urban services are within the mandate of city governments. The provision and application of hydro-meteorological, climate and environment urban services are within the current capability and capacity of relevant institutions. Due to co-dependencies, delivery of effective and efficient urban services requires the

integration, the co-operation and the collaboration amongst different scientific and technical disciplines, different urban professions, various levels of government, the public and the private sector.

Results from two targeted surveys indicate that the implementation of *Integrated Urban Services* are in preparation, development or at various stages of maturity. Urban service requirements are city-specific and driven by many local factors including: the natural and human-made environment, the science, the applications, the infrastructure, the organizational structure, the mandates and the socio-economic situation. 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. The challenge of local versus national mandates of roles and responsibilities can only be solved through collaboration. Multi-disciplinary and multi-agency approaches are needed. One size does not fit all and the implementation of IUS will be an evolutionary process.

This contribution focused on an overview of the capabilities, lessons learned and provided recommendations. There are still considerable knowledge gaps, scientific and implementation challenges and are the focus of future contributions.

8. Acknowledgements

The paper is prepared based on the WMO Guidance on Integrated Urban Hydrometeorological, Climate and Environmental Services (Volume I: Concept and Methodology). The authors thank to a number of WMO GURME SAG and Urban Expert Team members, participated in writing the IUS Guidance, members of the WMO Secretariat urban focal points team; and many NMHS colleagues and city experts that replied on the Surveys and developed and realized the UISS in different cities.

9. References

- CERC, 2019: <http://www.airtext.info/> Last accessed: 15 May 2019
- Amorim, J.H., Asker, C., Belusic, D., Carvalho, A.C., Engardt, M., Gidhagen, L., Hundedeha, Y., Körnich, H. Lind, P., Olsson, E., Olsson, J., Segersson, D., Strömbäck, L., Joe, P., Baklanov, A., 2018. Integrated Urban Services for European cities: the Stockholm case. *WMO Bulletin*, 67(2), 33-40.
- Baklanov, A., et al., 2010: MEGAPOLI: concept of multi-scale modelling of megacity impact on air quality and climate, *Adv. Sci. Res.*, 4, 115-120 doi:10.5194/asr-4-115-2010.
- Baklanov A, CSB [Grimmond](#), D Carlson, D Terblanche, X Tang, V Bouchet, B Lee, G Langendijk, RK Kolli, A Hovsepian **2018**: From Urban Meteorology, Climate and Environment Research to Integrated City Services *Urban Climate* **23**, 2018, 330-341 <https://doi.org/10.1016/j.uclim.2017.05.004> [ICSSP2](#)
- Baklanov, A., B Cárdenas, T Lee, S Leroyer, V Masson, L Molina, T Müller, C Ren, FR Vogel, J Voogt, 2019: Integrated urban services: experience from four cities on different continents, *Urban Climate*, (in review).
- Chan, Paul K.S., H.Y. Mok, T.C. Lee, Ida M.T. Chu, W.Y. Lam and Joseph J.Y. Sung, 2009: Seasonal Influenza Activity in Hong Kong and its Association with Meteorological Variation, *Journal of Medical Virology* 81:1797–1806.
- Ching, J. G. Mills, B. Bechtel, L. See, J. Feddema, X. Wang, C. Ren, O. Brousse, A. Martilli, M. Neophytou, P. Mouzourides, I. Stewart, A. Hanna, E. Ng, M. Foley, P. Alexander, D. Aliaga, D. Niyogi, A. Shreevastava, P. Bhalachandran, V. Masson, J. Hidalgo, J. Fung, M. Andrade, A. Baklanov, W. Dai, G. Milcinski, M. Demuzere, N. Brunzell, M. Pesaresi, S. Miao, Q. Mu, F. Chen, N. Theeuwes, 2018: World Urban Database and Access Portal Tools (WUDAPT), an urban weather, climate and environmental modeling infrastructure for the Anthropocene, 99, 1907-1924.
- Dabberdt, W.F., Baklanov, A., Carmichael, G.R., Chandrasekar, V., Grimmond, C.S.B., Nurmi, P., Petty, K., Wulfmeyer, V., Tang, X., Jalkanen, L., 2013. WMO GURME Workshop on Urban Meteorological Observation Design, Shanghai, China, 11–14 December 2011. WMO, Geneva (GAW Report No. 208). http://www.wmo.int/pages/prog/arep/gaw/documents/Final_GAW_208.pdf
- Grimmond, C.S., Gufran Beig, Barbara Brown, Greg Carmichael, Chen Baode, Fang Zheqing, Gerald Fleming, Agustin Garcia, Liisa Jalkanen, Haleh Kootval, Li Hong, Karla Longo, Mu Haizen, Peng Li, Shi Jianping, Tan Jianguo, Tang Xu, Deon Terblanche, Woo Wang-Chun and Zhang Jianlei, 2013: Establishing Integrated Weather, Climate, Water and Related Environmental Services for Megacities and large urban Complexes – Initial Guidance, WMO.
- Grimmond S, X Tang, A Baklanov, 2014: Towards Integrated Urban Weather, Environment and Climate Services. *WMO Bulletin*, 63, 1, 10-14
- Grimmond, C. S., Carmichael, G., Lean, H., Baklanov, A., Leroyer, S., Masson, V., Schluenzen, K. H., Golding, B., 2015: Urban-scale environmental prediction systems. Chapter 18 in the *WWOSC Book: Seamless Prediction of the Earth System: from Minutes to Months*, (G Brunet, S Jones, PM Ruti Eds.), (WMO-No. 1156), (ISBN 978-92-63-11156-2), Geneva, pp. 347-370.
- HABITAT-III, 2016: The new UN Urban Agenda. The document adopted at the Habitat III Conference in Quito, Ecuador, October 2016, <https://habitat3.org/the-new-urban-agenda>.
- HIWeather, 2019: The High Impact Weather Project, <https://public.wmo.int/en/projects/high-impact-weather-project-hiweather>
- Lau, K. K.-L., and Ren, C., 2018: Characteristics of Extreme Hot Weather in a Sub-tropical High-density City: Implications on the Heat-health Warning System, presented in the 10th International Conference on Urban Climate, New York, 6-10 Aug., 2018
- Lee, K. L., Y. H. Chan, T. C. Lee, William B. Goggins, Emily Y. Y. Chan, 2016: The development of the Hong Kong Heat Index for enhancing the heat stress information service of the Hong Kong Observatory, *International Journal of Biometeorology*, 60(7), 1029-39, DOI 10.1007/s00484-015-1094-7.

- Lee, T.C. and I. Leung, 2016: Protecting the elderly from heat and cold stress in Hong Kong: Using climate information and client-friendly communication technology, Case 3B, *Climate Services for Health: Improving public health decision-making in a new climate*. Eds. J. Shumake-Guillemot and L. Fernandez-Montoya. Geneva, WHO/WMO, 218pp.
- Lemonsu A., V. Masson, L. Shashua-Bar, E. Erell, and D. Pearlmutter, 2012 : Inclusion of vegetation in the Town Energy Balance model for modeling urban green areas, *Geoscientific Model Development*, 5, 1377-1393.
- Masson V., et al, 2013 : The SURFEXv7.2 land and ocean surface platform for coupled or offline simulation of Earth surface variables and fluxes, *Geoscientific Model Development*, 6, 929-960,doi:10.5194/gmd-6-929-2013.
- Mok, H.Y. and B. Leung, 2009: The impact of cold and hot weather on senior citizens in Hong Kong, *Hong Kong Meteorological Society Bulletin*, 19, August 2011.
- Ng, E., 2009: Policies and technical guidelines for urban planning of high-density cities - air ventilation assessment (AVA) of Hong Kong. *Building and Environment*, 44(7), 1478-1488.
- Ren, C., Ng, E., & Katzschner, L., 2011: Urban climatic map studies: a review. *International Journal of Climatology*, 31(15), 2213-2233. doi: DOI: 10.1002/joc.2237
- Ren, C., Yang, R., Cheng, C., Xing, P., Fang, X., et al., 2018: Creating breathing cities by adopting urban ventilation assessment and wind corridor plan – The implementation in Chinese cities. *Journal of Wind Engineering and Industrial Aerodynamics*, 182, 170-188. doi: <https://doi.org/10.1016/j.jweia.2018.09.023>
- Schoetter R., V. Masson, A. Bourgeois, M. Pellegrino, and J.-P. Lévy (2017) : Parametrisation of the variety of human behaviour related to building energy consumption in TEB (SURFEX v. 8.2), *Geoscientific Model Development*, 10, 2801–2831, doi : 10.5194/gmd-10-2801-2017
- Shun, C.M. and Chan, S.T., 2017: Use of Big Data in Weather Services – Past, Present and Future Challenges, *Symposium on Engineering and Operation Excellence through Technology and Innovation*, Hong Kong, 19 May 2017.
- Tan, J., Yang, L., Grimmond, C.S.B., Shi, J., Gu, W., Chang, Y., Hu, P., Sun, J., Ao, X., Han, Z., 2015. Urban integrated meteorological observations: practice and experience in Shanghai, China. *Bull. Am. Meteorol. Soc.* 96, 85–102.
- Tang, X., 2006. Managing disaster risk in a mega-city. *WMO Bull.*, 55 (4) (October 2006).
- UN, 2016: United Nations Sustainable Development Goals, <https://www.un.org/sustainabledevelopment/sustainable-development-goals/>
- UNDRR, 2015: Sendai Framework for Disaster Reduction 2015-2030. United Nations Office for Disaster Risk Reduction (UNDRR), 32p. <https://www.unisdr.org/we/inform/publications/43291>
- UN-HABITAT, 2011: Hot Cities: battle-ground for climate change. Report of United Nations Human Settlement Program, <http://www.unhabitat.org/downloads/docs/GRHS2011/P1HotCities.pdf> or mirror.unhabitat.org/downloads/docs/E_Hot_Cities.pdf
- Wang, D., Lau, K. K.-L., Ren, C., and Yuan, S., 2018: The Impact of Extreme Hot Weather Events (EHWEs) on Mortality in Hong Kong: A 10-Year Time Series Study (2006-2015), presented in the 10th International Conference on Urban Climate, New York, 6-10 Aug., 2018
- WMO, 2015: WWOSC book: Seamless Prediction of the Earth System: from Minutes to Months. Brunet, G., Jones, S., Ruti, P.M. (Eds.), World Meteorological Organization ((WMO-No. 418 1156), (ISBN 978-92-63-11156-2), Geneva).
- WMO, 2016: Guidelines on Multi-Hazard Impact-based Forecast and Warning Services, WMO No. 1150. https://www.wmo.int/pages/prog/www/DPFS/Meetings/ET-OWFPS_Montreal2016/documents/WMOGuidelinesonMulti-hazardImpact-basedForecastandWarningServices.pdf
- WMO, 2018a: Global Framework for Climate Services. <http://www.wmo.int/gfcs/>
- WMO, 2018b: Guidance for Urban Integrated Hydro-Meteorological, Climate and Environmental Services. Volume I: Concept and Methodology, https://library.wmo.int/index.php?lvl=notice_display&id=21512#.Xdr5Pi17HAJ
- WMO, 2018c: Multi-hazard Early Warning Systems: A Checklist: Outcome of the first Multi-hazard Early Warning Conference. WMO, https://library.wmo.int/doc_num.php?explnum_id=4463
- Wong, H. T., Y. L. Chiu, S.T. Wu, T. C. Lee & SCHSA, 2015: The influence of weather on health-related help-seeking behavior of senior citizens in Hong Kong, *Int. J. Biometeorol.*, 59(3), 373-6, DOI 10.1007/s00484-014-0831-7.
- World Bank, 2013: Reducing the Impact of Hydro-meteorological Hazards – National Meteorological and Hydrological Services and Emergency Response