# Good Practices in High-resolution Modelling for Integrated Urban Services

2023 edition

WEATHER CLIMATE WATER

WORLD
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WMO-No. 1313

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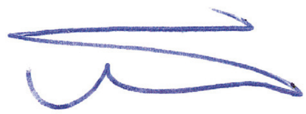
## FOREWORD

As the world continues to urbanize at an unprecedented pace, the need for sustainable and resilient urban development has become increasingly urgent. The rapid growth of urban populations and development has brought many challenges for cities worldwide, particularly in relation to sustainability and the provision of essential urban services. WMO continues to develop guidance, technical standards and services to support the implementation of the United Nations New Urban Agenda and Sustainable Development Goal 11 (SDG 11: Sustainable cities and communities).

One of the key areas of focus for the WMO Study Group on Integrated Urban Services has been the development of the present guidance document, *Good Practices in High-resolution Modelling for Integrated Urban Services* (IUS). This document provides an overview of the possibilities for using models to support the provision of urban services to stakeholders and inhabitants. Furthermore, the importance of expanding dedicated observing networks, improving models, disseminating information and training urban experts to advance the application of modelling systems for IUS is recognized.

Good practices are the result of the successful implementation of IUS in several cities with interdisciplinary coordination and cooperation between stakeholders. Success stories include various domain-spaecific applications, covering air-quality models, hydrological models, wave, tide and storm surge models, statistical models and artificial intelligence. These examples illustrate how to address the challenges posed by accelerating urban growth with an effective, value-driven service delivery strategy.

WMO is committed to supporting its members and other stakeholders in their efforts to build sustainable and resilient cities. *Good Practices in High-resolution Modelling for Integrated Urban Services complements the Guidance on Integrated Urban Hydrometeorological, Climate and Environmental Services* (WMO-No. 1234), Volume I: Concept and Methodology and Volume II: Demonstration Cities, consolidating valuable resources for those working in the field of urban services towards the implementation of the United Nations New Urban Agenda and SDG 11.



Prof. Petteri Taalas
Secretary-General, WMO

# PREFACE

More than half of the world's population lives in urban settings, and by the next decade, an estimated 60% of all people will become permanent residents of cities. Population growth drives the demand for infrastructure and services in cities worldwide, and puts enormous pressure on both the resources and the resourcefulness of local governments to sustain and improve integrated urban services (IUS).

The WMO Commission for Weather, Climate, Hydrological, Marine and Related Environmental Services and Applications (SERCOM), with the lead support of the Study Group on Integrated Urban Services (SG-URB), has developed the present *Good Practices in High-resolution Modelling for Integrated Urban Services* (WMO-No. 1313) to guide applied research, development and implementation of IUS in partnership with local governments, national meteorological and hydrological services, academia and the private sector.

The value placed on integrated urban services changes across regions based on priorities, impacts, opportunities and insights. However, high-resolution modelling is a flexible approach to building value in service delivery. This is because it allows stakeholders to better understand and predict the impacts of highly complex weather, water, climate and related environmental processes, by representing them in a simple, iterative, progressive and scientifically proven framework.

It is my hope that the good practices summarized in this publication will support innovation and implementation of IUS for cities around the world, and will contribute to the continued search for and improvement of actionable advice to protect lives and livelihoods in urban settings.

I would like to thank WMO Members and the Secretariat for the continuous support, encouragement and commitment provided for making this publication available to novice and expert practitioners alike.

Ian Lisk
President, WMO Commission for Weather, Climate, Hydrological, Marine and Related Environmental Services and Applications (SERCOM)

# EXECUTIVE SUMMARY

Recognizing accelerating growth of urban populations as well as cities and urban development, WMO works towards establishment of related guidance, technical standards and services relating to cities, in order to support implementation of the United Nations New Urban Agenda and Sustainable Development Goal 11: Sustainable cities and communities (SDG 11). The WMO Study Group on Integrated Urban Services (SG-URB) that operates under the Commission for Weather, Climate, Hydrological, Marine and Related Environmental Services and Applications (SERCOM) has developed the present *Good Practices in High-resolution Modelling for Integrated Urban Services* (WMO-No. 1313) to support high-resolution forecasting and predictions. It based this document on the successful implementation of integrated urban services in a number of cities and put this experience in the context of urban stakeholders' requirements.

The present guidance document aims to provide an overview of state-of-the-art possibilities for using models to provide fine-scale, even intra-urban information, to be incorporated into and improve urban services for city stakeholders and inhabitants. It explains the model's set-up and adjustments that are required to support specific urban services. A substantial part of the present document describes the connections or integration between different domain-specific models. It also guides decision-making on selecting and tailoring a high-resolution model for specific applications, on the kinds of additional input data and post-processing/integrated methods that will be needed and used, on the specific products and services to provide, and other relevant information.

The present guidance document first presents the models for the various domain-specific applications, including air-quality models, hydrological models, wave, tide and storm surge models, and statistical models (including those based on artificial intelligence). Consideration is then focused on the necessary data and observations, and the need for homogeneous approaches and standards. Finally, several examples demonstrate modelling approaches in support of integrated urban services in various cities. These examples illustrate the range of possibilities for building such services based on state-of-the-art urban models, providing good practices that can be replicated in other cities.

In order to advance the application of modelling system for integrated urban services in the future, there are four elements that play an essential role, namely: expansion of the dedicated observing networks; improvement of the models themselves; dissemination of information; and training of specific urban experts. Integrated urban services are still in an early stage: providing tailored urban services is the challenge being faced. Interdisciplinary coordination and cooperation between WMO Members, international organizations, government institutions, academia, users, stakeholders and the private sector needs to be built step-by-step as a key component of success.

# CHAPTER 1. INTRODUCTION

## 1.1 Challenges of modelling for integrated urban services

While cities cover only a small portion of continental surfaces, they are home to most of the human population and are the primary sites of human activity. Due to their small spatial coverage, they were historically, and still often are, overlooked in weather prediction systems and meteorological/hydrological services for users. The present guidance on good practices for high-resolution modelling for integrated urban hydrometeorological, climate and environmental services aims to present an overview of state-of-the-art models for fine-scale modelling that can provide intra-urban information to city stakeholders and inhabitants. Also, modelling for integrated urban services (IUS) allows for consistent, integrated provision of the meteorological, climate, hydrological and air-quality information to urban stakeholders for short-term preparedness and long-term urban planning. A complete description of IUS is available in the related WMO publication *Guidance for Urban Integrated Hydrometeorological, Climate and Environmental Services* (WMO-No. 1234), Volume I, with examples of implementation and application in various cities in Volume II.

The general structure of IUS includes the following (see WMO-No. 1234, Volume I): (i) Observation and monitoring; (ii) Data, databases and data sharing; (iii) Modelling and prediction capability; (iv) Tailored urban service applications; (v) Decision support systems to support decision-making; (vi) Products, service delivery, communications and outreach; (vii) Evaluation, assessment, societal impacts; (viii) Research and development; and (ix) Capacity development. The process of IUS tailoring is much more complex than simple improvement of post-processing of models. In fact, it requires a process of co-construction in which model developers receive support from and interact with other involved actors for co-design of specific outputs.

IUS may cover a wide range of domains and applications (urban weather and climate, water, transport, energy management, health, air quality, urban planning, city adaptation to climate change, mitigation strategy and so forth) that relate to and interact with each other. The systemic characteristics of urban systems induce further interactions between these areas of interest. It is therefore necessary to consider these coupled aspects when using models for IUS.

Meteorological services traditionally observe and forecast weather at the synoptic scale (cyclones, anticyclones, air-mass movements) and subsynoptic scale (meso-scale flows, such as sea breezes, mountain flows and so forth). Observing networks are then typically tailored to these scales. Historically, meteorological stations were used to support aviation activities and are therefore mostly located outside cities, often on airfields. Associated meteorological numerical weather prediction systems (including the recently developed convection-permitting atmospheric models that typically have grid meshes of the order of 1 km) are also tuned to represent these synoptic and mesoscale processes, and most often do not consider urban effects.

Only in the last 20 years has a tendency for linking weather stations with the measurement of air pollution emerged in several cities and towns. Yet, during that period, the collected weather measurements were not of good enough quality and thus were neither very useful nor representative of the urban-scale processes. Such measurements were often used only to calibrate the inflow in the air-quality measuring equipment. In some cases, meteorological services can provide input data for hydrological and air-quality forecasting services. Input data for hydrology may include observed and forecasted precipitation, evaporation, temperature, humidity and some other variables, while air-quality forecasting systems require seamless weather forecasting.

The situation is not much different when moving from weather forecasting to climate projections. Some meteorological services provide climate projections tailored to the territories most relevant to them, using global or regional climate models (for example, with 100 km or 10 km grid resolution respectively), yet fail to represent the features of the urban scale.

Therefore, services for cities are often limited to data that is selected from the closest (airport) station, or that is extracted from the nearest grid point within the numerical model (for example, automatic weather forecast; climate projection in the city region). Services that specifically account for urban effects remain rare and are often specifically developed for a given city. They are therefore difficult to universalize and, in some cases, impossible to transfer directly to other urban areas. This deficiency may be due to the fact that, along with the atmospheric or hydrological processes in IUS, access to fine-scale data that describe the city itself is also required, and the requirements of the end user may vary.

The present guidance aims to inform users: how best to select and tailor a high-resolution model for specific applications; what kinds of additional input data and post-processing and integrated methods are needed and/or used; and what specific products and services to provide. The guidance covers urban heat island (UHI) impacts as well as other phenomena occurring in urban areas, including urban hazards. These may be caused by other meteorological events such as thunderstorms, tornadoes, tropical cyclones, heatwaves, cold waves, flash floods, landslides, river and lake flooding, drought, sea-level rise, coastal inundation, dust storms, wildfires, and air and water pollution episodes. The main focus of the document is on how to use and customize high-resolution models for IUS.

## 1.2 Spatial and temporal scales

The high-resolution models that will be considered here are those which cover the hydrometeorological, climate and air-quality related fields and which are intended to be used to produce IUS for resilient and sustainable cities.

Spatial scales covered by IUS are relatively diverse (see Figure 1), often well outside of the scales usually explored by national meteorological and hydrological services (NMHSs). These scales are driven by the needs and requirements of various users. Because these users are interested in territories directly linked to the city (upon which may be located infrastructure, inhabitants, buildings, activities, rivers and water networks, and so forth), the spatial scale of the targeted IUS can be very small (for example, a neighbourhood, a transport line or network, or blue or green infrastructure). The largest scale considered will be that of the city or agglomeration – a scale that is generally considered very small from the point of view of an NMHS. For example, the newest numerical weather prediction systems operate on a kilometric scale, and regional climate models have a scale of tens of kilometres, too large to resolve city features or the city itself. Similarly, hydrology services are based on the hydrological catchment models, which represent a larger scale than the city itself. Transport and chemistry models produce air-quality forecasts at up to 10 km at their finest scale, although a relatively dense measurement station network within cities may be available.

IUS require coupling of these different scales (and associated processes), which raises scientific, technical and acculturation challenges. Scale discrepancies make this even more difficult. These constraints in numerical modelling can explain the lack of advances up until now in services provided by NMHSs to users in cities.

The items in Figure 1 divide naturally into two temporal scales related to IUS: the warning timescale, and the urban planning timescale. One can consider that a given IUS does not treat the two temporal scales at once.

– The warning timescale, typically from hours to a few days, is associated with IUS that aim to protect the population or infrastructure in case of an emergency such as an air pollution episode, a hurricane or a flood event (or coupled such catastrophic events). From the meteorological point of view, such warnings are related to observations, nowcasting and short-range forecasting.

– The timescale for urban planning is much longer. Urban planning can be related to climate timescales, in the sense that urban planners take climate change issues into consideration,

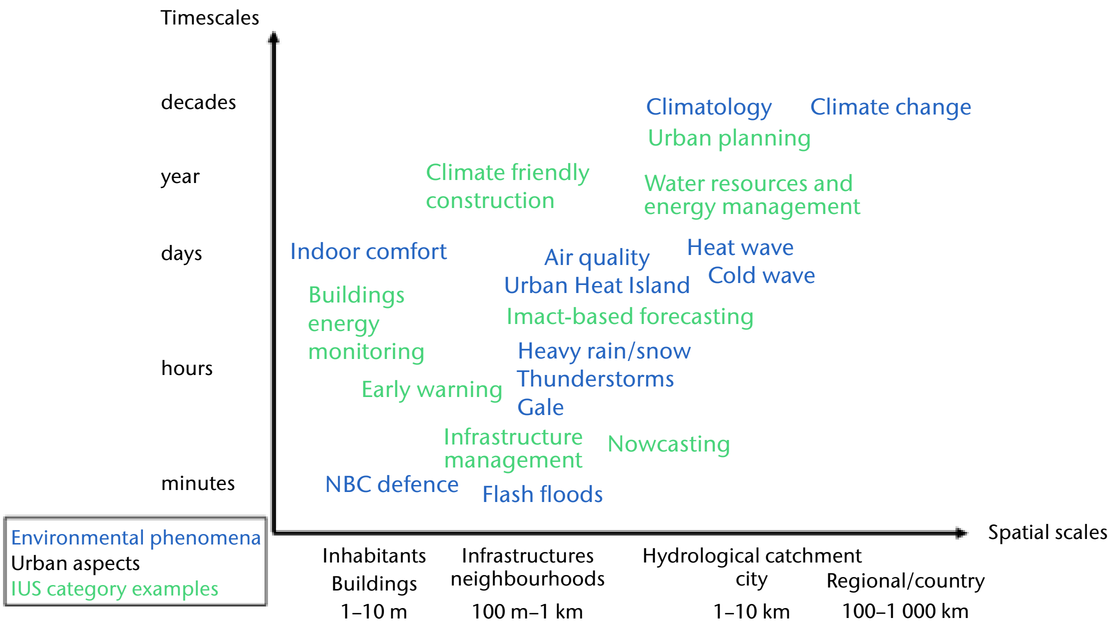



**Figure 1. Link between temporal and spatial scales of environmental phenomena and of some categories of IUS**

*Note:* (NBC = Nuclear Biological and Chemical Threats and Hazards)

although urban planning is typically shorter than physical climate timescales and is more aligned with the typical urban stakeholders' planning timelines: 5 to 10 years, and at most up to 2030–2050.

These two temporal scales can be linked: the (short-term) early warning timescale models can also be used for long-term urban planning, by studying past extreme events.

The integration of information about past events with modelling for long-term planning in a regional context has been advanced recently by the storylines or narrative approaches for decision-making (see for example Shepherd, 2019; Houet et al., 2016).

## 1.3 Services are different from one city to another

The experiences implementing IUS in cities to date suggest that in order to develop recommendations for IUS implementation, a detailed analysis is needed of a number of factors which would define and help select future best practices in cities representative of different continents and countries (WMO-No. 1234, Volume II). From the four cities examined in Baklanov et al. (2020), a potential list of factors is:

- Socioeconomic conditions (city's geographic size, size of the population, isolated or agglomeration, economic condition and so forth);
- Existing environmental activities (adopted climate action plans, activities of non-governmental organizations and citizens, mitigation and adaptation commitments, membership in city networks such as the C40 or International Council for Local Environmental Initiatives (ICLEI – Local Governments for Sustainability));
- Levels of infrastructure (for example, transport and communication, environmental management, monitoring and response mechanisms for environmental issues and concerns, according to the needs);

- Location, including continent, climate zone, weather classification and position in the landscape (inland, coastal, mountains, desert and so forth);
- Governance structure, policymaking powers (local, regional, national), responsibility pathways for addressing urban hazards, role of hydrometeorological service, management scheme of overall airshed;
- Types/combinations of hazards, focus on early warnings and/or long-term planning;
- Existing practices in the realization of integrated urban services (two or more hazards/elements integrated);
- Levels of integration of urban services: observation, infrastructure, modelling, decision-making.

It is very unlikely that a given IUS will be able to address all the needs of a city. Nevertheless, it would be preferable for any conceived IUS to be able to take into consideration as many of the various aspects listed above as possible. An ideal numerical model should be applicable to many types of cities, independent of their location, continent and position in the landscape, as long as appropriate input parameters and underlying data are provided. Models based on full-physics description have the ability to cover a wide range of urban specificities (Masson et al., 2020b). This can help to build models for IUS that are relatively transportable from one city to another, at least in similar climate zones, although targeting local aspects or specific user needs may still be necessary.

## 1.4 Identification of the level of integration and urban processes to be considered

As stressed in the *Guidance on Integrated Urban Hydrometeorological, Climate and Environmental Services* (WMO-No. 1234), Volume II, the sophistication of IUS can be evaluated through analysing the degree of cross-service and cross-sector integration. Such an analysis has been applied to a number of cities (WMO-No. 1234, Volume II) to classify each one according to the maturity of an IUS. This analysis demonstrated that integration, in many cases, does not occur at the level of the models (for example, fully online coupled/integrated models are seldom used), but that integration is possible at the other levels (data exchange, services provision) and depends on the end-user needs.

The first steps for such integration were demonstrated by the urban air-quality community. For example, integrated systems for forecasting urban weather, air pollution and population exposure were reported for seven European cities in 2007 (Baklanov et. al., 2007). More comprehensive integration would require more processes and their interactions to be taken into consideration when designing the IUS (for example, dependence of ozone production/destruction at a small scale on the positions and state of the urban vegetation and transport).

However, adding more integration in the models requires more technical expertise and advances in coupling between different elements of models. This leads to a higher demand for data, in the absence of which it will not be possible to produce the complex services. A recommended approach would therefore be to define from the outset the type of IUS that will be possible, given all the scientific and external constraints. It is important to recognize that building IUS requires close cooperation between hydrological and meteorological services and air-quality authorities. Several examples of how choices have been made in various cities and of the approaches taken to model selection are illustrated in later sections.

# CHAPTER 2. ADJUSTMENT OF MODEL COMPLEXITY FOR TARGETED SERVICES

Numerical models applied to describe environmental conditions within cities aim to provide forecasts (or to reproduce past events) of many variables linked to meteorology, climate, hydrology, air quality and other domains. Such models require the simulation of many interacting processes. The environment has additional urban-specific complexities, driven by physical, biophysical or socioeconomical small-scale processes, compared to larger scale numerical weather prediction (NWP) models. The focus of Chapter 2 is on describing high-resolution models and the modelling requirements for their application in urban areas, including utilization of statistical and artificial intelligence approaches.

## 2.1 Meteorological models

### 2.1.1 *Introduction*

NMHS scientists have an in-depth knowledge of the nature of the numerical models used for weather prediction and climate projections. These models are based on a discretization of the atmosphere with a grid on a given geographical domain, ranging from the whole Earth in the case of global models to the surrounds of a city in the case of high-resolution models. The equations of atmospheric fluid dynamics are solved on this grid, and a series of sub-grid physical processes are described using dedicated schemes (for example, turbulence, radiation, microphysics). Surface models (including for cities) are needed for the boundary condition at the bottom of the atmosphere. Various types of atmosphere observations can be incorporated into the atmospheric model at the beginning of the simulation through data assimilation. These aspects are well known to the meteorological community, but this is not the case for other scientists and city stakeholders. It is therefore recommended that these aspects be presented (even very briefly) to partners when developing IUS in order to make it clear that an atmospheric model is not a simple statistical model, but is one based on the physical laws of the atmosphere.

Computational fluid dynamics (CFD) models are not addressed in detail in the present guidance. These models can be applied to microscale domains and can be used to support studies at the building scale or at small neighbourhood scales. Such models are widely used in fluid mechanics, which is important to many scientific fields. The reader can refer to existing best practice guidance for the CFD simulation of flows in the urban environment (for example, in Franke et al., 2007).

### 2.1.2 *Model requirements for urban applications*

High-resolution modelling of weather and climate in cities requires the use of a state-of-the-art atmospheric model suitable for the targeted resolution. This implies, in particular, that for horizontal grid spacing of less than 1 km, the grey zone issue must be taken into consideration when representing the atmospheric boundary layer. This zone defines the spatial resolution, typically around 250–500 m, outside of which the turbulent processes are either entirely parameterized (for large mesh sizes) or individually represented by the advection (for small mesh sizes). Within the grey zone, it remains unclear how to treat the transition from one modelling approach to the other, and the physical processes must be treated with caution.

To run an urbanized atmospheric model, it is essential to correctly simulate the interactions between the urban surfaces and the atmosphere. Traditionally, urbanized surfaces are represented in atmospheric models (still used by many) using a soil-vegetation-atmosphere transfer model. This model is commonly used for representing vegetated surfaces, however in the urban setting, rocks replace vegetation at the location of the city. This approach represents the high roughness and imperviousness (and reduction of evaporation) of the urban cover, although it does have its limitations. It only reproduces roughness and daytime warming

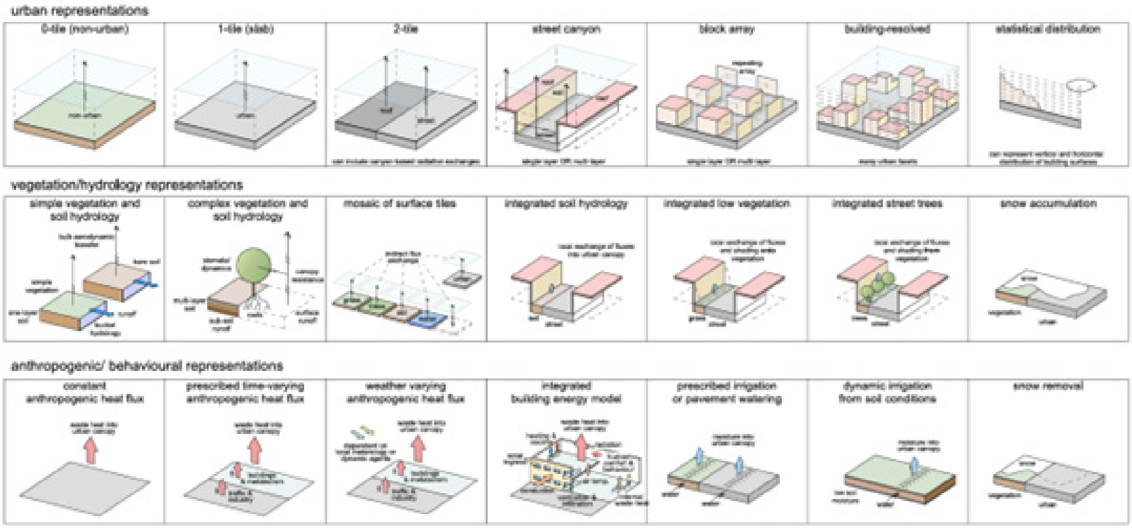



**Figure 2. Types of urban canopy models. The first row presents the possible geometrical assumptions (only one activated at once). The second row presents the possible options for urban vegetation and hydrology (many options can be cumulative). The third row presents the possible representations of the anthropogenic effects (many options can be cumulative).**

*Source:* Lipson et al. (2022)

(sometimes excessively so), without reproducing urban canopy features caused by high heat storage in the urban fabric (coming from solar heating and increased by the imperviousness of the materials and the three-dimensional (3D) shape of the city, inducing radiative trapping).

The use of an urbanized atmospheric model is especially needed for the evaluation of processes where the city and local meteorology strongly interact. Some examples include the urban heat island studies, wind fields and ventilation issues, weather forecasts and even very high-resolution climate studies. Urbanizing an atmospheric model can be done using so-called "urban canopy models" that represent these processes within a simplified 3D urban geometry (often urban canyons or urban blocks).

To describe urban vegetation, use of biospheric models embedded into the urban canopy model is recommended, in order to accurately simulate the water/energy fluxes. Some such models provide information on $CO_2$ uptake (linked to climate change mitigation issues) or emissions of volatile organic compounds (linked to air-quality issues). However, these models are still mostly in the research phase.

As presented in Figure 2, different types of urban canopy schemes can be used, including: for modelling of entire cities up to neighbourhood scales, single-layer and slab/bulk-type urban canopy schemes and multilayer urban canopy schemes. High-resolution here refers to grid meshes of 100 m to 1 km horizontally. For very small areas (typically less than 1 km$^2$) and short periods (a few days), it is also possible to use obstacle-resolved microscale models (at a horizontal resolution of a few metres) that represent details of the flow between individual buildings. A recent review of urban canopy models (UCMs) was undertaken by Garuma (2018).

Building energy modules (BEMs) also exist in some state-of-the-art UCMs. They are based on the building's energetics, with a description of the radiative and convective interactions inside the building (some simplification of the number of levels or rooms is often made) and of the incoming solar radiation through windows. These BEMs allow energy consumption estimates from domestic heating or air conditioning for energy-oriented IUS. It is also possible to include in BEMs solar panel parameterizations on roofs and to evaluate both the energy production and the impacts on the urban heat island (Masson et al., 2014a; Zonato et al., 2021). However, BEMs require a large amount of data to describe the building fabric, which is not easily available.

## 2.2 Air-quality models

### 2.2.1 *Introduction*

Current scientific advancements in NWP and air-quality forecasting have been made using 3D integrated meteorology-chemistry modelling systems and advanced data assimilation techniques, combined with near-real time observations. Certainly, these modelling systems are complex and may be difficult to adopt for real-time operational implementation. Recognizing the urgent need for the successful implementation and application of 3D numerical models for chemical weather and air-quality forecasting (CW-AQF), WMO published in 2020 the *Training Materials and Best Practices for Chemical Weather/Air Quality Forecasting* (ETR-No. 26) It is expected that broad adaptation of these practices could help with the utilization of 3D CW-AQF models in combination with NWP for operational forecasting, early warning, policymaking and action-taking to reduce air pollution and to minimize its associated effects on human health. This modelling can also provide a basis for efficient measures to combine air-quality and climate co-benefits.

The uncertainty and sensitivity of air-quality simulations depends upon the following aspects:

- the capability of reproducing the local-scale meteorological conditions of the urban boundary and canopy layers;
- the representativeness of the emission inventory to reflect the dynamic changes of sources;
- the gaseous and aerosol reaction chemistry schemes that reflect the formation and transformation of pollutants;
- the physical-chemical interactions with the atmosphere.

For air-quality models at various geographical scales – the global scale, regional scale (<200 km), urban scale (5–50 km), microscale (<2 km) and building scale (<100 m) – the complexity in the modelling (especially for the meteorological processes, emissions, and the physical-chemical interactions with the atmosphere) grows dramatically as the scale becomes finer (Kadaverugu et al., 2019). Currently, the most common air-quality models in use are at the regional scale.

### 2.2.2 *Model requirements for urban applications*

In cities, urban-scale air-quality models are preferred, as they cover small areas with a very high resolution to provide enough information to be as useful as possible. Urban-scale air-quality models can be used to simulate pollutant distribution at a small scale following such urban phenomena as the heat island, the urban canopy, or detailed street canyon streams, making this type of model more appropriate for air-quality and health-related warnings. Use of urban-scale air-quality models would help decision makers to mitigate the occurrence of acute air pollution episodes and to reduce the associated impacts on agriculture, ecosystems and climate.

To facilitate air-quality model application at the urban scale, the representation of meteorology, emissions and physical-chemical interactions with the atmosphere should be further emphasized and strengthened, based upon former experiences with regional-scale applications. Coupling between different processes is essential.

There is of course some level of uncertainty associated with predictions generated by urban-scale air-quality models. The first area of uncertainty is related to representation of urban meteorology. Meteorology is key in forecasting episodes of deteriorated air quality. Therefore, urban air-quality models must be unbiased in terms of NWP/meteorological models as well as air-quality prediction. This leads to online and offline coupled NWP and atmospheric chemistry models for urban areas (see Figure 3). In addition, it is important to simulate the urban landscape dominated by anthropogenic and natural surfaces, both of which have distinct hygrothermal characteristics.

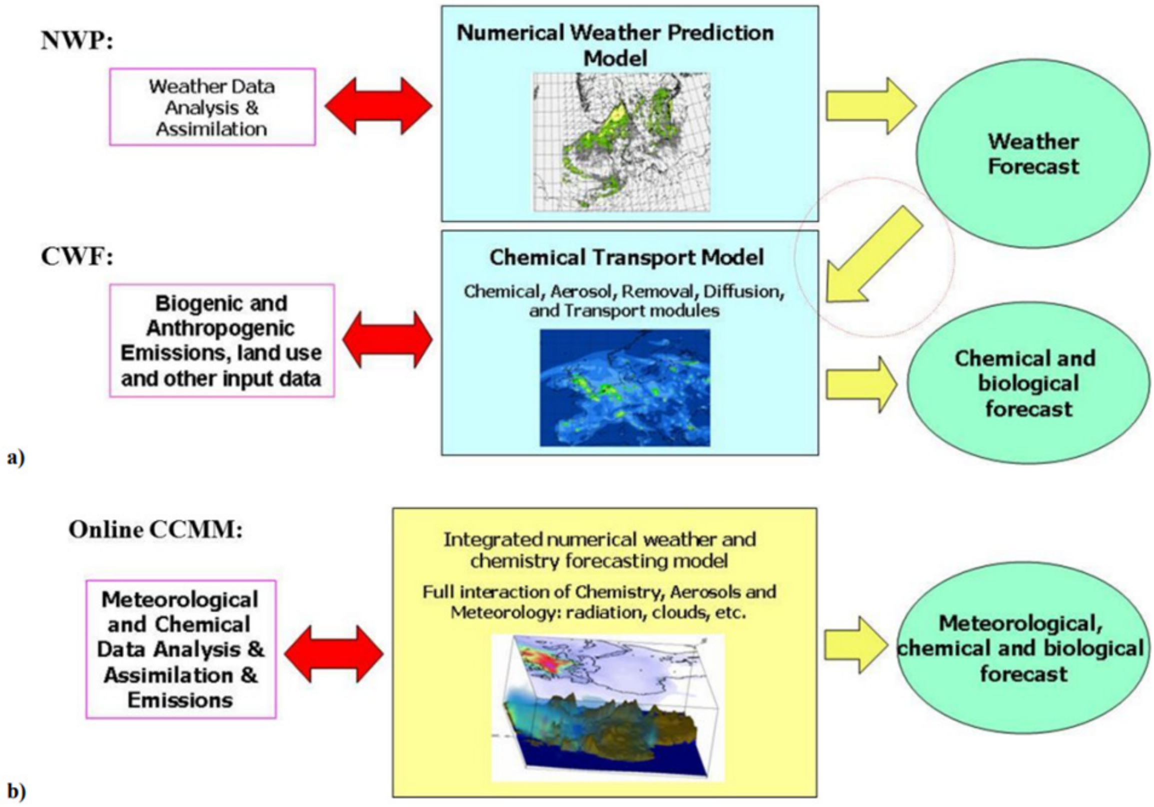



**Figure 3. Schematic diagram of (a) offline and (b) online coupled NWP and chemical weather forecasting (CWF) modelling approaches for atmospheric composition and meteorology simulation**

*Note:* CCMM = Coupled Chemistry and Meteorology Models
*Source:* Baklanov, 2017

To tackle this issue, both high-resolution geospatial data input and parameterizations to resolve transport of heat, moisture, radiation and momentum should be strengthened in urban-scale air-quality models, in order to accurately represent the surface energy budget.

The second uncertainty in urban-scale air-quality models derives from the so-called "bottom-up" emission inventories, in terms of the total amount of emissions as well as the spatial-temporal representativeness of gridded emission input. This is related to the fact that emission inventories are based on statistical methodology. It is well understood that the severe air-quality pollution in urban areas is caused by excessive anthropogenic emissions in unfavourable meteorological conditions (strong stagnancy, poor dispersion and so forth). Due to the methodology used to generate the gridded emission inventory (Zhang et al., 2009), the uncertainty grows at urban and intra-urban scales: the total emissions are usually estimated from national statistics using emission factors (for example, pollutants per unit fuel consumption, unit production) and certain proxy variables (such as energy consumption by fuel types, or power/industry product amounts). The total amount is then spatially allocated by activity/population, and temporally allocated by the features of diurnal activity patterns to match the high-resolution modelling requirements. Other uncertainties related to anthropogenic emissions come from special fine-scale urban sources that are not taken into account in the traditional inventory, including, but not limited to, waste burning, road dust and off-road engines (for example, construction).

In developed countries, national emission inventories are well-established and updated frequently. For example the United States Environmental Protection Agency produces a National Emissions Inventory, including for point (power, industry), vehicle (https://www.epa.gov/moves), residential and agriculture sources. This gridded inventory, at 4 km resolution, has been made publicly availably every three years since 2005 (https://www.epa.gov/air-emissions-inventories/national-emissions-inventory). Anthropogenic emission inventories in other countries such as China are mostly created by research communities. As a result, large uncertainties lie not only in the total amount of emissions but also in terms of the spatial-temporal allocation processes for urban-scale air-quality model application in those regions. High spatial-temporal resolution emission input based on local specific emission investigation and management is essential for urban-scale air-quality models.

The third uncertainty is related to the description of physical-chemical interactions within the atmosphere. This third uncertainty is the most challenging for urban-scale air-quality model application. Aerosol can modulate and interact with meteorological conditions through aerosol-radiation interaction (ARI) and aerosol-cloud interaction (ACI) (Zhong et al., 2018; Lou et al., 2019; Liu et al., 2018; Miao et al., 2019; Ding et al., 2016). With heavy fine particulate matter ($PM_{2.5}$) pollution, incoming solar radiation below the aerosol layers is reduced by aerosol scattering and light absorption. This leads to decreases in maximum surface temperatures and a stabilized thermal stratification of the lower atmosphere, which further aggravates the pollution. Aerosol also plays a role in changing cloud lifetimes by forming cloud condensation nuclei (CCN) and ice condensation nuclei (ICN), which cause the redistribution of precipitation. Although the importance of aerosol in a changing climate has been considered in global NWP, the meteorological impacts of aerosol-radiation-cloud interactions on regional- or city-scale NWP or on air-quality models have not yet been well considered. Therefore, neglecting ARI/ACI in urban-scale air-quality models would bring uncertainties in model simulations, both for pollutants and meteorological parameters. Despite recent progress in NWP when handling air quality in urban areas, the urban effect parameterizations, particularly the physical-chemical interactions within the atmosphere at the urban scale, are still under development. In order to overcome such uncertainties, tight coupling between physics and chemistry parameterization would be necessary, such as the consideration of aerosol-radiation-cloud interactions, of mixing of chemical species in boundary layer processes and so forth. From this point of view, coupled meteorology-chemistry models would be preferable for applications at the urban scale.

In order to reduce the large uncertainties in air-quality simulation and improve forecasting skill, data assimilation (DA) methods, which combine observations and numerical air-quality model output, have received increasing attention. Various DA approaches have been applied, including aerosol initial concentration DA (Liu et al., 2011; Sun et al., 2020) by three-dimensional variational data assimilation (3Dvar), precursor and primary emission updating based on an ensemble Kalman filter (EnKF) (Miyazaki et al., 2013; Peng et al., 2017) and four-dimensional variational data assimilation (4Dvar) (Guerrette and Henze, 2017). To improve DA performance and air pollution forecasting at the urban scale, more high-temporal surface observations from local monitoring networks are required.

## 2.3 Hydrological models

### 2.3.1 *Introduction*

Urban hydrology pertains to the hydrological processes that occur within an urban environment. These include the specific aspects that affect precipitation, surface run-off, groundwater, receiving water bodies (lakes, reservoirs) and water flow in the sewer system infrastructure. Understanding urban water dynamics requires modelling strategies capable of assessing and responding to the support needs of operational activities, flood risk management, environmental assessment, urban planning and other urban services. High-resolution hydrological urban models provide a better understanding of the water dynamics in cities. These tools, also known as urban flood models, are numerical models that have the capability of representing the main hydrological processes (rainfall-run-off transformation) and hydraulic processes (transport on rivers and streams, streets and the sewage network).

There are multiple interactions between people and urban infrastructure and water dynamics at various spatial and temporal scales. High-resolution urban modelling requires a rainfall description with high levels of temporal and spatial precision and a detailed representation of the physical system. Depending on the service, it is necessary to detect the main intervening processes and their scales for an adequate simulation and response (in terms of precision and computational effort).

### 2.3.2 *Model requirements for urban applications*

In principle, high temporal and spatial resolution models should more accurately simulate the fast dynamics of urban basin processes and their interactions. According to the type of service required, urban hydrological and hydraulic high-resolution models can mainly be characterized by their approach: either overland flow or dual-drainage system models. Typically, urban hydrodynamics are studied using either 2D hydraulic modelling (overland flow), or 1D/1D or 1D/2D (dual-drainage system, depending on the overland flow approach) hydraulic modelling spatial scales (Figure 4).

The urban surface run-off is commonly a shallow-water flow. Overland flow models are developed based on shallow-water equations (SWEs) and can provide detailed flood information in urban areas, such as the distributions of flood water depths and velocities.

Dual-drainage system modelling considers not only the flow through the sewer system but also the surface. This system has two parts: a minor system (with conduits, drains, manholes and so forth) and a major system (with channels, streams/rivers, streets and control structures).

Both systems require a detailed spatial and temporal description of the rainfall. In addition, overland flow models need an accurate digital elevation model (DEM) for their set-up. Full dual-drainage system modelling requires the best possible description of the physical system: detailed topography, street network dimensions, channel/streams/rivers geometry, and complete characterization of the sewer system.

Detailed full hydrodynamic overland flow or 1D/1D and 1D/2D dual-drainage models are well-established approaches that simulate urban hydrodynamics. These models, even in urban applications, are widely used by multiple users across academic, consultancy and governmental sectors. However, these models may not be suitable for operational use due to high computational costs (for example, real-time applications or forecasts ensembles). Therefore, the need for low computational cost models supported the development of simplified and surrogate models of the dual-drainage system. For this task, two general modelling approaches can be considered: (i) the use of physically-based models of lower precision, in which some of the processes of the original model are simplified (for example, cellular automata (CA) models); and (ii) the development of surrogate or data-driven models that emulate the responses of the original model without relying on the physics of the problem (for example, artificial neural networks (ANNs)).

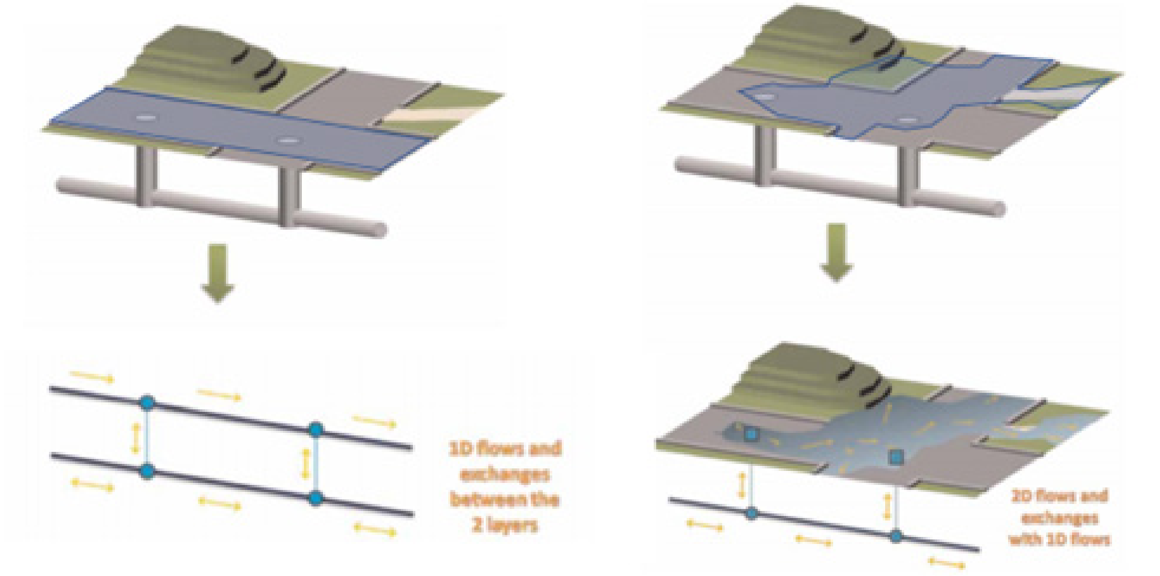



**Figure 4. Concepts of 1D and 2D hydrological urban modelling**

*Source:* Adapted from Henonin et al., 2013. Reprinted from *Journal of Hydroinformatics*, volume 15, issue number 3, pages 717–736, with permission from the copyright holders, IWA Publishing.

Choosing the most appropriate model, depending on the type of service that must be attended to, means balancing accuracy[1] (depending on the user requirements), computational cost and data availability. One must also consider the element of the relevance of the exchanges between the major and minor drainage systems.

## 2.4 Wave, tide and storm surge models

### 2.4.1 *Introduction*

Coastal cities are mainly subject to processes of the dynamics of the water bodies of their coastline (seas or estuaries). In these cases, the water level, forced by waves or tides, is the variable of greatest interest to be evaluated and forecast. In addition, the water level dynamics can condition the behaviour of urban basins.

The extension, dynamics and complexity of estuarine and marine systems require that the generation of operational services for coastal cities be solved using numerical models combined with observations, simulating present (nowcasts), future (forecasts) and past (hindcasts and reanalysis) conditions of oceans.

Operational management in coastal cities requires a broad knowledge of hydrodynamic signals: astronomical tide, storm surge (meteorological tide) and waves. Global information systems do not provide appropriate information for continental shelves and coastal regions and estuaries, and therefore do not apply to coastal cities. For this reason, the development of high-resolution models in coastal environments implies a better description of the coastal dynamics for the management of urban services.

[1] Following the definition of the Bureau International des Poids et Mesures (BIPM) and International Organization for Standardization (ISO) GUM standards, "accuracy" is a qualitative not a quantitative term (ISO and IEC, 2008). Accuracy qualitatively describes quality (that is, good, average, bad) to a specific user's (not all users') requirement. On the contrary, "uncertainty", (like, but different from, "precision") is a quantitative term that is independent of user requirements; a particular uncertainty may have good or bad accuracy, depending on the user.

The processes that affect sea-level dynamics in coastal cities mainly include winds, atmospheric pressure, swell and wind-driven waves, astronomical tides, river flows and bottom friction. Storm tides and waves can be simulated using numerical models that are based on these physical processes. Wave models appropriate for shelf seas and coastal and nearshore areas can simulate wave generation, propagation and dissipation and include the effects of refraction, shoaling and blocking in wave propagation. It has become increasingly feasible to adopt coastal wave models with unstructured grids (Brus et al., 2021) and coupled hydrodynamic and surge models (Deb and Ferreira, 2018) to meet the needs of IUS.

Data-driven models that quantify the relationship between the main variables of the system have not yet been sufficiently explored. High-density observational data, such as from light detection and ranging (LIDAR), satellite imagery, radar altimetry, echo-sounding and others, have significantly improved the accurate characterization of the coastal system, facilitating the implementation of high-resolution models for their description.

The outflow of polluted air over the ocean perturbs biogeochemical processes. Contaminant inputs can damage downstream coastal zone ecosystem function and resources (including fisheries), induce harmful algal blooms and feed back to the atmosphere via marine emissions. The scale of influence of megacities in the coastal zone is hundreds to thousands of kilometres in the atmosphere and tens to hundreds of kilometres in the ocean (von Glasow et al., 2013).

Urban–coastal interactions may also impact the hydrological cycle through changes in the occurrence of fog, clouds and precipitation in and around megacities and coastal areas. These changes are linked to alterations in circulation patterns (see preceding paragraph) and increases in the concentration of aerosol particles, and are within the context of the potentially large humidity gradients that exist between the air over the ocean and inland (von Glasow et al., 2013). A successful example is presented by Parrish et al. (2016), where changes over the past decades in the city of Los Angeles, USA, have led to vastly improved air and coastal water quality.

### 2.4.2 *Model requirements for urban applications*

Detailed spatio-temporal modelling efforts are critical to understanding physical processes. Such modelling can accurately describe sea levels in coastal cities. High-temporal resolution of model input and output, especially in the description of the meteorological forcing of the system, offers an improved description of the events. A high-resolution grid model is useful when high spatial gradients exist in the coastline and topo-bathymetric features, as well as in the waves, storm tides and currents.

The modelling spatial resolution of the sea level must be considered both vertically and horizontally. The vertical resolution is determined according to need: barotropic forecast services (2D models; waves, water level and mid-currents) and baroclinic forecast services (3D models; temperature, salinity and current profiles). High-resolution horizontal discretization can be addressed through nested models or adaptive mesh refinement. Nesting computational domains allows increasing precision by incorporating the resolution domains of greater detail. This modelling strategy could imply high computational costs. However, strategies such as adaptive mesh refinement for modelling a situation in an ensemble forecasting framework can be an alternative way to reduce computational resources (that is, for hurricanes, typhoons).

Coupling high-resolution models can result in a better understanding of coastal urban flood processes and enhanced forecasts. To account for the non-linear interactions between tides, waves and atmospheric forcing during storm surges, coupling storm tide and wave propagation simulations can be a useful approach. For example, in low-lying coastal cities, compound floods could occur as a result of meteorological systems impacting inland and coast dynamics. These situations can be addressed with coupled high-resolution hydrologic (rainfall-run-off) and coastal dynamics (storm tide and waves interaction) modelling.

## 2.5 Downscaling from synoptic or mesoscales to urban scale

High-resolution models may not be accessible at the scale which the city service is targeting, for practical, temporal or financial reasons. For example, a stakeholder could wish for a service using regional climate models at 20-km resolution for climate projections over their city. However, both the coarse resolution and the lack of urban parameterization in the models miss the effects of the city on the projections, and produce projections for the rural landscape instead. Still, the urban service is often based on such (rural) model outputs. The same drawback occurs when using observations from a meteorological station at a rural (or airport) site near the city to produce a service.

Combining various high-resolution model forecasts using more advanced ensemble post-processing methods (Craven et al., 2020) has been shown to improve forecast skill and to support the operational missions of NMHSs. However, such techniques are not yet applied for urban-related focus and issues.

Therefore, when the service is based on (modelled or observed) quantities that do not correctly account for the required urban specificities, it is recommended that, in addition to these, a method of downscaling be used to consider the effects of the city. A recent review paper presents several ways to downscale meteorological and climatic information at urban and infra-urban scale (Masson et al., 2020b).

## 2.6 Statistical models (including artificial intelligence)

It is also possible to produce fast and relatively efficient services using only statistical models (with the concept being extended to artificial intelligence when dealing with huge amounts of data). However, as the development of numerical prediction models has matured, and with the unremitting efforts of WMO, almost all NMHSs can at least receive the data of global numerical models. Statistical approaches can also be used to correct NWP outputs using knowledge from past observations.

Statistical models require observation of the quantity to be forecasted or estimated, depending on pertinent input variables. These input variables could be linked to the meteorological conditions, hazards characteristics or the city itself (such as global population). If provided with a high enough resolution, input variables can be used through statistical models as a proxy for the other variables of interest.

Such models can be used independently of the numerical models presented above and rely solely on pertinent observations. This is the case for IUS based on urban meteorology (for example, air temperature) monitoring stations to produce real-time urban heat island maps. In this case, geospatial statistics are used to interpolate station data with urban description data. The estimation of domestic heating needs using the heating degree days measure is an example of a simple service using this statistical approach. If the objective is to forecast a quantity, achieving that objective requires access to both present and historical data that are used in the learning process of the statistical model.

The recent availability of very large amounts of data from crowdsourcing opens the way for new methods and models to produce IUS. This is particularly true in cities where the amount of such connected sources of data from citizens (for example, from low-cost meteorological stations and air-quality sensors, smartphones), infrastructure (for example, from connected cars) or stakeholders (for example, from city meteorological station networks), is significant. Harnessing their potential may require the use of new machine learning algorithms and artificial intelligence.

A very efficient potential of statistical models arises when they are combined with numerical models to improve the forecast. They can correct systematic errors in the numerical model output (for example, a particular atmospheric model that is always too cool in the city under a given meteorological situation). Several methods to do this exist, but the common point is that, in addition to the numerical model output, one needs to have access to data to evaluate the numerical model errors and uncertainties. The statistical approach therefore allows for coupling models and past and present observations.

# CHAPTER 3. DATA FOR HIGH-RESOLUTION FORECASTING

## 3.1 Need for high-resolution observations

The urban environment is impacted by continuous long- and short-term changes that can occur at the scale of a few metres. This is the reason why the monitoring and modelling of urban landscapes is so challenging. Development, use, assessment and improvement of modelling-based urban services require various data, particularly real-time or near-real-time observation data with high temporal and spatial resolutions. Observational data stem from a wide range of sources: surface measurements, vertical profiles (for example, sondes), ground-based vertical measurements (for example, LiDAR, ceilometers), aircraft-based measurements, and radar and satellite observations. The temporal and spatial availability of these measurements varies considerably. Observational data are critical for urban model set-up, initialization and verification.

### 3.1.1 *Set-up and initialization of numerical models*

Global/regional-scale meteorological, hydrological and chemical observations are necessary in preparing initial and boundary conditions for weather, hydrology and air-quality models. Namely, high-frequency (both temporal and spatial) and long-term observations are required. Yet such observations are rarely available at appropriate spatial and temporal resolution, which leads to interpolation errors and low representability of timescales, and consequently impacts modelling results. For example, operational urban weather station networks that can be assimilated to improve the initial condition of urban canopy models currently do not exist. Such observations will also be critical for improvement of the models' physics.

### 3.1.2 *Models' evaluation*

High-resolution observations (both spatial and temporal) are required to evaluate models' ability to simulate weather, hydrological and air-quality processes (Marsigli et al., 2021), and also to improve models' forecasting skills. After post-processing, model outputs are evaluated with regards to temporal variation and spatial distribution using real-time or near real-time observations. Some models employ bias correction techniques to correct large systematic biases for forecasts based on observations.

The first step in model evaluation is to understand the availability of observational data. Such data may come from surface networks, special field campaigns, satellites or aircraft. The second step is to understand the model output variables and establish the evaluation protocols and criteria for targeted variables. The third step is to select methods of model evaluation that cover the spatial and temporal production skills of the model. One very important consideration when using in situ observations to evaluate numerical models is to match the scales of models and observations. High-resolution models need high-resolution spatial and temporal observations. Furthermore, data quality (and management) should be fit for purpose.

### 3.1.3 *Data assimilation in integrated urban services models*

Data assimilation in the urban environment is an area that requires extensive exploration and should be considered as part of new observational network design (Grimmond et al., 2015). One of the key modern trends to improve IUS systems is to develop new methods of utilizing modern observational data in models, including data assimilation and data fusion algorithms, machine learning methods and bias correction techniques (Baklanov and Zhang, 2020). Operational NWP models usually do not assimilate urban meteorological observations. However, in recent decades the techniques and possibilities of data assimilation from multiple platforms (in situ, ground, aircraft and satellite remote-sensing), including observations such as urban air pollution and atmospheric parameters, as well as citizen science data have dramatically improved.

Data availability in near real time or real time further assists the development of techniques for data assimilation. This leads to a revision of the concepts of urban meteorological and environmental forecasting, and increases the importance of data assimilation (both chemical and meteorological measurements) in IUS and air-quality forecasting systems (Sokhi et al., 2021). Data assimilation in coupled models is in its early stages and applications are illustrating the co-benefits of improved forecasts that are possible by assimilating meteorological and atmospheric composition observations (Bocquet et al., 2015).

### 3.1.4 *Set-up of statistical models (including artificial intelligence)*

Statistical models are based on observations (some artificial intelligence algorithms use image or video data, which is also a type of observation). They are trained with or fitted to historical data. The statistical approaches usually require a large quantity of dense historically measured data under a variety of conditions. They are simple to use, yet they cannot predict unusual situations that may deviate significantly from the historical record. Thus, the high-resolution forecast precision from a statistical model typically depends on the high-resolution data availability and quality.

### 3.1.5 *Post-processing and data fusion*

Data fusion is a post-processing technique to statistically combine model forecasts with a large variety of data sets provided by different sources, including air-quality networks, meteorological and hydrological observations, satellite retrievals and other model outputs, in order to produce improved forecasts.

A few examples of meteorological, hydrological and air-quality data sources are: surface stations; instrumented balloons; atmospheric soundings; aeroplanes; ships; retrievals from radar, satellites and other ground-based remote sensors; and hydroacoustic devices. The major observational variables that are needed for urban modelling are summarized in Table 1.

**Table 1. Typical physical and chemical quantities to be observed in support of integrated urban services**

| *Meteorological observations* | *Hydrological observations* | *Air-quality observations* |
|---|---|---|
| Sky conditions (cloud cover, cloud height), visibility, air temperature, dewpoint temperature, precipitation, humidity, solar radiation, soil temperature and moisture, atmospheric pressure, wind speed and direction | Precipitation, evapotranspiration, soil moisture, snow cover, surface water and groundwater levels, water discharges | Concentrations of carbon oxides (COx), sulfur oxides (SOx), nitrogen oxides (NOx), volatile organic compounds (VOCs), ozone ($O_3$), particulate matter (PM); wet and dry deposition amounts |

Despite the importance of high-resolution modelling for the provision of integrated urban services, engagement from NMHSs has been rather limited so far. One of the reasons is that urban modelling requires expertise which is usually not a part of the meteorological modeller's background (see section 5). Another reason is the potential larger uncertainty of this modelling, in comparison to weather forecasting models, either because the urban/high-resolution models are not properly initialized or because of the difficulty in validating them. Such validation is especially difficult for high-resolution simulations at urban or infra-urban scales, given the lack of high-resolution networks of urban observations. In comparison with synoptic weather observation data that are used in NWP, high-resolution urban observations for operational urban forecasting (mainly for use in model initialization and validation) are non-existent or too rare and the frameworks to exchange this kind of observations are lacking. Furthermore, in many cases urban observation networks may be managed by different institutions; weather data is managed by meteorological services, hydrological data by hydrological services, and air-quality data by environmental agencies. Data collection therefore requires additional coordination/communication between the different organizations.

The need for high-resolution observations requires substantial improvement of the traditional observational networks and their cross-domain integration. Weather observations are usually made at meteorological stations located at airports, and are very seldom present in cities, and, where they are, are mostly located in parks. It is more common to find hydrology and especially air-quality measurement stations over urban areas. These stations are mainly dedicated to hydrology monitoring, while the data are used for modelling, emission control, establishment of policies and assessment for air-quality improvement. However, networks are still very sparse and often only have one surface level. They lack multi-vertical layer observations that can represent the full extent of the urban boundary layer and underground, limiting opportunities for high-resolution modelling. As such, to improve high-resolution models, the main concern should be increasing the number of fit-for-purpose (and operationally managed) urban observation networks. NMHSs are encouraged to implement more urban observation stations as recommended in the *Vision for the WMO Integrated Global Observing System (WIGOS) in 2040* (WMO-No. 1243). WMO published a new guideline in 2023 with additional information relevant to the observations needed to assess the urban heat island effect (see *Guidance on Measuring, Modelling and Monitoring the Canopy Layer Urban Heat Island* (WMO-No. 1292)).

## 3.2 Types of urban data required to initialize models for different applications

A pertinent and sufficiently refined description of a city is required for the urbanized high-resolution models that is used for the urban service. The key words here are "pertinent for the urban service". The ranges of details and parameters that are needed strongly depend on the objective and resolution of the service to be provided. For example, generation of high-resolution bathymetric and topographic data sets are essential for generating forecast products for urban areas.

There are many types of parameters that may be required to describe the urban surface for atmospheric models (see review by Masson et al., 2020a). The reader is referred to this review for details of the various ways to compute these parameters (that could come from remote-sensing, building inventories, crowdsourcing and so forth). The parameters are:

– Land use and land cover. The minimum requirement is to define the extent of the area that is considered "urban". Most land-use/land-cover maps have one "urban" class. A finer description of the urban tissue, with several classes, is preferable. Several classes are sufficient for kilometre-scale atmospheric simulations, provided that the translation of these urban classes into urban parameters (such as building fraction, mean building height) for the model is coherent with what is expected in the agglomeration, on average;

– Morphological parameters. These describe how impervious elements affect the surface. Such parameters include the mean building height, the wall and building densities, the road and impervious densities, and so forth. When running models at hectometric resolution (~100–200 m), the various neighbourhoods that may be of the same land use/land cover (for example, suburban) may be very different in terms of morphological parameters at this scale. Input maps of morphological parameters are therefore recommended for very high-resolution models;

– Permeable elements. These include trees, broader vegetation cover and structures, which are also critical for many urban modelling applications;

– Other parameters. These include architecture, socioeconomic characteristics (such as building equipment and usage) and urban vegetation characteristics. Information needed for these parameters primarily depends on the target service, not the resolution. For example, the estimation of outdoor impacts from energy consumption or air conditioning requires information on architecture and building equipment and usage. The estimation of outdoor thermal comfort indices benefits from a good description of the vegetated areas and green spaces watering policy;

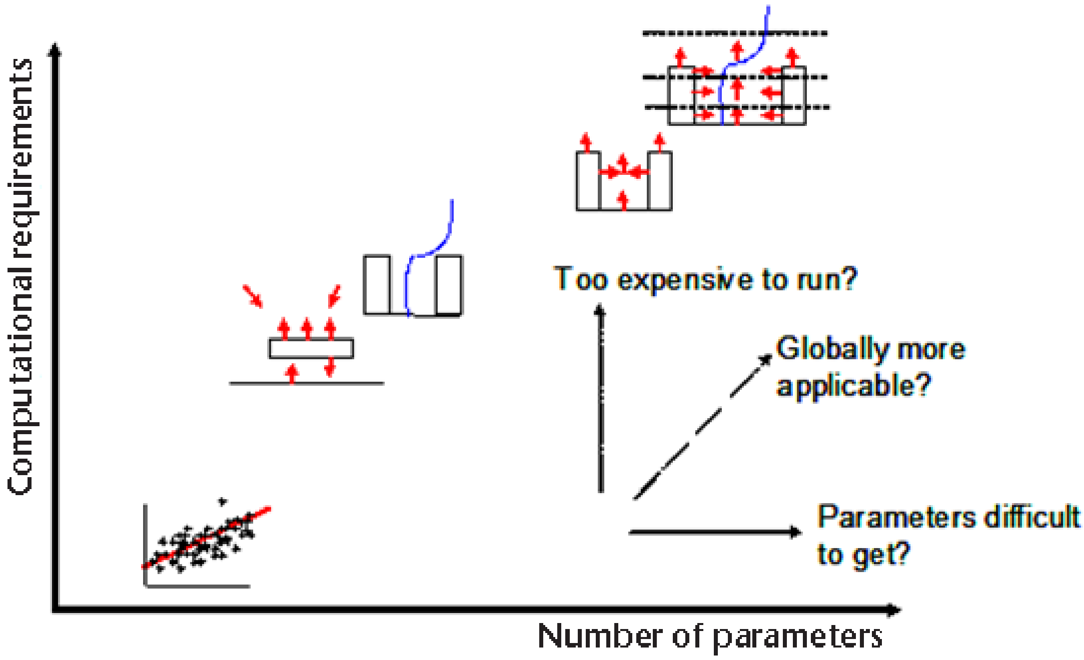



**Figure 5. Visual illustration of the trade-off between the precision and completeness of models, and the required parameters needed to use them at their full potential. Bottom left graph: statistical model. In the other graphs, the surface is represented by a horizontal thin black line, the concrete slab model is represented by a horizontal block floating above ground, buildings are represented by vertical blocks, energy fluxes are represented by red arrows, wind profile is represented by a blue line, and atmospheric levels intersecting buildings are represented by dashed black lines.**

*Source:* Reprinted from Baklanov et al., 2009. Model Urbanization Strategy: Summaries, Recommendations and Requirements, pages 151–162. In: *Meteorological and Air-quality models for Urban Areas*. Springer Dordrecht, Heidelberg, London, New York, with permission from the copyright holders, Springer Nature.

– Information on the drainage system is needed for hydrological models. These include rivers and streams data (georeferencing, cross-section dimensions, bottom slope and rugosity features), streets data (georeferencing, dimensions and rugosity features) and sewer system data (georeferencing, component types and materials, dimensions and bottom slope);

– Emissions of pollutants. Timely, updated and accurately represented fine-scale data are required for air-quality models. Sources of pollutant emissions are diverse and mostly of anthropogenic origin in cities (industries, traffic, domestic heating and so forth), but also come from sources outside cities (agriculture, energy plants and so forth) or from biogenic emissions (such as forest). In addition, high spatial-temporal resolution data accurately representing anthropogenic and biogenic emissions' variability are essential. For example, weather-dependent emission parameterizations associated with home heating, the stack size and plume injection height of point sources, up-to-date urban vegetation-associated emissions and so forth, are required.

It is important to remember that more sophisticated models require more input data. However, it becomes more difficult to provide sufficient quality as input data needs increase. It is necessary to seek a balance between the number of required parameters and their availability, as illustrated in Figure 5. IUS therefore should take advantage of fine-scale and complete urban data that could be available in the city. However, this should be put in perspective with the genericity of the IUS and the possibility of using it in other territories.

## 3.3 Need for standards and homogeneous approaches for replicability and comparability

In order to produce services that can be generalized and replicable in other cities and countries, it is important to follow general rules and standards.

Urban climate studies are often, rightfully, done by local experts and scientists, due to their closeness with the involved stakeholder(s) and their knowledge and use of local urban data. However, the drawback of this approach is that it can be territory-specific. For example, the urban tissue may be described by a local land-use/land-cover typology, that does not translate easily to the classes of other typologies. Even if there are many ways to produce each of the urban parameters (see Masson et al., 2020a), common approaches should be sought in standardizing the form and content of the parameter map (or information).

Concerning land-use/land-cover typologies, an important advance for the urban climate community was the LCZ (local climate zone) concept developed by Stewart and Oke (2012). In this typology, 10 classes represent urban neighbourhoods (differentiated by properties expected to lead to differences in canopy layer air temperature), and 7 rural classes (necessary for urban–rural analyses). Even if the number of rural classes is too low for state-of-the-art vegetation models used in atmosphere models, the 10 urban classes represent a great advance compared to the use of a single urban land-use/land-cover class. Several approaches have been developed to compute LCZ maps (for example, the World Urban Database and Access Portal Tools (WUDAPT) initiative described in Ching et al., 2018, or in Hidalgo et al., 2019). Once created, LCZ maps can subsequently be used by many models.

Using open data is also a method that should be followed and encouraged. This would be of great help in producing urban parameters for any city wishing to have access to an urban climate or hydrological service based on high-resolution modelling. Open Street Map may be used to compute urban morphological parameters or to define the street network for surface water flow.

From a technical point of view, in a situation where weak coupling (that is, where each model runs separately or successively and exchanges information) is adopted for the hierarchy of models involved in the IUS, it is best to standardize the data transfer between the models. Standardization can include variable names, file format and data precision. For example, WaterML 2.0 is a data exchange standard in hydrology that can be used to exchange hydrometeorological observations. The WaterML 2.0 standard is part of the joint activities of WMO and Open Geospatial Consortium (OGC) and is used within the framework of the WMO Hydrological Observing System (WHOS) as the hydrological component of the WMO Integrated Global Observing System (WIGOS). The focus of the standard is time series data, commonly used for hydrological applications such as flood forecasting, environmental reporting and hydrological infrastructure (Taylor et al., 2014). WaterML 2.0 provides an interoperable exchange format that may be used to address a wide range of user needs: in situ observations (time series and sections), forecast products and emergency or operator-oriented alerts. Other types of couplers for different combined models (for example, water and atmospheric, or meteorological and air quality) used in offline coupled models were developed by the Partnership for Research Infrastructures in Earth System Modelling (PRISM) support initiative with version 4 of the Ocean Atmosphere Sea Ice Soil (OASIS4) coupler (Valcke and Redler, 2012).

A first general recommendation is then to favour the use of standards that enable further use of the developed IUS in other territories with greater facility and at a lower cost. A second recommendation is to produce data in close collaboration with the modeller (of the model used in the IUS) and the other partners (stakeholder recipients of the IUS, or other developers, scientists and data providers). This will have the advantage of better fitting the needs of the IUS, while also creating an acculturation between the partners, and a better comprehension of the capabilities as well as the limits of the IUS. This will mean better final use of the IUS and a reduced risk of misuse or misinterpretation.

# CHAPTER 4. TYPICAL APPLICATIONS FOR INTEGRATED URBAN SERVICES AND CITY EXAMPLES

## 4.1 Past events: what can be learnt from them for the future of the city?

Many climate hazard-related services for cities are based on past meteorological events. For example, evaluation of adaptation strategies related to floods or heat stress is performed using high-resolution modelling of the effects of such strategies on past thunderstorm or heatwave situations, respectively.

This approach, in addition to the practical aspects of focusing on a past event (from days to season, typically), has the considerable advantage of being easily appropriated (understood and used) by the city stakeholders. As an event that occurred in their city, it will be well remembered by the city stakeholders and people. This was the case, for example, for the 2003 heatwave in Europe which initiated many studies on heatwaves and urban heat islands.

The modelling systems that are used to model such events can be the same high-resolution systems as those used for forecasting (as was the case for Beijing: see section 4.2). However, they are not used for the same purpose. Instead of simply simulating weather or other impacts on the actual city, they rather serve to evaluate urban scenarios. Masson et al. (2014b) describe a chain of models applied to the Paris and Toulouse (France) agglomerations to simulate many impacts linked to the future evolution or expansion of the city. A crucial point in the development of this type of IUS is that it requires strong interactions with stakeholders and urban planners. It is important to discuss the limits of the models and what they can and cannot evaluate in the urban scenarios.

**Table 2. Examples of IUS for urban planners**

| *City* | *Objective/ problem* | *Type of model* | *Resolution* | *Good practice/ added developments* | *Status* |
|---|---|---|---|---|---|
| Beijing | Urban planning | Numerical atmospheric model with urban canopy model | 1 km, coupled to a 3 km model at boundaries | Urban database<br><br>Cooling-tower model for air conditioning<br><br>Evaluation of urban scenarios | Completed (He et al., 2019) |
| Paris | Heat waves and UHI<br><br>Urban planning and construction of emergency cooling strategies<br><br>Urban air-quality episodes | Atmospheric model with urban canopy model | 250 m | Urban database<br><br>Evaluation of urban adaptation strategies<br><br>Allowed in situ experiments of cooling strategies by the city stakeholders (e.g. road watering) | Completed (Masson et al., 2014b) |
| São Paulo | Urban planning and thunderstorms | Numerical atmospheric model with urban canopy model | 1 km | Urban expansion scenarios | Research (Bender et al., 2019) |

## 4.2 Forecast

Currently, what is considered "high-resolution" is the km or sub-km scale. Many countries now have operational models at 1 km resolution. Some meteorological institutes perform 300–500 m resolution simulations on small areas of specific interest, such as cities, often in demonstration mode. Urban weather forecasts at high resolution are a novel field of research.

Interestingly, one of the first requirements linked to numerical weather forecasting would be to have access to observations at the infra-urban scale in order to perform model verification, to improve forecasts using artificial intelligence algorithms, to fuse model outputs with these observations, and to potentially assimilate these before the simulation. Such observations can come from a dedicated monitoring observation network of the city, opportunistic data or (for surface temperatures only) satellite data.

It is also crucial not to confuse surface and air temperatures when developing the service, as satellite surface temperature data are often wrongly presented as a proxy of the air temperature field and air urban heat island (Stewart et al., 2021).

Table 3 shows several examples of IUS that are based on, or use, high-resolution models for various cities. They are based on a range of different types of high-resolution models, which illustrates the variety of possibilities to construct and implement IUS.

In the cases of Beijing, Moscow and Amsterdam, IUS are mostly built upon numerical weather prediction models that include an urban canopy model. In order to take advantage of the physics included in the urban parameterization, it is notable that all three cases did utilize high-resolution urban data (for example, He et al., 2019; Samsonov and Varentsov, 2020). The data sets were computed from local or national databases, satellite images or crowdsourced data. In these models, no city-owned urban data was incorporated, likely because of the necessary large spatial domain, which was much larger than the agglomeration. Urban networks of weather stations were used for validation of these models in these cities (for example, Ronda et al., 2017 in Amsterdam). Specific developments can be made in accordance with the specificities of the cities. For example, in the case of Beijing, a cooling-tower model was included in the modelling system to better estimate energy released by air conditioning (Yu et al., 2019). This output provides information to the electric power management authorities.

Other IUS are based on the NMHS's weather prediction system. Their forecasts are then treated in a way that is suitable to the specific needs of the city. This pragmatic approach promotes the development of IUS on meteorologically-dependent phenomena, even if it may miss some interactions between processes. This is typically the case for air-quality forecasts based on regional offline models. An application for air quality at 5 m resolution at street level has been developed for Helsinki (Johansson et al., 2015). Online air quality models are still not commonly used, although interest in such models is growing (for example, some developments have been made in São Paulo). For Singapore, the NWP information is blended with nowcasting models of thunderstorm tracking, in order to produce heavy rainfall forecasts.

Finally, many operational IUS are based on observations from urban networks of meteorological stations, using geospatial statistical models and machine learning to spatialize the data and provide forecasts. This is the case for Hong Kong, China (Chang et al., 2021) with production of an air temperature map at ~10 m resolution up to 2 days ahead. To reach such fine scales, in addition to the meteorological measurements, it also incorporates urban data (building height, sky view factor). A similar approach was chosen for Toulouse, France (Dumas et al., 2021). Impact models can then take advantage of the fine-scale spatialized urban meteorological information that is produced. For example, estimates of energy consumption are provided for Hong Kong, China. In Shanghai, Han et al. (2020) developed an IUS on wind risks for train carriages. It applies a risk model to train routes of the metro system at a fine scale, while considering the wind (from forecasts or observations) and the characteristics of the railways and their environment.

**Table 3. Example of IUS using high-resolution models in various cities across the world**

| *City* | *Objective/ problem* | *Type of model* | *Resolution; Domain* | *Good practice/ added developments* | *Status* |
|---|---|---|---|---|---|
| Beijing | Weather and electric load hourly forecasts for the electric power management authorities | Numerical atmospheric model with urban canopy model | Resolution: 1 km;<br><br>Domain: Coupled to a 3 km model at boundaries | Urban database;<br><br>Cooling-tower model for air conditioning | Operational (He et al., 2019) |
| Shanghai, China | Wind risk warning system for urban metro transport | Spatial interpolation plus risk model (based on criteria of aerodynamic forces on carriages) | Resolution: Roadways: wind field at 30 m;<br><br>Domain: Interpolated from 3 km weather forecast model | Vulnerability of carriages analysed using computational fluid dynamics (CFD);<br><br>Effect of angle of attack of wind on aerodynamic forces are quantified | Operational (Han et al., 2020) |
| Moscow | Weather forecast, including tailored outputs (e.g. GIS-web) | Numerical atmospheric model with urban canopy model | Resolution: 1 km | Urban database from data of existing products, satellite, Open Street Map;<br><br>Post-processing optimization | Pre-operational, although was used for the Sochi Winter Olympics (Samsonov and Varentsov, 2020) |
| Hong Kong, China | Extreme heat, heavy rainfall, hurricanes | Geo-statistical model based on meteorological observations and urban data;<br><br>Short-term energy consumption model (neural network) | Resolution: A few 10 metres;<br><br>Domain: 110 meteorological stations in the city | Real-time data;<br><br>Test of smaller weather stations using Internet of Things (IoT) | Operational (Chang et al., 2021) |
| Toulouse, France | Extreme heat with UHI | Geo-statistical model based on meteorological observations and urban data | Resolution: 100 m;<br><br>Domain: 70 meteorological stations in the city | Real-time data using IoT technologies;<br><br>Observation network property of, and managed by, the city;<br>Leading to gains in expertise by the city stakeholder | Operational (Dumas et al., 2021) |

| *City* | *Objective/ problem* | *Type of model* | *Resolution; Domain* | *Good practice/ added developments* | *Status* |
|---|---|---|---|---|---|
| Copenhagen | Urban meteorology, air pollution, emergency preparedness, e.g. for nuclear, biological, chemical (NBC) defence | Online and offline coupled urbanized numerical weather prediction and atmospheric chemistry transport models | Resolution: Street canyon scale (10 m);<br><br>Domain: From 1.4 km air-quality (AQ) model | IUS for urban NWP, air quality, NBC and health | Pre-operational (Baklanov et al., 2006a; Baklanov et al., 2006b; 2008; Nuterman et al., 2021) |
| Amsterdam | Heat and UHI<br><br>Forecasts | Numerical atmospheric model with urban canopy model | Resolution: 100 m;<br><br>Domain: Coupled to 2.5 km and 500 m weather forecast model | Post-processing to develop products for cyclists (choice of path) | Operational (Ronda et al., 2017) |
| Helsinki | Air quality<br><br>Forecasts | Theoretical model (Gaussian dispersion), based on observations | Resolution: 15 m;<br><br>Domain: 30 AQ mid-priced sensors have been added to the AQ observation network;<br><br>Meteorological data comes from 1 km numerical model with urban canopy model | Use of data fusion to correct model forecasts with observations;<br><br>Uses various sources of data for emissions and activity;<br><br>AQ Index visualizations are shown on public transport displays (screens, posters, etc.) | Operational (Johansson et al., 2015) |
| Singapore | Flash flooding and thunderstorms<br><br>Nowcasting system | Tracking of observed thunderstorms;<br><br>Post-processing of weather forecasting model rainfall | Resolution: 1.5 km | Data fusion | Operational |
| São Paulo, Brazil | Air quality | Online atmospheric model with urban canopy model;<br><br>Street-scale conceptual AQ model | Resolution: 3 km | Online chemistry with urban atmospheric effects considered;<br><br>Health impacts | Research and development (Takano et al., 2019) |

From the point of view of understanding and forecasting water dynamics in cities, the development and use of high-resolution models is asymmetric and incomplete. Depending on the type of problem (pluvial and/or fluvial floods, coastal flooding and so forth), the availability of these tools and their integration with other urban services is still in the process of expansion.

There are a wide range of possible strategies to apply high-resolution hydrological and hydraulic models in cities and to integrate their simulation results with different urban services. Therefore, as highlighted in the *Guidance on Integrated Urban Hydrometeorological, Climate and Environmental Services* (WMO-No. 1234, Volume II), during the IUS co-construction process it is essential to adequately define the modelling needs, depending on the type of service to be provided. Additionally, this definition should consider the requirement of a significant amount of detailed data, both for the model set-up and calibration and validation. Table 4 highlights some coastal and hydrological urban high-resolution modelling experiences, which provide good practices, with the possibility of being replicated in other cities.

The challenge of having information for an adequate representation of urban hydrological processes is presented in the example of London. Implementation of a very high resolution model involves an exhaustive digital elevation model (DEM) review, urban micro-features assessments, flood information collection and flood physical processes analysis (Wang et al., 2018). As shown by the case of Barcelona, Spain, (Velasco et al., 2018), the association between those who develop the models and those who provide the other services (multisectoral approach) favours the exchange of detailed information necessary for the implementation of models. In the case of Stockholm (Gidhagen et al., 2020), the quality of the forcing data for the hydrological modelling system provided through numerical modelling strongly conditioned the results.

There are a wide variety of services that can be integrated with high-resolution hydrological and hydraulic models. The case of Barcelona (Velasco et al. 2018), which used this type of approach to plan activities, presents the relationships with electricity distribution, waste collection and transit services. In Antwerp, Belgium, high-resolution modelling efforts integrate hydrometeorological services with experiences in water supply (Li and Willems, 2020). Coastal modelling systems allow forecasting for defence infrastructure management, as in the case of Saint Petersburg, Russian Federation, with gate management (Popov and Lobov, 2017). Along these lines, the example of Rotterdam, Kingdom of the Netherlands, (Bachmann et al., 2016) is of interest not only because of its predictive capacity in terms of threat but also because of its links to the possibility of failure of the city's defence structure (dykes) and the possible impacts.

The visualization and communication of urban hydrological model results is a necessary aspect to tackle. Among the experiences surveyed, both the case of the Dorim stream basin in Seoul, with the communication of the hydrological modelling results through a web page (Lee et al., 2020), and the case of the modelling in Rotterdam (Bachmann et al., 2016), with the availability of the results in interoperable formats, are considered good practices.

**Table 4. Examples of early warning IUS for coastal and hydrological modelling**

| *City* | *Objective/ problem* | *Type of model* | *Resolution; Domain* | *Good practice/ added developments* | *Status* |
|---|---|---|---|---|---|
| London | Pluvial floods | A cellular automata-based model (CADDIES-2D) for 2D overland flow | Resolution: 1 m x 1 m;<br><br>Domain: Area around Wallington station (south London), (0.25 $km^2$) | Very high resolution;<br><br>Multi-source data (including social media data);<br><br>Urban micro-features assessment | Research (Wang et al., 2018) |

| *City* | *Objective/ problem* | *Type of model* | *Resolution; Domain* | *Good practice/ added developments* | *Status* |
|---|---|---|---|---|---|
| Antwerp, Belgium | Pluvial floods | A detailed data-driven modelling approach, based on a 1D sewer system teaching model | Resolution: Variable (< 50 m);<br><br>Domain: Antwerp city centre (11.6 $km^2$) | Probabilistic flooding nowcasting;<br><br>Surrogate modelling for real-time urban flood;<br><br>Teaching model provided by local water company | Pre-operational (Li and Willems, 2020) |
| Barcelona, Spain | Pluvial floods | A 1D/2D dual-drainage model: 2D overland flow and 1D sewer system (Infoworks integrated catchment modelling (ICM) software) | Resolution: Variable (grid cells from 25 to 100 $m^2$);<br><br>Domain: City of Barcelona and contributing basins (120 $km^2$) | Multisectoral approach (local government, services companies, universities, etc.);<br><br>Planning: flood risk assessment for people and properties and assessment of flood hazard and flood impacts on traffic and electric and waste collection systems | Not operational (Velasco et al., 2018) |
| Rotterdam, Kingdom of the Netherlands | Coastal floods/pluvial floods | A 2D hydrodynamics model (3Di) | Resolution: 25 m x 25 m grid cells;<br><br>Domain: Pernis and IJsselmonde dyke rings | Risk-based flood forecasting system;<br><br>Assessment of the defence line performance (dykes: probability of failure) and the impact of flooding;<br><br>Interoperability | Pre-operational (Bachmann et al., 2016) |

| *City* | *Objective/ problem* | *Type of model* | *Resolution; Domain* | *Good practice/ added developments* | *Status* |
|---|---|---|---|---|---|
| Saint Petersburg, Russian Federation | Coastal floods (storm surge and waves) | A multi-model approach: both a barotropic spectral model (BSM) and a baroclinic model (BALT-P) for hydrodynamics; the Nucleus for European Modelling of the Ocean (NEMO) model for thermodynamics; and one wave model (Simulating Waves Nearshore (SWAN)) | Nested grid models with 90 m maximum discretization;<br><br>Domain: Baltic Sea and Neva River estuary | Multi-model ensemble-based simulations and data assimilation for application to storm surge and waves forecasting | Operational (Popov and Lobov, 2017) |
| Seoul metropolitan area | Fluvial floods/ pluvial floods | A long short-term memory (LSTM) model (a type of recurrent neural network) for short-term prediction;<br><br>A 1D, sewage network system model (Storm Water Management Model (SWMM));<br><br>A 1D model for river hydrodynamics (Hydrologic Engineering Centre-River Analysis System (HEC-RAS)), simplified versions for very long-term prediction) | Resolution: subcatchments of approximately 1 Ha;<br><br>Domain: Dorim stream basin area (42.5 km$^2$) | Integrated flood forecasting and warning system in web page;<br><br>Inundation prediction modules with good performance: short-term (30–90 min) and very short-term (10–70 min);<br><br>Rainfall forecasting by radar | Pre-operational (Lee et al., 2020) |
| Stockholm | Fluvial floods/ pluvial floods | A semi-distributed, physically-based hydrological model (Hydrological Predictions for the Environment (HYPE)) | Resolution: 602 sub-basins;<br><br>Domain: total modelled area (6 840 km$^2$) | An adequate determination of the upstream basins of the city;<br><br>The hydrological results underline the need for further development of the precipitation downscaling method | Operational (Gidhagen et al., 2020) |

## 4.3 Climate

Regional climate models (RCMs) now provide a resolution of a few tens of kilometres. The drawback is that these scales are much too large for urban studies and require various downscaling methods to produce urban services.

However, very high-resolution RCM outputs are beginning to appear at kilometric scale, with convection-permitting models being used for climate runs, even if sometimes they are only run for a few years or decades (which is considered too short by global and regional climate modellers). Given the novelty of the science in this subject, the good practices required to run such models are not yet established. They will require cross-knowledge of climate modellers and high-resolution mesoscale modellers from convection-permitting models. For urban studies, this will require, as for NWP models, implementation of urban canopy schemes inside these very high resolution convection-permitting regional climate models.

Amorim et al. (2018) present IUS based on dynamical downscaling (using an atmospheric model at 1 km resolution from 20 km regional climate projections) for Stockholm for present and future climate prediction. This system allows an assessment of how the city's climate is expected to evolve in the future, considering also urban expansion and densification. This modelling system was included as a case study in the WMO *Guidance on Integrated Urban Hydrometeorological, Climate and Environmental Services* (WMO-No. 1234, Volume II).

The coupling of information from non-urbanized RCMs and urbanized high-resolution atmospheric models allows the development of statistical-dynamical downscaling methods to produce IUS over long time periods (twentieth or twenty-first century). Le Roy et al. (2021) use a method based on weather types to detect which urban heat islands (simulated using a high-resolution urbanized model) to add to the signal coming from the Euro-CORDEX ensemble. Such downscaling approaches allow evaluation of various sources of uncertainty in the model (climate change, RCM model and so forth).

**Table 5. Examples of climate projection IUS**

| *City* | *Objective/ problem* | *Type of model* | *Resolution* | *Good practice/ Added developments* | *Status* |
|---|---|---|---|---|---|
| Stockholm | Heat stress, air quality;<br><br>Climate-sensitive urban planning;<br><br>Evaluation of urban evolution scenarios | Numerical atmospheric model with urban canopy model;<br><br>Offline numerical air-quality model | 1 km<br><br>Downscaling from 11 km analyses or 20 km climate projections | Both historical and present/future climate conditions are simulated;<br><br>Production of Essential Climate Variables (ECVs) and Sectoral Impact Indicators (SIIs) | Operational (Amorim et al., 2020) |
| Paris | Energy consumption;<br><br>Heat stress | Euro-CORDEX RCM simulations;<br><br>Numerical atmospheric model with urban canopy model | Approx. 10 km<br><br>250 m | Dynamical downscaling using an urbanized model coupled to statistical downscaling for use of climate ensemble | Research (Le Roy et al., 2021) |

# CHAPTER 5. FUTURE CHALLENGES AND RECOMMENDATIONS

## 5.1 Systemic approaches to urban services

### 5.1.1 *Need for a multidisciplinary approach*

It is always necessary to have an interdisciplinary approach when tailoring urban services. Even if only one scientific field is a priori involved (for example, meteorology), the translation of the high-resolution results for inclusion within an urban service will require interaction and co-construction with the urban stakeholder, in order to ascertain whether the produced service responds to a demand.

In addition, since cities are complex systems by nature, developing and using high-resolution models that represent urban processes often requires incorporating various scientific disciplines, such as architecture, geography, hydrology, meteorology, climatology and sociology.

For example, urban-scale air-quality modelling is becoming more and more important. Such modelling is helpful, not only from a public guidance perspective (for warning announcements), but also for policy and decision-making in emergency emission control and in air-quality improvement. Furthermore, since air quality can impact climate change (for example, some pollutants such as ozone ($O_3$) cause the climate to warm, while some pollutants such as particulate matter (PM) cause cooling) and conversely, climate change can impact air quality (for example, more severe $O_3$ pollution with heatwave and drought), it is essential to address air quality and climate change together and thus to develop synergistic policies. Recent studies showed that for both developing and developed countries, the implementation of an emission control strategy/air-quality improvement not only helps to reach the World Health Organization (WHO) Global Air Quality Guidelines (WMO, 2021), but also contributes to the air-quality co-benefits of ambitious climate action (Cheng et al., 2021; Thambiran and Diab, 2011; ACP, 2018). In the future, to further reduce the exposure of the majority to pollution levels, more ambitious climate mitigation efforts are likely required. In this case, the goals of air quality and climate change would converge.

From a scientific perspective, integrated research on air quality and climate change is becoming more important. For example, the United States Environmental Protection Agency (EPA) is promoting relevant research (https://www.epa.gov/air-research/air-quality-and-climate-change-research), such as research into: methods to investigate impacts of global-scale changes in air temperature and precipitation patterns on local-scale meteorology conditions that affect air quality; the influence of climate change on fine particulate matter and other air pollutants; co-benefits of reducing air pollutants that also reduce the impacts of climate change; and how mitigation options to reduce carbon dioxide can affect emissions of particulate matter, ozone, precursors and other air pollutants, and so forth. These integrated studies require the coupling or considering of climate change information within the air-quality modelling framework.

Urban hydrology and flood management systems are an important part of urban integrated services. The Flood Forecasting Initiative (WMO FFI) aims at promoting the end-to-end flood forecasting and early warning strategy and serves as an umbrella for finding and coordinating synergies between different WMO activities sharing a common disaster risk reduction objective (for example, the Associated Programme on Flood Management (APFM-WMO)). Seamless coupling of urban weather and climate observation and modelling systems with urban hydrology systems is one of several urgent and challenging tasks for research and service communities (Baklanov et al., 2018).

In addition to the coupling between hydrological, atmospheric and air-quality models described above, the systemic aspect of cities, as well as the broad needs of stakeholders, invite extending the coupling to models, or concepts, from other disciplines. Coupling of urban-scale models presented above with economic, energy or health models in support of urban or climate policies should also be developed for future integrated co-benefit studies. Model developments would require incorporation of more complex urban processes (within the Earth system concept) in existing models.

The process of coupling models from different disciplines is itself complicated, and the approach is dependent on the particular IUS models. However, the common aspect is that it requires interdisciplinary acculturation to understand the processes and limits of the various models, and the significance of the results provided. This also contributes to the co-construction process of the IUS (see 5.2.2).

### 5.1.2 *Strong or weak integration of models?*

When multiple disciplines are involved, and when a service is built upon high-resolution models, the question of how such models should interact becomes important. This is the case when dealing with a model simulating the city's evolution, the urban microclimate, or hydrology and floods.

A number of questions arise, such as: Should they be strongly coupled, with each model interacting with the others during a coupled simulation? Or should they run sequentially, with each considering the outputs of the other model(s)? There are no easy answers to these questions. However, one lesson which has arisen from the interdisciplinary studies in which the authors have been involved is that whatever the coupling method, using several models and having them interact helps to facilitate the acculturation process between disciplines. This interaction forces each scientist to better understand the other science or the city practitioner's field requirements and processes.

## 5.2 The last mile

### 5.2.1 *Impact-based integrated urban services*

Because IUS are fit for purpose, there is always a need to link the model output to the user's need. End users are often interested in impact-based aspects, for example impacts on the economy, health, comfort and so forth. This can be done through the use, and development, of indicators. The same indicators could be used differently for early warning applications and urban planning. This stage of using and developing indicators most often requires an interdisciplinary approach, collaboration and specific partnerships.

The question of how to transform the model outputs in terms of useful indicators depends on the risks identified by the user. There are a few important points to keep in mind in this phase:

- One should not forget to do this as part of the IUS methodology (see Chapter 7 of the *Guidance on Integrated Urban Hydrometeorological, Climate and Environmental Services* (WMO-No. 1234), Volume II).

- Indicators may use direct model outputs but can also use external data. They can merge information from a general high-resolution model and the urban data provided by the stakeholder, and therefore, better fit the needs.

- Production of an indicator often needs simplification of the information, though the uncertainty of model prediction should be considered.

However, one recommendation is to consider impacts in a general way, so this is simpler to adapt the IUS to specific cities afterwards. This underlines why the use of data that follow standards is important.

### 5.2.2 *Co-construction and interaction with stakeholders on indicators and models*

As emphasized in the *Guidance on Integrated Urban Hydrometeorological, Climate and Environmental Services* (WMO-No. 1234, Volume I), co-construction is essential in the development of IUS. This is justified, even when focusing on parts of the IUS and especially models (while this could be viewed as a technical aspect only).

Information to the stakeholders on the capabilities and the limits of the models facilitates the conception of pertinent indicators that can then be used to best fit the user's requirements. Given the need to integrate services from NMHSs with other urban services, it is necessary to assess the needs, capacities and levels of understanding prior to developing indicators. The detection of comprehension problems regarding the information generated from the NMHSs is very relevant for its use and integration.

The advantage of high-resolution models is that they can provide spatially and temporally refined prediction or simulation products. When including them in IUS products, it is better to retain this advantage as much as possible. Digital technology is widely used in city management today. Through cooperation with stakeholders and users, high-resolution model products can be applied to urban management information systems to provide more intuitive decision support in a visual way.

It should be noted that, if required, and if urban and observation data are available, modelling can be used anywhere. Therefore, integrating models within IUS helps export IUS from one city to another. In some ways, this can build on the co-construction already realized with some stakeholders, to define a (relatively) generic IUS. This IUS could then fit many (if not all) purposes of another stakeholder in another city.

## 5.3 **Conclusion**

Because of the relatively small size of cities, and even megalopolises, compared to meteorological, hydrological and environmental phenomena, many IUS rely on high-resolution models. The choice of the model and resolution depends on the purposes and specific tasks: this is governed by a fit-for-purpose approach.

To advance modelling system development for IUS application in the future, four aspects are suggested, including: expanding observing networks; improving models; disseminating information; and training specific urban research experts.

### 5.3.1 *Expanding observing networks*

Observations are crucial within and around cities, even for model-based IUS. Because uncertainties and biases unavoidably occur in models, observation-based evidence is of great interest, both for model calibration and verification (and potentially for data assimilation), but also for achieving full acceptance of the IUS by the city stakeholders and end users.

It is therefore recommended that NMHSs and other actors increase both the number of observations in urbanized areas and improve exploitation of existing observations, including from crowdsourcing and participatory sources.

### 5.3.2 *Improving models*

The application of models requires the parameterized description of the mechanisms/processes known to influence urban climates. For IUS application in cities, the situation is even more complex due to the impacts of human activities, which are different from natural laws.

Meteorological models need to represent the urban surface, as specific processes strongly influence the atmospheric boundary layer and urban weather and climate (such as the urban heat island). This can be done using state-of-the-art urban canopy models that simulate the energy, water and momentum exchanges with the atmosphere through buildings, infrastructures and urban vegetation. For air-quality models, urbanizing the model means implementing a high-resolution emission inventory, urban data and more accurate descriptions of chemistry-meteorology interactions at urban scales, all of which aim to better describe the impacts of human activity on cities. The urbanization of hydrological models means identifying the needs for useful services for the protection of people and property within the scope of a city. For this, it is essential to calculate the flood levels, as well as their duration and the overland run-off velocity in order to reach a good level of accuracy for the IUS. The urbanization of coastal models would imply that their interaction with urban services is linked not only to coastal defences: it is also necessary to link them to services related to operative sewage dynamics and water supply, as well as urban planning, due to sea-level rise.

Due to the fit-for-purpose nature of IUS, it is mandatory to include modelled impacts that may be of interest or required by stakeholders in addition to the general requirements for high-resolution urban modelling.

### 5.3.3 *Disseminating information*

Dissemination of information can be viewed at two levels: dissemination between scientists and modellers, in order to improve the conception and potential of the IUS, and dissemination between scientists and end users.

Interoperability is highly recommended for IUS conception as it simplifies the integration of services. The communication and visualization of high-resolution modelling results promote collaboration in the identification of possible new integrations. Coupling between models of several types is desirable scientifically, but it is also necessary to provide systemic impacts. Scientifically and technically, this could be done at different levels (coupling of models, coupling of results, integration into decision-making) that depend on specific tasks and IUS.

Information dissemination is essential between the various actors of the IUS. Co-construction is recognized as a critical approach that will often determine the success of the IUS and its appropriation and use by the city end user. This dissemination can be facilitated by collaborations as well as by technical facilities. City authorities could collect urban information and make it available following Spatial Data Infrastructure (SDI) standard formats and protocols. Furthermore, harmonization of input urban data is necessary to be able to produce cost-efficient and portable IUS from one city to another. It also helps the cross-fertilization between cities.

### 5.3.4 *Training specific urban research experts*

While cities are socially of primary importance and in need of early warning, urban planning or climate change adaptation IUS, NMHSs still encounter difficulties when targeting urban issues and developing specific IUS. Cities are (very) complex systems, and there is a need for collaboration between scientists of many disciplines: not only in the fields of the atmosphere, hydrology or environment, but also architecture, energy, economics, geography, social sciences and so forth. Such collaborations will build the necessary acculturation to comprehend the city and effectively exchange with other urban actors. It should be noted that this acculturation process takes time, and therefore should be started as soon as possible. Expertise from urban researchers will then facilitate communication with stakeholders and the public, and the conception and exploitation of IUS.

### 5.3.5 *Recommendations to National Meteorological and Hydrological Services*

Development of IUS is still in the early stages. Stakeholders may not be aware that NMHSs can provide pertinent information. Because NMHSs are national services, city stakeholders may think they provide services at the national scale , but not necessarily at the scale of the city. This may be perceived as a gap between the remit of the provider and receiver.

Implementation of the following recommendations would facilitate future development of IUS:

- NMHSs should develop urban research, in order to think generally (nationally) but to act locally (cities);
- NMHSs should strengthen urban hydrometeorology research, in order to improve high-resolution model performance in urban areas;
- NMHSs should coordinate with stakeholders/partners to improve the urban 3D observation network and urban environment data;
- WMO encourages the development and use of common, interoperable and replicable data standards;
- WMO Members are encouraged to set up joint demonstration projects with stakeholders, in order to test and assess high-resolution model applications for IUS.

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