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# Government-involved urban meteorological networks (UMNs): A global review

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ABSTRACT

Studies on urban climate are important to this rapidly urbanizing world as they play a role in monitoring the quality of life in urban areas. Urban meteorological networks (UMNs) have thus emerged in recent decades to collect data for urban climate research worldwide. Government involvement in an UMN project is beneficial to standardizing network configurations, maintaining stations durability, striking a balance between stakeholders from various disciplines, and the implementation of future climate-related policies. This review draws upon a total of 33 government-involved projects, examining their project objectives and outcomes, UMN configurations, and management methods. There are two common network types: single-sourced UMNs which are deployed more systematically, and crowdsourced UMNs which can be managed in a more cost-efficient manner while promoting citizen science. A major advantage of UMNs over conventional regional meteorological networks is its high-density setting that can increase spatial resolution of weather observations within the city. However, most UMNs are still at an experimental stage, and have room for improvement in data quality and robustness. Nevertheless, the reviewed projects demonstrated their importance in improving the understanding of urban microclimates, weather services, and cross-disciplinary research. To facilitate further advancement in the field of urban climate research, more comprehensive yet locally-adaptable guidelines are recommended regarding UMN setup, management, data quality check and interpretation. Governments are encouraged to continue taking the lead in collaborating with local communities and other cities, so that the full potential of UMNs in enhancing urban living quality and formulating future climate-related policies can be unleashed.

## 1. Introduction

Meteorological observation networks play a crucial role in monitoring climatic processes in cities, providing observational data for urban climate research. Understanding urban climate is essential for mankind as the global population residing in urban areas is continuously growing, being projected to reach 68 % by 2050 (United Nations, 2019). However, forecasting urban climate has become more challenging under the complex coupling between climate change and urbanization. The ascending frequency of extreme temperature events is visible under global warming (Mishra et al., 2015; Slater et al., 2021; Zhao et al., 2021), as well as compound

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extremes of temperature and humidity in urban areas (He et al., 2023; Li et al., 2020). Additionally, changes in rainfall patterns add stress to urban water supply and drainage systems, increasing the exposure of urban inhabitants to both drought and flooding (Güneralp et al., 2015; Warren et al., 2022). Meanwhile, heterogeneous urban environments further complicate microclimatic processes, which are influenced by various dynamic and thermal effects from the artificial landscape. For example, a high-density urban environment reduces advective ventilation from peripheral areas, retaining excess heat in city centers (He et al., 2021; Qiao et al., 2023; Rajagopalan et al., 2014). In light of the accelerating climate risks in cities, there is an urgent need to improve the understanding of meteorological network configurations specific to the unique characteristics and scales of urban areas.

Conventional meteorological observation networks are initially designed for synoptic and regional weather observation. These networks, hereafter referred to as regional meteorological networks (RMNs), are built systematically following the World Meteorological Organization (WMO) Document No.8: the Guide to Instruments and Methods of Observation (WMO No.8). This guideline provides detailed instructions and clear explanations for setting up an automatic weather observing system (AWOS) or automated surface observing system (ASOS) with optimized instrument performance (World Meteorological Organization, 2023b). However, automatic weather stations (AWSs) in RMNs are rather scattered, and may not adequately represent the diverse characteristics within urban landscapes, as highlighted by Oke, 2004 and Muller et al., 2013. The number of meteorological stations is often insufficient in high-density areas, and thus the geospatial differences in microclimate within the built environment cannot be captured.

Recently, meteorological observation networks specifically set up for urban areas, hereafter referred to as urban meteorological networks (UMNs), have been introduced and established in some cities worldwide. In general, UMNs are equipped with simple weather stations across a city, focusing on specifically one or several atmospheric parameters. Some are set up by universities or institutions for research purposes (e.g. Skarbit et al., 2017; Smoliak et al., 2015), some make use of amateur weather stations or smartphones to harness the potential of big data for real-time urban weather monitoring and forecast (e.g. Overeem et al., 2013; Vulova et al., 2020), while some also involve the management and application by local governments. The prime advantage of UMNs is the higher density of meteorological stations within urban areas, providing data with finer resolutions compared to those recorded by conventional RMNs. However, unlike RMNs which are standardized globally by established technical guidelines, UMN configurations vary greatly for different cities as each location has its unique urban geometry. Although the Chapter 9 on Urban Observations has been introduced in the WMO No.8 (World Meteorological Organization, 2023c) since 2008, outlining the guiding principles and key points to note when establishing an urban station, there are no universal standards tailored for UMNs. As a result, observations from different UMNs may be incompatible with each other, impeding inter-city scientific comparisons or technical knowledge exchanges for future UMN development.

The last comprehensive review of urban meteorological networks traces back to almost ten years ago by Muller et al. (2013). Developing from the basis of this review, it is timely to investigate the improvement in techniques and set ups used in the latest UMNs across the globe. This paper reviews and synthesizes the current state of government-involved UMN projects worldwide. Our objective is to delineate the strengths of UMNs and highlight challenges still faced by the urban observation community, so as to offer insights for their future development. In recent years, the importance of UMN studies and climate policies has grown significantly across different disciplines that address climate change issues. Therefore, there is a need to establish a more comprehensive understanding of the current state of the government-involved UMN projects. This review could serve as a reference for government entities, researchers, and urban practitioners, facilitating the continual development and enhancement of UMN techniques and standards in the future.

## 2. Methodology

To clarify the scope of this research, we need to define a few important terms. Firstly, a meteorological observation network is considered an UMN if they are specifically set up at various urban settings in addition to conventional AWOS and are spaced at a city or neighbourhood scale (around 10 km or finer; Muller et al., 2013). Secondly, in order to formulate more relevant and focused recommendations for the way forward, this review targets at 'government-involved UMN projects', which must meet at least one of the following criteria:

1) Directly initiated or implemented by national meteorological services;
2) Had significant involvement from government bodies; or
3) Funded by the European Union (EU), national meteorological services, or government research departments.

It is difficult to conduct a systematic review as different countries have various terms, definitions, or overall presentations of their UMNs. Therefore, as many as possible UMN projects are included to the best of the authors' effort and knowledge. With the timeframe of the literature search limited up to end-2023, the first step of the review process was a global search with generic key phrases on the scientific search engine 'Web of Science' to identify potentially relevant publications in the urban climate field. After trial-and-error, the optimized input phrases were 'Urban scale meteorological observation network' and 'Urban scale citizen weather stations/crowdsourced network'. The search was repeated with combinations of these phrases with different country names (Appendix A).

A second step to filter UMN projects fitting into the scope of this paper was then conducted. For preliminary results with accessible full papers written in English, they were manually filtered based on the three criteria stated above, and their abstracts were skimmed through to check for keywords such as 'urban-scale', 'meteorological observation', 'crowdsourced' (Appendix A). Some publications (Muller et al., 2013; Tan et al., 2015; Honjo et al., 2015) have summarized past UMN projects in tables – qualified government-involved projects from them were also identified and included for review. Furthermore, a last step to look for open-access documentations on non-academic websites was performed on 'Google' in attempt to encompass more relevant projects. Finally, 33 government-involved UMN projects (a total of 36 publications) were selected for review in this paper (Appendix B).

## 3. Overview of government-involved UMN projects

This section presents an analysis on the essential components of implementing an UMN gathered from the reviewed projects. These components include the project metadata, UMN configuration, network management, overall outcomes and impacts. A summary table can be found in Appendix B.

### 3.1. Project metadata

#### 3.1.1. Objective

The objectives of an UMN project are pivotal as they define the UMN positioning in existing observation systems and guide their future development directions. In general, UMN projects are launched to enhance the current observation dataset from synoptic-scale networks by overcoming the spatial limitation of conventional RMNs, and to utilize the urban observations in socioeconomic and public applications. Reviewed UMN projects often include at least one of following four specific research purposes: (1) Developing quality assurance (QA) and/or quality control (QC) methods to assure the data quality (e.g. Beele et al., 2022; Napoly et al., 2018; Nipen et al., 2020); (2) Developing new datasets for research and daily operational use (e.g. Kuchcik et al., 2014; Lagouvardos et al., 2017; Tan et al., 2015); (3) Refining or downscaling conventional RMN data using novel UMN observations (e.g. Chapman et al., 2015; Hicks et al., 2014; Sgoff et al., 2022); (4) Evaluating the potentials and robustness of UMN during operations (e.g. de Vos et al., 2020; Droste et al., 2020; Zumwald et al., 2021).

#### 3.1.2. Location

An overview of the number of government-involved UMN projects and their geographic distribution is presented in Fig. 1. A majority of the UMNs reviewed in this paper were implemented by European governments. The European countries contribute about two-thirds of the reviewed UMN projects (20, 61 %). Within the region, the Netherlands is the leading country when it comes to government-involved UMN research (5, 15 %), followed by Germany (4, 12 %), Belgium (2, 6 %) and France (2, 6 %). The remaining countries have a touch regarding this topic with one publication for reference (Fig. 1). Although not as active as in Europe, some governments in Asia (9, 27 %), North America (3, 9 %), and Oceania (1, 3 %) have also conducted UMN projects.

The uneven project distribution may be attributed to more open access documentations in Europe. It is also possible that there are more meteorological collaborations between European countries, an example being the European Meteorological Network (EUMETNET), which provided initiatives for data exchange and experience sharing in urban climate research. On the other hand, the

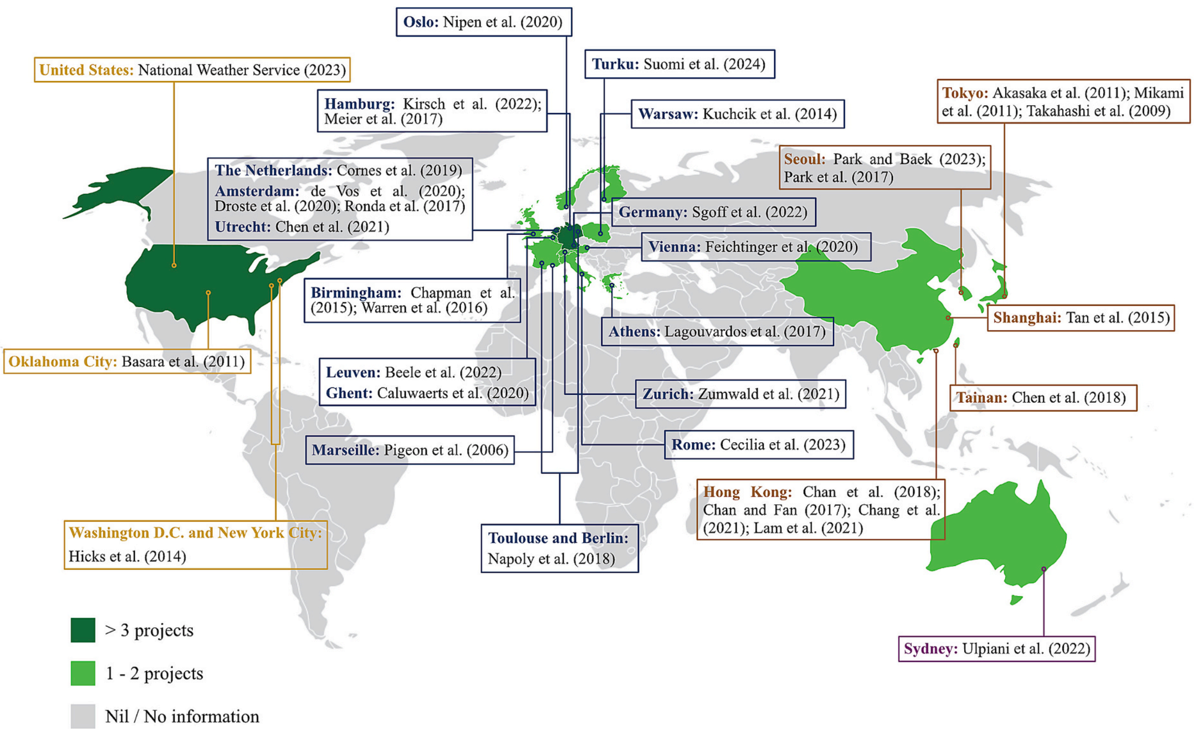


**Fig. 1.** The geographic distribution of UMN projects and associated publications worldwide.

vast landmass of North American countries could present challenges for their governments to set up and manage UMNs, while priorities would probably not be given to urban climate observations in developing nations where there are less funding and resources.

#### 3.1.3. *Duration*

In this review, the project durations are classified into three types: 1) Short-term, for projects lasting only for several days to at most 6 months; 2) Medium-term, for projects lasting from 6 months to 3 years; 3) Long-term, for projects that have been running more than 3 years. Most UMN are developed for long-term operations, but a shorter data period may be extracted from the long timeframe for specific studies, depending on the project type and objective. If the project ending date is not stated in the publications, we assume the project is still ongoing in 2023.

Reviewed studies are mainly long-term projects (18, 55 %), followed by medium-term projects (8, 24 %) and lastly, short-term projects (7, 21 %). The project duration is ~~also~~ highly dependent on the project objective, and is also related to the UMN type (see Section 3.2.1). For instance, the short-term projects are mainly for investigating one seasonal climate phenomenon or testing new equipment setup (e.g. Chan and Fan, 2017; Feichtinger et al., 2020; Kirsch et al., 2022), whereas the medium-term projects provide a foundation for trend analysis of specific climate events and developing robust data quality control methods (e.g. Kuchcik et al., 2014; Nipen et al., 2020; Park and Baek, 2023). The long-term projects usually do not solely focus on the scientific aspect, but also explore opportunities to incorporate urban weather observation data into different social applications (e.g. Chapman et al., 2015). Fig. 2 visualizes the data period of each project in the form of a timeline, showing an increasing popularity in UMN studies from the early 2010s. Since the earliest version of the WMO No.8 including the Urban Observations chapter was available in 2008, it may have may contributed to the growth of UMN studies.

### 3.2. *UMN configuration*

#### 3.2.1. *Network type*

UMNs can be classified into single-sourced UMNs or crowdsourced UMNs. A larger proportion of the reviewed government-involved UMNs belong to single-sourced networks (19, 58 %). Their weather stations are erected by the government. Official bodies have the right to amend original configurations and have full access to the initial data collected by these stations. The centralized management of such UMNs often allow them to be run for a longer duration of time. The remaining UMNs in this review can be classified as crowdsourced networks (14, 42 %), in which the stations are mounted individually by citizens or private bodies. This opportunistic sensing approach is becoming more popular for acquiring low-cost, high-density urban observations, but data from such crowdsourced UMNs may require additional in QC and maintenance as will be further discussed in Section 3.3.

It is a common practice for the government to outsource the data acquisition process and make requests for initial data from third parties who manage crowdsourced networks (e.g. Droste et al., 2020; Meier et al., 2017; National Weather Service, 2023; Nipen et al., 2020). Privately owned stations serve as a prevalent data source in current fine-scale urban climate research because there are fewer


**Fig. 2.** The duration and timeframe of each project specified in selected publications. Projects are assumed to run until 2023 if end date was not specified.

restrictions than conventional meteorological observation networks. They are more convenient in practice due to the flexible choice of sensors, which will be elaborated in the Section 3.2.4.

### 3.2.2. Station spacing

Referring to the spatial extent classification in Muller et al., 2013, conventional WMO-standard RMNs are typically of a mesoscale or a regional scale. In other words, their station separations are around 10–1000 km. Existing UMNs are mostly in a city or neighbourhood scale, where the station separations are below 10 km and much smaller than in RMNs. Specifically, neighbourhood-scale ($10^2$–$10^4$ m) networks account for around two-thirds (22, 67 %) of the reviewed UMNs (e.g. Akasaka et al., 2011; Basara et al., 2010; Chapman et al., 2015), while networks with city-scale ($10^4$–$10^5$ m) coverage only make a small proportion (5, 15 %). As an indication of the spatial resolution in weather data typically achieved by UMNs, the most common distances of separation between urban weather sensors and stations in previous research are 2.5–3 km and 5–10 km, respectively (Chapman et al., 2015; Chen et al., 2018; Kirsch et al., 2022). For crowdsourced networks, the distances between stations are highly variable as they depend on the spatial distribution of individual station owners. Yet, less restriction in spatial siting allows the density of some crowdsourced networks to be even higher, and as a result falling into the neighbourhood scale (8, 24 %) with distances between stations down to only a few hundred metres (Chen et al., 2021). By narrowing the separation distances between stations, UMNs can increase the spatial resolution of weather data and enhance the data richness within urban areas. Nevertheless, it should be noted that most of the reviewed UMNs currently do not provide coverage for the entire city, but cover only selected areas of interest.

### 3.2.3. Station siting

A conventional AWS should be placed in a flat, open space larger than 25 m × 25 m, assuring the measurements are not interfered by any obstacles in surroundings (World Meteorological Organization, 2023b, Volume I Chapter 1.3.3 Siting and Exposure). Noting that it is impossible for urban stations to conform to the same standards for site selection and instrument exposure of conventional AWSs due to the complexity of urban environments, the WMO has in fact laid out principles on the ideal site selection adapted for urban meteorological observations in Chapter 9 of the WMO No.8 Volume III (World Meteorological Organization, 2023c). It emphasizes on choosing a representative site that could reflect the typical conditions for the surrounding urban terrain. The sensor siting criteria should also be adjusted based on the UMN objectives and installation environment. Three typical approaches for weather station siting are identified from previous single-sourced networks. The deployment location of sensors will impact the quality and accuracy of data, which is crucial to subsequent meteorological research and application.

The first approach is based on the land use type in the city. As shown in Fig. 3a, covering as many as possible of the different land covers present, such as buildings, parks, roadside, etc., is the simplest method to ensure spatial diversity in the collected data (e.g. Cecilia et al., 2023; Chan and Fan, 2017). Local climate zone (LCZ), a climatic-based landscape classification method on the local-scale (i.e., hundreds of meters to several kilometres; (Stewart and Oke, 2012), is a more systematic way to distribute the weather stations according to the zoning classifications. Fig. 3b shows an example of such approach by Caluwaerts et al., 2020. This scheme facilitates inter-comparison of the observation data representative of each LCZ worldwide.

The second approach considers siting density when deciding the weather station locations. There are two strategies for distributing

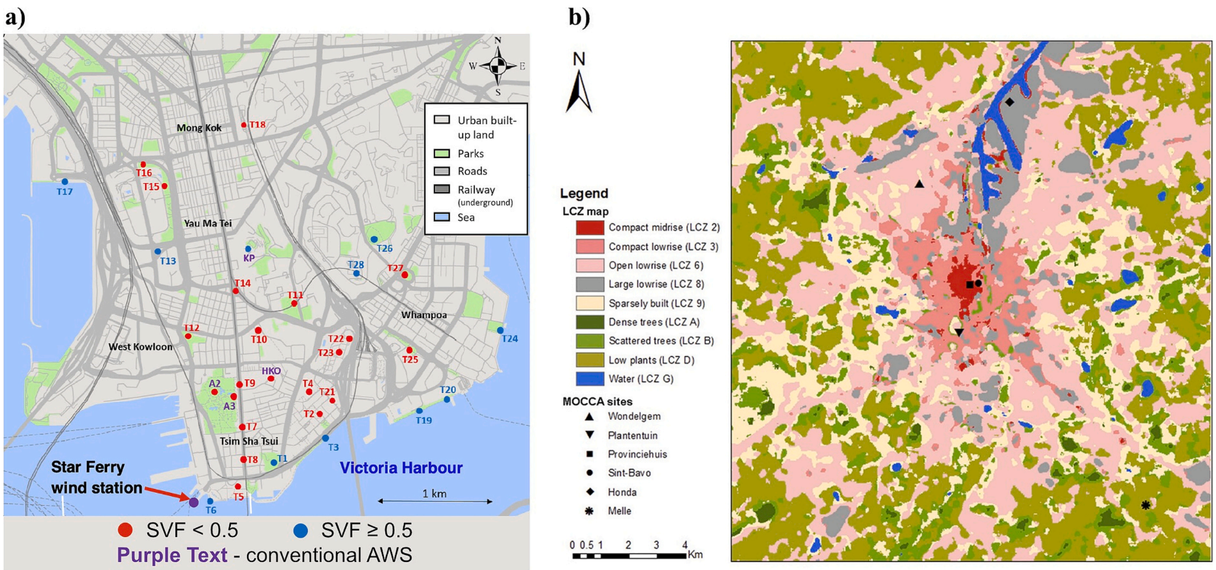


**Fig. 3.** Station siting based on a) spatial diversity and b) LCZ. Station maps are retrieved and modified from Chan and Fan, 2017 Fig. 1 '*i-button temperature observation network over the Kowloon peninsula.*' and Caluwaerts et al., 2020 Fig. 3. '*Overview of the MOCCA network on a local climate zone map of the study area.*', respectively.

sensors: homogeneous distribution in the urban areas or radiative distribution from the city centre to the suburban region. The homogeneous distribution method attempts to scatter the stations evenly within the site of investigation as illustrated in Fig. 4a (e.g. Cecilia et al., 2023; Chen et al., 2018; Ulpiani et al., 2022). As for the radiative distribution, the weather sensors are unevenly spaced as shown in Fig. 4b, with density being the highest at the city centre and gradually decreasing with distance from the city centre (e.g. Basara et al., 2010; Kirsch et al., 2022; Mikami et al., 2011). The choice of siting density distribution depends on the project objectives, for example whether the UMN is targeted for obtaining higher data resolution in the city centre or for investigating the transition in microclimate between urban and rural areas.

Weather sensors can also be distributed depending on weather parameters. These weather stations are strategically placed at locations exhibiting the most representative data characteristics for designated parameters, such as temperature and humidity (e.g. Pigeon et al., 2006; Warren et al., 2016). For example, in urban heat island (UHI) studies, weather stations are often placed at a location where it is the most suitable for capturing the urban temperature variability in built-up regions against greenery areas (e.g. Caluwaerts et al., 2020; Cecilia et al., 2023; Chen et al., 2018). There are also recommendations on measurement approaches for UHI studies by the WMO (World Meteorological Organization, 2023a). This approach is typically applied in UMNs implemented with specific research objectives, thereby accommodating the data collection and analysis processes.

There are some additional considerations for the station siting. The selected site should have a stable power source and communication network to ensure sensors collect and upload data promptly in real-time (e.g. Basara et al., 2010; Lagouvardos et al., 2017; Warren et al., 2016). Meanwhile, the locations should be easily accessible to technicians and volunteers (if any) for the convenience of maintenance (e.g. Kirsch et al., 2022; Lagouvardos et al., 2017). Furthermore, the urban weather stations should, as far as possible, be placed in relatively open spaces and at a distance from tall buildings. Commonly selected locations include the rooftops of schools, mounted on traffic lights, and inside urban parks. It is crucial to ensure that there is enough exposure for the sensor and it is not directly obstructed by neighbouring artificial structures or influenced by anthropogenic emissions. Reference can be made to the WMO siting classification scheme (e.g. Akasaka et al., 2011; Chan et al., 2018; Chapman et al., 2015).

It is worth mentioning that for crowdsourced networks, systematic or strategic planning of station siting is difficult as each station is operated by individual owners. The layout and distribution of crowdsourced UMN weather stations therefore cannot be determined at the early network design stage. Overall, the siting of urban weather stations within the city depends on the complex physical environment and needs to be fit for purpose.

### 3.2.4. Station type

It is common for the two introduced network types to adopt different types of stations. In single-sourced UMNs, weather stations are typically more multifunctional and are maintained by government meteorological services or volunteers recruited by officials. The stations can be categorized as all-in-one stations and self-assembly stations. An all-in-one station is a professional weather station that has been calibrated and can be used instantly after purchase to measure multiple variables, such as temperature, humidity, wind, radiation, etc.. Contrarily, a self-assembly station is assembled using the same/different brand(s) of sensors and data loggers. It is recommended that these sensors are calibrated against reference stations before being deployed into the observation network.

In crowdsourced UMNs, weather stations are often plug-and-play weather stations. They are simple to use, compact in design, and do not have fixed initial physical configurations nor specific software settings. This kind of amateur weather station is popular among

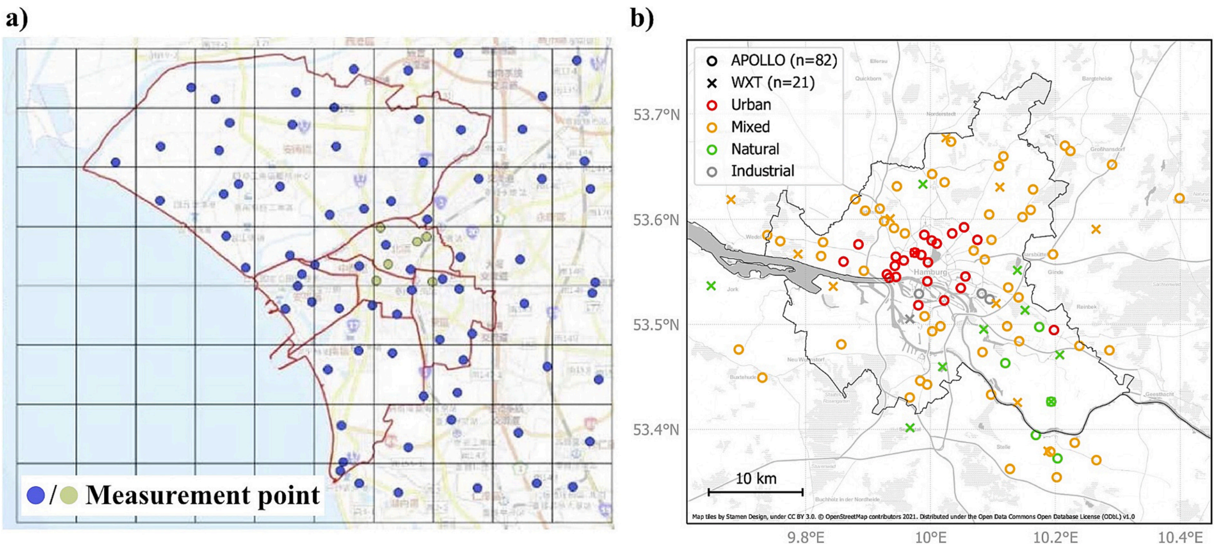


**Fig. 4.** Station siting in a) homogeneous distribution and b) radiative distribution. Station maps are retrieved from Chen et al., 2018 Fig. 3e. '*The results of total 100 measurement points.*' and Kirsch et al., 2022 Fig. 5 '*Map of measurement locations of APOLLO and WXT weather stations during the FESST@HH 2020 experiment.*', respectively.

citizens as they are available at affordable prices. Installing the stations in dwellers will concurrently form a dense sensor network in a city. In this context, governments can receive local scale observation data via various data sources by accessing companies' online databases or inviting the public to upload their data to government-managed crowdsourcing platforms. Among the reviewed projects involving crowdsourced data provided by different brands of personal weather stations, Netatmo appears to be the most widely adopted in urban climate research. (e.g. de Vos et al., 2020; Droste et al., 2020; Feichtinger et al., 2020; Meier et al., 2017).

### 3.2.5. *Sensor position*

Heights of 2–3.5 m above ground and on building rooftops are the two most prevalent vertical positions adopted in the reviewed single-sourced UMNs. These positions prevent the data from being disturbed by human activities near the surface.

Most of the UMNs set the sensor height at 2–3.5 m above ground (Caluwaerts et al., 2020; Chen et al., 2018; Kuchcik et al., 2014; Lagouvardos et al., 2017; Pigeon et al., 2006; Ulpiani et al., 2022). Some sensors installed on lampposts are placed between 3.5 m and 10 m (Basara et al., 2010; Ronda et al., 2017). As for sensors located on rooftops, their approximate height above ground is 12–16 m for a building with four to five floors and assuming each floor is 3 m in height (Akasaka et al., 2011; Cecilia et al., 2023; Lam et al., 2021). The crowdsourced networks do not provide information about the vertical siting height because the sensor height is subject to the users' preference.

According to the World Meteorological Organization, 2023b, the screen height of urban-based stations can be 0.5–1.5 m greater than their suggestion, which is normally 1.25–2 m above ground. This adjustment is made considering the practical aspects of the network execution, such as security concerns, mounting prerequisites, and internet access. The World Meteorological Organization, 2023b mentions that the observation height should preferably not have a significant deviation from standard height observations of ASOS. It also pointed out caveats of placing stations on rooftops as they often create a unique microclimate from that within the urban canopy due to modified airflows and different construction materials. Nevertheless, studies by Lam et al., 2021 and Cecilia et al., 2023 indicate that sensors on the rooftop are also reliable in obtaining representative data of the urban atmospheric processes. Therefore, the vertical siting height of sensors in most of the reviewed projects are generally in the acceptable range for obtaining representative data.

### 3.2.6. *Weather variables measured*

An UMN typically records several weather variables, and air temperature is the most analysed variable for research application and network validation after the measurement. More than half of reviewed projects measure 4–6 weather variables (20, 61 %), and some even more than 7 (5, 15 %). Self-assembly stations are usually simpler and designed to observe only 1–3 specific variables (8, 24 %). Most reviewed projects configured networks capable of measuring various weather variables, but most projects did not utilize all available variables in the network validation stage and urban climate analysis. The most studied variable from the reviewed UMNs is temperature (31, 94 %), followed by wind speed (13, 39 %) and wind direction (9, 27 %). Other variables that have been measured but less commonly utilized in follow-up analyses are humidity (8, 24 %), pressure (8, 24 %), precipitation (6, 18 %) and solar radiation (4, 12 %). This result indicates that current urban climate research heavily focuses on fine-scale temperature analyses, such as the UHI phenomenon. Other emerging areas of interest are on wind variability, street canyon ventilation and dispersion studies (e.g., Droste

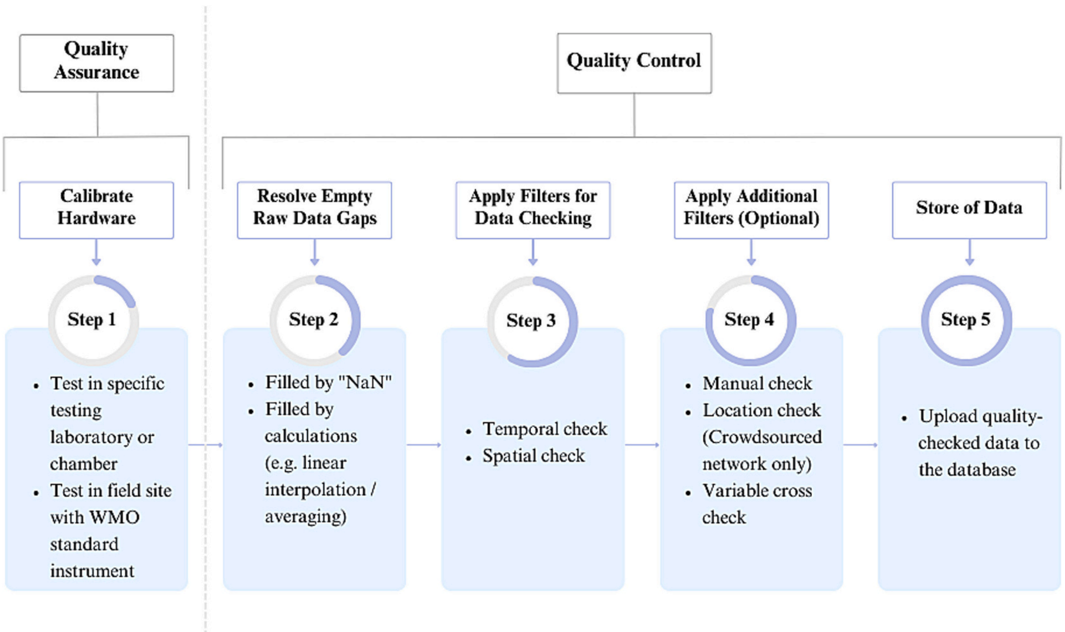


**Fig. 5.** General QA and QC procedures in previous UMN projects.

et al., 2020; Feichtinger et al., 2020; Hicks et al., 2014). By making use of all the available weather variables from UMNs, the research topics could be further diversified with the urban microclimate more comprehensively understood.

## 3.3. Network management

### 3.3.1. Data processing and quality control

Data measured by UMN stations must be processed appropriately before they can be used in relevant studies and applications.

First, it is necessary to review the raw data time interval as the data timestamp is important to future data manipulation and analysis. There are two ways to adjust the time interval of the raw data before uploading them to the server – time aggregation and direct transmission. Time aggregation means that the data are temporally averaged to a time interval larger than the one actually measured before being uploaded and saved to the database. A few of the reviewed networks aggregate the raw data time interval (4, 12 %). For example, with the original measurement interval being <20 s, data are aggregated to 1–10 min intervals for storage (Beele et al., 2022; Caluwaerts et al., 2020; Kuchcik et al., 2014). The advantages of this method are saving up storage and filtering out noise from high-resolution data; however, some temporal details in the measurements may be lost and it requires an additional setup in the initial upload settings. Direct transmission refers to unprocessed data being directly uploaded to the server after measurement. In other words, the data time interval equals the sensor timestamp. This method is more straightforward and easier to implement. A significant proportion of networks apply the direct transmission method at the data collection stage (23, 70 %). The data time interval of this data transmission method is usually between 1 and 10 min (e.g. Basara et al., 2010; Meier et al., 2017; Warren et al., 2016). The goal of raw data time interval adjustment is to ensure the data are representative as the temporal resolution significantly impacts the quality control procedures, research methodologies, and future data analyses.

Typically, the collected data are then passed through a network data validation process to ensure data quality. Quality assurance (QA) is executed before the station deployment, while quality control (QC) is conducted after the raw data acquisition. The general procedures of QA and QC are shown in Fig. 5. Two-thirds of the projects conduct QC procedures to detect missing and erroneous data (22, 67 %), while QA is a less popular practice in the reviewed projects (12, 36 %). QA focuses on hardware calibration with standardized equipment before the start of a project. It is often a time-consuming process. Most projects, especially the ones employing plug-and-play stations, adopted the sensor calibration range from manufacturers. It is easier for single-sourced UMNs to perform QA procedures, such as calibration with a standardized RMN station or laboratory testing (e.g. Chapman et al., 2015) before installation. On the other hand, the data quality of crowdsourced UMNs with stations independently installed by different owners relies heavily on the QC procedures after the observation. Reviewed projects either develop their own QC method (e.g. Lam et al., 2021; Napoly et al., 2018) or perform QC methodology scripted by previous researchers as open-sourced codes (e.g. Feichtinger et al., 2020; Zumwald et al., 2021). Given the importance of data representativeness and quality for subsequent analyses, it would be more ideal to include both QA and QC in UMN projects. However, only a minority of projects include both QA and QC stages (8, 24 %). There is thus still room for improvement in data quality enhancement in the future.

### 3.3.2. Station maintenance

The station maintenance routine is occasionally covered in the documentations of previous projects. Around one-third of the reviewed projects briefly describe their station maintenance routines (10, 30 %). Station maintenance is essential as it ensures the proper functioning of the network and extends its time of service. The basic maintenance procedure involves regular site visits for sensor inspection and calibration. The assessment period depends on the type of weather station. All-in-one stations are approximately checked every 1–2 years (e.g. Basara et al., 2010; Ulpiani et al., 2022), while self-assembly stations require more frequent checking, varying from every 10 days to 3 months, mainly for battery replacement and preventing them from malfunctioning due to network disruption etc. (e.g. Mikami et al., 2011; Warren et al., 2016). Systematic, top-down station maintenance is often not applicable to crowd-sourced networks because the stations managed individually by the station owners and may be set up on private land. From the experience of the reviewed projects, the maintenance of UMNs requires substantial resources, including staff to visit the stations one by one regularly. Thus, the denser the UMN, the more time is required for the maintenance routine. With the involvement of the government, it seems more resources can be leveraged for maintaining such UMNs.

## 3.4. Outcome and impact

The fine scale data collected by the reviewed UMN projects provide a solid foundation and useful indication for policy implementation and climate change mitigations. As mentioned in Section 1, the intensification of extreme weather and growing imperatives in recent decades have prompted nations to react to the adverse impacts brought by climate change, particularly in cities where a majority of the global population resides. The deployed UMNs, therefore, become crucial reference data sources (e.g. Cecilia et al., 2023; Kuchcik et al., 2014; Meier et al., 2017; Pigeon et al., 2006). The data collected help to quantify current urban climate phenomena and extremes within urban areas, such as the UHI, making it easier for policymakers and stakeholders to grasp the intensity of events. The climatological information could also be combined with different environmental and health data for a coupled analysis of their impacts on the society and ecosystem. Most of the reviewed government-involved UMNs were launched in effort to provide a scientific basis for supporting future policy and legal implementation. The role of urban-scale observation data must therefore be acknowledged in future climate change adaptation planning.

In addition to facilitating the policy planning process, UMNs also foster smart city evolvement as the physical component of the network can be integrated into the intelligent systems of a smart city (e.g. Park and Baek, 2023). Though UMNs are initially designed for urban meteorological observation, the spectrum of data collected can be expanded by installing additional equipment, such as an air pollutant sensor and noise level meter, at the same locations. Real-time urban information can be applied in different disciplines when the network coverage is sufficient and the integrated systems become mature. There are only several reviewed projects that have considered extending the UMN to smart cities applications thus far (Akasaka et al., 2011; Chapman et al., 2015). Governments are encouraged to consider extending the applications of the deployed UMNs towards smart city development in the future.

Besides the tangible benefits in data collection and urban climate research, an UMN can act as a pioneer in exposing citizens to different scientific fields. Nowadays, more projects try to combine citizen science concepts in their implementation. Citizen science is not only an effective way of public education, but also a channel to engage layman participants in science. More importantly, these participation programs can engage stakeholders in science and policy planning, bridging citizens with the government and researchers. In the context of UMNs, most projects with citizen science elements have proven that crowdsourced data can be a reliable data source (e.g., Chapman et al., 2015; Meier et al., 2017; Nipen et al., 2020; Ulpiani et al., 2022). These projects not only encourage the progress of research and public data sharing, but could also narrow the gap between the general public and official authorities, and stimulate public interest in research and science. With proper public education and active support by the general public, the deployment of UMNs would be more widely accepted and the number of reliable observation points could increase significantly.

In a nutshell, UMNs provide valuable real-time meteorological observations in the urban areas. They also yield unprecedented effects outside the science field, providing a concrete and solid foundation for social, technological, and policy development in the city.

## 4. Discussion

In this discussion, we first summarize the strengths and challenges of UMNs with respect to RMNs drawn upon the extensive review of UMN projects. For our regional interest, experience from UMN projects in Hong Kong are highlighted and briefly discussed. Finally, some suggestions for the way forward of global UMNs are provided.

### *4.1. Strengths and challenges of UMNs*

#### *4.1.1. Strengths of UMNs*

- Compared to conventional RMNs, UMNs have a much higher station density and thus finer data resolution for real-time monitoring and subsequent analyses. The WMO standard guidelines for RMNs required stations to be installed in open, unobstructed, and vegetated spaces, which are scattered and rarely found within city centers. Contrarily, the siting and installation guidelines for UMNs are less strict and most previous research adjusted them according to their study objectives and characteristics of local urban environments. The flexibility and freedom in station siting and configuration give rise to dense urban UMNs set up at accessible locations all over the city.
- With a high-density station network, UMNs can serve as a supplementary network that overcomes the limitations of RMNs by representing local weather conditions more accurately and in more detail. They can also better reflect the spatial variations in weather elements within urban areas felt by citizens. By assimilating UMNs' observations to the traditional weather forecasting systems, errors and biases in the forecasting models can be corrected, improving the overall weather forecast (e.g. Nipen et al., 2020).
- Located at accessible locations in cities, UMNs can be an excellent medium for citizen science education and public participation. They can also fit into the bigger picture of a smart city development, carrying multiple functions in addition to weather monitoring. There have been several successful examples in the United Kingdom, Japan, and South Korea (e.g. Akasaka et al., 2011; Chapman et al., 2015; Park and Baek, 2023.

#### *4.1.2. Challenges of UMNs*

- The first challenge lies in siting and representativeness of data. It is inevitable that the UMN stations sited within the urban areas can be substantially influenced by the heterogeneous urban environment and human activities. The measured data may therefore only represent conditions representative of a very limited area. While local governments are enjoying high flexibility in setting up urban stations, guidance for optimizing their siting to minimize potential influences from the urban surroundings should be better established and followed. Though the WMO dedicated a section to urban observations in the Guide to Instruments and Methods of Observation to UMNs, it is difficult to apply universal standards to all cities worldwide each with their own highly variable and complex urban configurations. Most of the reviewed UMNs adopt local standards catering individual project needs; however, the

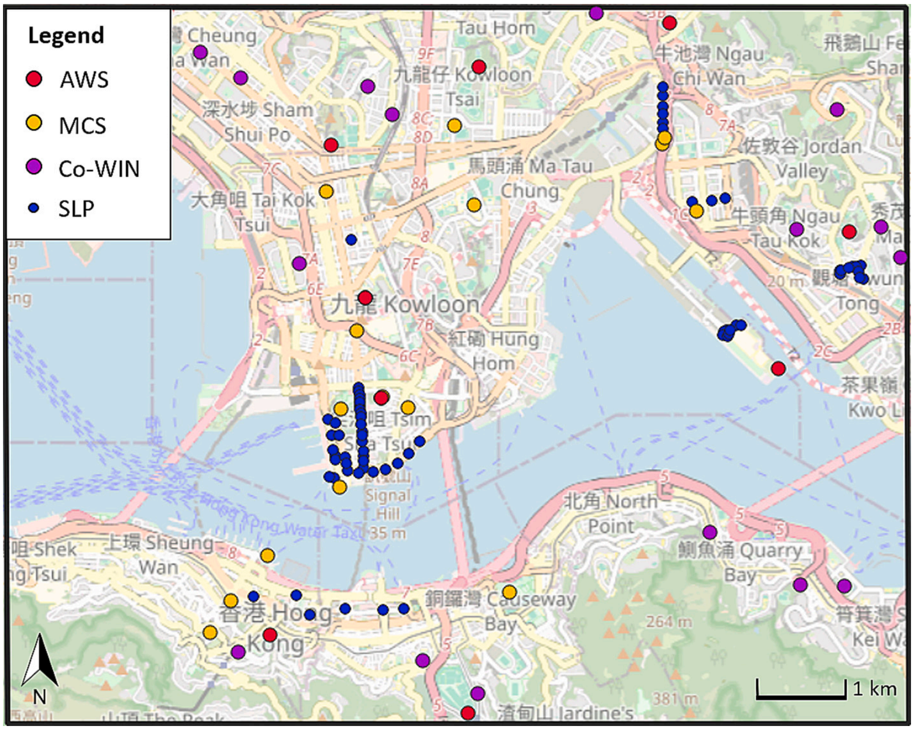


**Fig. 6.** Locations of AWS, MEMS microclimate stations (MCS), Co-WIN stations, and SLPs over the major urban areas of Hong Kong (base map retrieved from OpenStreetMap 'openstreetmap.org' under the Open Database License 'opendatacommons.org').

inconsistency in siting and instrumentation result in measurements being incompatible with other networks, hindering inter-comparison against other UMNs or RMNs.

- Another challenge is on UMN data processing and analysis. Given the diverse equipment setup and sensor locations of urban stations, data QA and QC would be essential to ensure data robustness and representativeness. As noted by Chapman et al. (2015), the sensors should be intercompared and calibrated with official stations complying WMO standards before being installed in the weather station to ensure they can function properly and operate to standards throughout the observation period. After the observation, the data should pass through dedicated QC procedures to further reduce erroneous data (Warren et al., 2016). The entire process effectively raises the robustness of the data, such that the data can be reliably utilized in real-world applications. However, it is uncommon to see projects implementing both the QA and QC procedures in their research.
- Most UMNs did not adopt the FAIR principle, which emphasizes the findability, accessibility, interoperability, and reusability of scientific data for facilitating the long-term use and stewardship of data in research communities (Wilkinson et al., 2016). Most collected data by current UMNs are kept for in-house study purposes and not shared in open-access platforms, therefore lacking interoperability and reusability. Data from crowdsourced networks are usually slightly more findable and accessible as data they can be automatically synchronised or manually uploaded by weather station owners to weather data websites (e.g. Weather Observations Website, Netamo Weather Map). Besides, governments may be reluctant to publicize the data collected by UMNs due to concerns over data security and confidentiality of internal operations.
- In synoptic scale analysis based on RMNs, it is often reasonable to map out contours of weather elements (e.g. mean sea level pressure in weather charts) to depict the prevailing weather patterns. However, when it comes down to the city scale or smaller, it could be a challenge given the rapidly and sharply changing microclimate processes in time and space. Some studies make use of a simple spatial interpolation between a dense UMN (e.g. Chan and Fan, 2017; Nipen et al., 2020) in attempt to obtain a full coverage of the microclimate variations within an urban area, but the interpolated data may be susceptible to large errors as they did not take into account of the local heterogeneities in between stations. Therefore, extra care must be taken when interpreting and generalizing the measured data in urban climatic analyses.
- Lastly, with a much greater number of stations in an UMN compared to a RMN, the cost of maintenance would be higher. A lot of labour and time would be required for regular health check of sensors. Stations that are set up at public and exposed locations may also bear risks of being stolen or damaged. As many UMNs are still at an experimental stage, a dedicated team or workers and

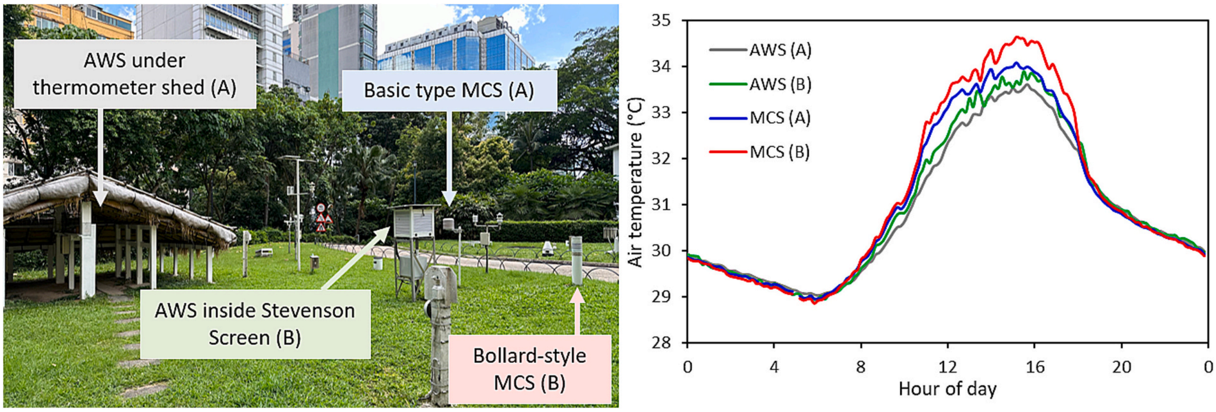


**Fig. 7.** (left) Different sensors located on the HKO meteorological garden and (right) their recorded mean diurnal variation of air temperature from 9 to 31 July 2022 (data plotted at 10-min intervals).

continuous source of research funding may be more difficult to secure, especially with the change of political parties having different priorities in social development and technological initiatives.

### *4.2. Case study: Government-involved UMN projects in Hong Kong*

Hong Kong is a subtropical coastal metropolis located over the eastern part of the Pearl River Delta, China. With a total area of just above 1000 $km^2$, of which only a quarter is classified as built-up (Planning Department, 2023), it is home to about 7.5 million people. Its diverse landscape and complex urban environment make it a perfect testbed for urban climate studies. Experiences from three government-involved UMNs implemented in Hong Kong are briefly discussed in this section.

Hong Kong Observatory (HKO), the governmental body responsible for providing the city's meteorological services, launched a collaborative project with local universities and schools since 2007 called the Community Weather Information Network (Co-WIN). The primary objective of Co-WIN is to promote weather and climate education among participating schools. A crowdsourced UMN equipped with low-cost 'do-it-yourself' (or self-assembly) modular sensors at over 100 locations was thus formed (Lam et al., 2021; Lee and Lee, 2021; Tam et al., 2017). The weather data, including temperature, humidity, rainfall, wind, solar radiation, mean sea level pressure, gathered are publicly shared online in real-time (https://cowin.hku.hk/), and can supplement the official weather observations made by the AWOS of HKO. However, the locations of these stations, mostly on the rooftops of school buildings, are subject to environmental constraints and the maintenance of stations depend heavily on resources and support available at individual schools, leading to high data variability and unstable availability of observations. Therefore, much work has to be done on data QC before application in scientific research (Lam et al., 2021).

In addition to its well-established network of over 100 AWSs in operation, the HKO initiated a microclimate observation project in 2017 using 'i-button' temperature sensors set up over Kowloon, an urban centre of Hong Kong (Chan and Fan, 2017). The project faced a major challenge of sustainable human resources, as the sensors powered by internal batteries required manual data retrieval regularly. With government technology funding support in 2018, the network was enhanced and expanded with solar-powered microelectromechanical system (MEMS) sensors (Chan et al., 2018) which allowed real-time automatic data transfer via the 4G or LoRaWAN network. These stations measured additional weather elements, including relative humidity, air pressure, and UV-index. The HKO also patented a bollard-style housing for the MEMS sensors such that they can blend in better to urban landscapes. As of the end of 2023, around 30 microclimate stations (MCS) have been established over urban and suburban areas of Hong Kong and covering various environments such as dense urban districts, urban greening, coastal areas (Lau et al., 2024).

A third government-involved UMN in Hong Kong was implemented as part of the Multi-functional Smart Lampposts (SLP) pilot scheme (GovHK, 2019), aiming to promote smart city development by collecting real-time city data, such as air quality and traffic flow, and supporting a city-wide 5G mobile network. This project missed the search radar of the review as it was not packaged as an 'urban climate' project, nor was it documented by any academic publications. Over the past few years, around 70 SLPs equipped with off-the-shelf compact meteorological sensors that measure air temperature and relative humidity, as well as wind speed and direction for roughly half of them, were progressively installed along selected roads. The sensors are placed at two levels, 3–5 m or 10–12 m off the ground, depending on the height of the lamppost. The data collected are released to the public as open data, but their usage in scientific research and applications are still currently limited, probably due to the relatively short data period and the highly concentrated yet uneven sensor distribution within the city for comprehensive studies.

The locations of operational AWS and microclimate stations with active measurements (as of 2024) from the three UMNs mentioned above within the urban areas of Kowloon and Hong Kong Island are plotted in Fig. 6. It is clear that such UMNs can increase the spatial resolution of weather observation data and help to delineate neighbourhood-scale weather conditions more precisely. However, observations made by microclimate stations are more susceptible to environmental influences, including surrounding landscapes, surface properties of artificial materials, and human activities. Besides, compared to RMNs which have pretty standard AWS setup with meteorological sensors housed inside Stevenson Screen, the configuration of UMNs vary in equipment setup and sensor types. In particular, UMNs often adopt more light-weight and compact protection covers for more flexible deployment (Kwok, 2022; Lee and Lee, 2021). During a fine spell in mid- to late July 2022, the mean temperature recorded by different equipment setup at the same location was found to differ up to 1.5 °C during the day (Fig. 7) and the maximum temperature difference for a certain timestamp could even reach 3 °C (not shown). This example illustrates the potential challenge in integration and comparison of data between UMNs and the importance in QA and QC procedures before conducting urban climate analyses. Nevertheless, observations from UMNs in Hong Kong have been applied to better understand the temporal and spatial temperature variations in the city under different wind regimes (Chan et al., 2018; Chan and Fan, 2017) and as a result of different land surface characteristics (Lam et al., 2021; Lau et al., 2024). The HKO has also attempted to develop urban temperature forecasts by incorporating measurements from UMNs into statistical downscaling models (Chang et al., 2021) and post-processing algorithms (Kwok et al., 2023), so to enhance public weather services and allow citizens to gain better access to weather changes within urban areas when planning activities or assessing health risks especially related to urban high temperatures. Moreover, the real-time temperature data collected by a microclimate station next to the district cooling system in east Kowloon was utilized to adjust chiller plant outputs, thereby saving electricity (Lau et al., 2024). Therefore, although challenges remain in standardizing and managing UMNs, there is much potential in their contributions to urban climate investigations, local weather services, and even inter-disciplinary applications in the energy or health sectors as illustrated by the lessons learnt from Hong Kong.

### *4.3. Recommendations and outlook*

#### *4.3.1. Standardization in setup and management of UMNs*

The WMO No.8 serves as an essential reference for development of weather observation networks globally. Inclusion of the general guidance on urban observations has likely encouraged more meteorological agencies and researchers to develop UMNs since 2008. Positive response from the urban climate research community may have then fostered subsequent revisions of the WMO No.8 Chapter 9, forming a positive feedback cycle. On the other hand, standard synoptic weather stations set up in compliance with the WMO No.8 standards were often used to crosscheck and calibrate observations from UMNs (e.g. Caluwaerts et al., 2020; Cornes et al., 2020; de Vos et al., 2020; Lagouvardos et al., 2017).

However, previous research noted that it was difficult to follow the ideal principles set out in WMO No.8 and thus many preferred to adopt self-defined siting and instrumentation approaches, especially for crowdsourced networks (e.g. Cecilia et al., 2023; Feichtinger et al., 2020; Lam et al., 2021; Nipen et al., 2020; Sgoff et al., 2022; Zumwald et al., 2021). With less comprehensive and restrictive guidelines adopted globally for UMNs, much inconsistency in station siting, network configurations, equipment setup, and data processing exists among different countries or even within the same city, e.g. the three different UMNs in Hong Kong (see Section 4.2). Urban environmental constraints and other factors such as station management and available resources also lead to differences in UMN configurations. These factors impede comparative studies or project collaborations as the so-called standards may not be compatible between networks. Moreover, though the LCZ scheme has been introduced by Stewart and Oke (2012), there is currently no universally accepted scheme on urban classification specific for the purpose of microclimate monitoring.

Being a representative scientific organization, the WMO could further enhance the current guidelines on urban weather observations (World Meteorological Organization, 2023c) by providing more comprehensive standards and concrete requirements for UMN setup that could ensure similar data representativeness and quality across cities, yet adaptable to the wide spectrum of urban forms. Examples of UMNs in demonstration cities could be provided such that others can learn from their success. Practical suggestions on choice of sensors and guidance on network management are also recommended for sustaining the data quality and improving the network's durability. To facilitate future UMN development and allow intercity comparative studies, it is crucial that governments work together to adopt similar standards when setting up their UMNs. The FAIR principle for scientific data could also be promoted to UMN managers so to further improve the usability of collected weather data among interested stakeholders. However, such standardization process would take time and more challenges are foreseen when it comes to crowdsourced networks which governments often has less control over. Nevertheless, implementation of city-specific and non-standardized UMNs are still highly encouraged to enrich the database in urban observations and for citizens and researchers to gain more experience in the field of urban climate.

#### *4.3.2. Roles of the government in UMN projects*

The reasons for a government to initiate an urban weather observation project can be twofold. First, the government can provide stable financial support for the UMN, which requires notable implementation and maintenance costs. This will contribute to prolonging the lifespan of an UMN and ensuring sustainable management and operation. It is also more convenient to deploy standardized setup within a top-down, single-sourced UMN. Secondly, the government can utilize data collected by the UMN to improve official weather services and benefit from the fine-resolution weather data by applying them to other disciplines, such as energy saving. Besides, with evidence from microclimate observations, the government can react more promptly in the review of policies relating to urban heat-health or environmental quality issues. There would be less misunderstandings and a more effective communication process between science and policy stakeholders when discussing climate policies and mitigation strategies. With reference to the Hong Kong case study, HKO has implemented various types of UMN in the past decade in collaboration with local universities and community stakeholders to test which UMN is the best-fit network in the urban settings of Hong Kong. This example demonstrates the importance of government involvement in scientific research and foresight in data implementation for different social disciplines. Hence, to launch a durable, cost-effective and community-accepted UMN, the active involvement, or leadership, of a government is indispensable, especially in the provision of reliable financial resources and bringing various sectors in society and science together.

Global governments have visibly put more emphasis on urban climate research in recent decades. However, notable time is still required before reliable and persuasive results can be obtained and widely applied. Thus, there is more work for the full potential of UMNs to be unleashed. In the short term, governments could aim to continue developing and promoting permanent UMN networks, both single-sourced and crowd-sourced. In the long term, governments should share experiences and work towards establishing a set of comprehensive and standardized guidelines under the framework of WMO for future UMNs. Under climate change and urban population growth, UMN projects serve as crucial drivers in connecting science and different stakeholders regarding climate change issues and mitigation policies.

## 5. Conclusion

In this paper, we reviewed 33 worldwide government-involved projects with UMNs that are dedicated to urban climate observations. The network nature, strengths and constraints of the projects can be summarized as follows:

- UMNs are developed to overcome the limitations and complement the measurements of conventional RMNs. They can capture sub-synoptic scale atmospheric dynamics and processes unique within cities, providing a high-resolution urban weather observation dataset for diverse applications in urban climate research and other social disciplines.
- Government officials and research groups configure their networks according to their project objectives and goals. The two main network types are single-sourced and crowdsourced, each with their advantages and challenges in terms of station setup, spatial siting and network management, impacting the corresponding data representativeness and network sustainability.
- UMN development remains in its nascent stages with yet a globally standardized measurement approach, and thus posing difficulty in large-scale inter-city comparative studies. QA and QC procedures are essential to ensure consistency and reliability in the measured data. Moreover, subsequent analysis and applications of the observed data are rather focused on urban temperature studies. Nevertheless, governments have much incentive to continue in UMN projects as they are effective in promoting citizen science and are important in future climate change policy decision-making.

The main purpose of this study is to give an overview of the current state-of-the-art of the government-involved UMN projects worldwide. This review will hopefully serve as a useful reference for future UMN development or the implementation of more comprehensive standard guidelines. Governments play a crucial role in the development of sustainable cities. Their involvement in UMNs benefit research and applications in various physical and social science topics, such as human thermal comfort, urban greening, liveable city designs, climate mitigation etc.. All these studies are key drivers for achieving Goal 3 (Good health and well-being), Goal 11 (Sustainable cities and communities) and Goal 13 (Climate action) laid out in the 2030 Agenda for Sustainable Development (UN General Assembly, 2015). Hence, the fine-scale, high-quality observations of microclimate processes within cities by UMNs can be a pivotal game changer in climate mitigation efforts and sustainable city development, bringing synergistic effects to urban social studies and climate science in the foreseeable future.

Lastly, it needs to be acknowledged that the list of UMN projects reviewed in this paper is by no means exhaustive. A major limitation of this review comes from the difficulty in identifying all relevant UMN projects using a systematic screening process. The lack of a standard definition of the term 'government-involved', as well as variations in project naming and documentation in different countries also make it difficult to ensure no existing projects are left out, especially those not documented in scientific publications that are accessible online and written in English. The somewhat manual shortlisting method detailed in Section 2 may have overlooked some potential research but we have tried our best to include as many UMN projects as possible.

## CRediT authorship contribution statement

**Carmen Hau Man Wong:** Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Yu Ting**

**Kwok:** Writing – review & editing, Writing – original draft, Formal analysis. **Yueyang He:** Writing – review & editing, Methodology. **Edward Ng:** Supervision, Conceptualization.


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## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.


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## Appendix A. Supplementary materials on the literature search process

Publication search formula in the 'Web of science':

| | | | | |
|---|---|---|---|---|
| Urban Scale | + | meteorological observation network<br>citizen weather stations / crowdsourced network | + | (Name of country)# |

# List of country names applied in the search formula:

| Albania | Cambodia | Estonia | Israel | New Zealand | Slovenia |
|---|---|---|---|---|---|
| Argentina | Canada | Finland | Italy | Norway | South Africa |
| Australia | Chile | France | Jamaica | Peru | Spain |
| Austria | China | Georgia | Japan | Philippines | Sweden |
| Bangladesh | Colombia | Germany | South Korea | Poland | Switzerland |
| Belarus | Costa Rica | Greece | Latvia | Portugal | Taiwan |
| Belgium | Croatia | Hungary | Lithuania | Romania | Thailand |
| Bhutan | Cuba | Iceland | Luxembourg | Russia | Turkey |
| Bosnia and Herzegovina | Cyprus | India | Malaysia | Serbia | United Kingdom |
| Brazil | Czech Republic | Indonesia | Mexico | Singapore | United States |
| Bulgaria | Denmark | Ireland | Netherlands | Slovakia | Vietnam |

Supplementary keywords for manual filtering and search in the public search engine 'Google':

- Automatic Weather Stations
- Observation Network
- Crowdsourced
- Meteorological observations
- Microclimate
- Urban / City / Neighbourhood – scale
- Urban Weather / Climate

## Appendix B. Summary of the reviewed publications

**Table B1**

Summary of the 36 reviewed publications regarding their project metadata (Section 3.1), UMN configuration (Section 3.2) and network management (Section 3.3). Numbers in the project objective column refer to: (1) Developing quality assurance (QA) /quality control (QC) methods to assure the data quality; (2) Developing new dataset for research and daily operational use; (3) Complementing the conventional RMN observations with the novel UMN observations; (4) Investigating the potentials and robustness of UMN during operations (More details can be found in Section 3.1.1.). Applied variables in validations/research column are presented in abbreviation form: Temperature (T), Humidity (RH), Air Pressure (P), Wind speed (WS), Wind direction (WD), Precipitation (PR) and Radiation (RAD). Articles with missing information for specific categories are marked as 'Did Not Mention' (DNM).

| Reference | Country (City) / Region | Project Objective (s) | Project Duration | Network Type | Station Spacing | Station Type | Number of measured weather variables | Applied variables in validations/ research | Data transmission time | QA | QC | Station Maintenance |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Akasaka et al., 2011 | Japan (Tokyo) | 2 | Long | Single-sourced | Neighbourhood-scale | Self-assembly | 6 | T | Direct transmission | Yes | DNM | Yes |
| Basara et al., 2010 | United States (Oklahoma) | 2 | Long | Single-sourced | Neighbourhood-scale | All-in-one | 6 | T, WS, WD | Direct transmission | Yes | Yes | Yes |
| Beele et al., 2022 | Belgium (Leuven) | 1 | Medium | Crowdsourced | Neighbourhood-scale/Microscale | Plug-and-play | 7 | T | Aggregation | DNM | Yes | Yes |
| Caluwaerts et al., 2020 | Belgium (Ghent) | 2 | Short | Single-sourced | Neighbourhood-scale | Self-assembly | 5 | T | Aggregation | Yes | DNM | DNM |
| Cecilia et al., 2023 | Italy (Rome) | 2 | Short | Single-sourced | Neighbourhood-scale | All-in-one | 5 | T, WS, WD | Direct transmission | Yes | Yes | DNM |
| Chan et al., 2018 | Hong Kong | 2 | Medium | Single-sourced | Neighbourhood-scale | Self-assembly | 2 | T | Direct transmission | DNM | DNM | DNM |
| Chan and Fan, 2017 | Hong Kong | 2 | Medium | Single-sourced | Neighbourhood-scale | Self-assembly | 2 | T | Direct transmission | Yes | DNM | Yes |
| Chang et al., 2021 | Hong Kong | 2 | Medium | Single-sourced | Neighbourhood-scale | Self-assembly | 2 | T | Direct transmission | Yes | DNM | Yes |
| Chapman et al., 2015 | United Kingdom (Birmingham) | 2, 3 | Long | Single-sourced | Neighbourhood-scale | All-in-one, Self-assembly | 7 | T, RH, P, WS, WD, PR, RAD | Direct transmission | Yes | Yes | Yes |
| Chen et al., 2018 | Taiwan (Tainan) | 2 | Long | Single-sourced | Neighbourhood-scale | Self-assembly | 2 | T | Direct transmission | Yes | Yes | Yes |
| Chen et al., 2021 | The Netherlands (Utrecht) | 1 | Long | Crowdsourced | Neighbourhood-scale | Plug-and-play | 8 | WS | Aggregation | DNM | Yes | DNM |
| Cornes et al., 2020 | The Netherlands | 3 | Medium | Crowdsourced | Neighbourhood-scale/Microscale | Plug-and-play | 8 | T, RAD | Direct transmission | DNM | Yes | DNM |
| de Vos et al., 2020 | The Netherlands (Amsterdam) | 4 | Short | Crowdsourced | Neighbourhood-scale/Microscale | Plug-and-play | 6 | T, RH, P, WS, PR, RAD | Direct transmission | DNM | Yes | DNM |
| Droste et al., 2020 | The Netherlands (Amsterdam) | 1, 4 | Medium | Crowdsourced | Neighbourhood-scale | Plug-and-play | 5 | WS | Direct transmission | DNM | Yes | DNM |
| Feichtinger et al., 2020 | Austria (Vienna) | 4 | Short | Crowdsourced | Neighbourhood-scale/Microscale | Plug-and-play | 5 | T | Direct transmission | DNM | Yes | DNM |
| Hicks et al., 2014 | United States (Washington DC, New York) | 3 | Long | Single-sourced | Neighbourhood-scale | All-in-one | 3 | T, WS | Direct transmission | DNM | Yes | DNM |
| Kirsch et al., 2022 | Germany (Hamburg) | 2 | Long | Single-sourced | Neighbourhood-scale | All-in-one, Self-assembly | 6 | T, WS, WD, P | Direct transmission | Yes | Yes | Yes |
| Kuchcik et al., 2014 | Poland (Warsaw) | 2 | Long | Single-sourced | Neighbourhood-scale | Self-assembly | 2 | T | Aggregation | DNM | DNM | DNM |
| Lagouvardos et al., 2017 | Greece (Athens) | 2 | Long | Single-sourced | City-scale | All-in-one | 7 | T, RH, P, WS, WD, PR, RAD | Direct transmission | Yes | Yes | Yes |

(*continued on next page*)

**Table B1** (*continued*)

| Reference | Country (City) / Region | Project Objective (s) | Project Duration | Network Type | Station Spacing | Station Type | Number of measured weather variables | Applied variables in validations/ research | Data transmission time | QA | QC | Station Maintenance |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Lam et al., 2021 | Hong Kong | 1 | Long | Crowdsourced | Neighbourhood-scale | All-in-one | 6 | T | Direct transmission | Yes | Yes | DNM |
| Meier et al., 2017 | Germany (Hamburg) | 4 | Medium | Crowdsourced | Neighbourhood-scale/Microscale | Plug-and-play | 5 | T | Direct transmission | DNM | Yes | DNM |
| Mikami et al., 2011 | Japan (Tokyo) | 2 | Long | Single-sourced | Neighbourhood-scale | Self-assembly | 6 | T | Direct transmission | Yes | DNM | Yes |
| Napoly et al., 2018 | France (Toulouse), Germany (Berlin) | 1 | Medium | Crowdsourced | Neighbourhood-scale | Plug-and-play | 4 | T | Direct transmission | DNM | Yes | DNM |
| National Weather Service, 2023 | United States | 2 | Long | Crowdsourced | City-scale | Plug-and-play | 2 | T, PR | DNM | DNM | DNM | DNM |
| Nipen et al., 2020 | Norway (Oslo) | 3 | Medium | Crowdsourced | Neighbourhood-scale/Microscale | Plug-and-play | 4 | T | DNM | DNM | Yes | DNM |
| Park and Baek, 2023 | South Korea (Seoul) | 1 | Medium | Crowdsourced | Neighbourhood-scale | Plug-and-play | 4 | T | Direct transmission | DNM | Yes | DNM |
| Park et al., 2017 | South Korea (Seoul) | 2 | Long | Single-sourced | City-scale | All-in-one, Self-assembly | 6 | T, P, WS, WD | DNM | DNM | Yes | DNM |
| Pigeon et al., 2006 | France (Marseille) | 2 | Short | Single-sourced | Neighbourhood-scale | Self-assembly | 2 | T, RH | Direct transmission | DNM | DNM | DNM |
| Ronda et al., 2017 | The Netherlands (Amsterdam) | 2 | Long | Single-sourced | Neighbourhood-scale | Self-assembly | 4 | T | Direct transmission | DNM | DNM | DNM |
| Sgoff et al., 2022 | Germany | 3 | Short | Crowdsourced | Neighbourhood-scale/Microscale | Plug-and-play | 5 | T, RH, P, WS, WD | Direct transmission | DNM | Yes | DNM |
| Suomi et al., 2024 | Finland (Turku) | 2 | Long | Single-sourced | Neighbourhood-scale | Self-assembly | 2 | T, RH | DNM | DNM | DNM | DNM |
| Takahashi et al., 2009 | Japan (Tokyo) | 2 | Long | Single-sourced | Neighbourhood-scale | Self-assembly | 6 | T, WS, WD | Direct transmission | Yes | DNM | Yes |
| Tan et al., 2015 | China (Shanghai) | 2 | Long | Single-sourced | City-scale | All-in-one | 6 | T, RH, P, WS, WD, PREC | DNM | DNM | Yes | DNM |
| Ulpiani et al., 2022 | Australia (Sydney) | 2 | Long | Single-sourced | City-scale | All-in-one | 6 | T, RH, P, WS, WD, PR | Direct transmission | Yes | Yes | Yes |
| Warren et al., 2016 | United Kingdom (Birmingham) | 2, 3 | Long | Single-sourced | Neighbourhood-scale | All-in-one, Self-assembly | 7 | T, RH, P, WS, WD, PR, RAD | Direct transmission | Yes | Yes | Yes |
| Zumwald et al., 2021 | Switzerland (Zurich) | 4 | Short | Crowdsourced | Neighbourhood-scale/Microscale | Plug-and-play | 4 | T | DNM | DNM | Yes | DNM |

## Data availability

Data will be made available on request.

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