

# Trends, topics, and lessons learnt from real case studies using mesoscale atmospheric models for urban climate applications in 2000–2019

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## ABSTRACT

Researchers have made immense progress in understanding the urban-induced microclimate by numerical modelling. It has been around two decades since urban canopy models now commonly employed in mesoscale atmospheric models for operational and applied research purposes have emerged. To drive further advancement, it is timely to conduct a review of the state-of-the-art and lessons learnt from the relevant literature. In this paper, 102 urban climate real case modelling studies published in 2000–2019 are reviewed. Patterns and preferences in their study locations, periods, model choices, land cover databases, topics discussed, and scenarios investigated are holistically examined. There is an evident improvement in model complexity and urban surface data precision during the period reviewed. Most studies focus on the urban thermal climate and effects of urbanization. Based on the research gaps identified, more work is needed on the currently underrepresented but vulnerable cities in developing countries with tropical, arid, and cold climates. Collaborative field campaigns, initiatives to characterize cities in a consistent manner, and multi-scale modelling approaches have proven to benefit the progress in urban climate studies and should therefore be encouraged. More importantly, efforts should be invested in translating the science into information relevant to human well-being, urban planning, and policymaking.

## 1. Introduction

It is no new discovery that cities, home to more than half of the world's population (UN, 2018), have modified the natural surface energy balance (SEB), and have thus created the distinct climate conditions over urban areas. Cities experience higher temperatures than their rural surroundings, i.e. the urban heat island (UHI; Oke, 1973) effect, and other environmental problems such as intensified air pollution (e.g., Hidalgo et al., 2008), changed wind and precipitation patterns (e.g., Changnon Jr et al., 1971; Bornstein and Lin, 2000), and disrupted urban ecosystems (e.g., Pickett et al., 2008). Research on urban climatology has come a long way since the first detailed report of London's heat island in the 1800s (Howard, 2007). Early classical works also include those by Landsberg (1981) and Oke (1987), which laid out the fundamental principles and facilitated the progressive development in the field of urban climate research. Advancements in understanding the urban boundary layer by both observational and modelling techniques have been reviewed by Barlow (2014). Expedited by the practical relevance to public health (Kovats and Hajat, 2008) and sustainable societies

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(Rosenzweig et al., 2018), the field further expanded to interdisciplinary research with implications for urban planning, policymaking, and other integrated urban services (Baklanov et al., 2018; Hidalgo et al., 2019).

Climate models facilitate experiments on the complex interactions among the atmosphere, land, and oceans. They are particularly useful for testing hypothetical scenarios and assessing potential environmental impacts in the future. They offer advantages over field studies such as their consistency in performance governed by conservation equations and their ability to isolate the effects of certain processes of interest. Some of the first models developed to simulate the UHI phenomenon date back almost half a century ago (Lee and Olfe, 1974; Bornstein, 1975). Today, there exist a wide range of numerical models suited for applications at different spatial and temporal scales. General circulation models operate at the coarsest scales to simulate synoptic-scale processes and project global climate changes (Stocker et al., 2013), while computational fluid dynamics (CFD) models allow a detailed simulation of microscale flows (Topalar et al., 2017) but are computationally expensive. Mesoscale atmospheric models (MAMs), which provide a good flexibility and balance in the resolution resolved and computational costs required, are commonly employed for city-scale studies at resolutions of a few hundred meters up to 100 km (Martilli, 2007; Oke et al., 2017).

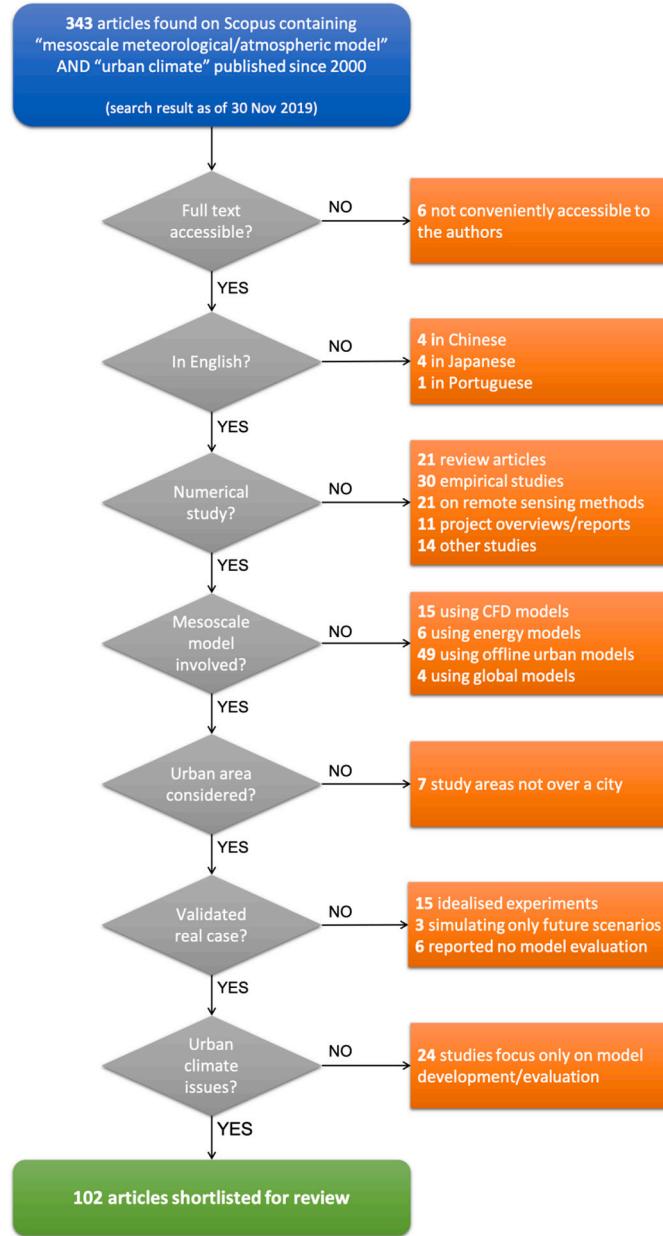
To simulate more precisely the urban SEB, urban land surface models are frequently coupled to MAMs to provide parameterizations for subgrid-scale processes (Martilli, 2007). Such models vary in level of complexity from the simplest bulk representations adapted from vegetation schemes, to single- and multi-layer urban canopy models (UCMs). Grimmond et al. (2010, 2011) compared the performance of 33 different models in the International Urban Energy Balance Models Comparison Project to understand the requirements for simulating the urban SEB and to reveal opportunities for model improvement. The history and evolution of these models have been critically reviewed by Masson (2006) and Garuma (2018). Notably, UCMs that are now actively used in MAMs for near weather prediction and other urban applications emerged in the late 1990s to early 2000s (e.g. Brown and Williams, 1998; Masson, 2000; Kusaka et al., 2001; Martilli et al., 2002; Dupont et al., 2004; Best, 2005). Since then, making use of MAMs with improved urban considerations, an increasing number of urban climate modelling studies with diverse applications have been carried out in cities worldwide. It is therefore timely to conduct a general review of these studies, to summarize what have been learnt and prepare for upcoming challenges.

Rather than focusing on certain aspects of the literature on urban climate applications and modelling, such as the requirements on urban input data (Masson et al., 2020), climate mitigation solutions (Aleksandrowicz et al., 2017; Lamb et al., 2019), or specific community modelling systems (Ching, 2013), as in other recent reviews, this paper aims to present an overview of the trends, topics, and lessons learnt in the subject matter through a holistic analysis of 102 systematically selected regional/local case studies in the first 20 years of the 21st century (2000–2019). By doing so, areas that require further research can be identified. Note that technical details on modelling, most of which already discussed in existing reviews (e.g. Garuma, 2018), are intentionally omitted in the course of writing to allow easy comprehension by a broader readership, especially those who are newly exposed to the field. In the following sections, the criteria to select studies for review are first established (Section 2); the state-of-the-art in terms of study locations and periods, choice of models and urban parameterization, as well as surface input data is then presented (Section 3); the common topics (Section 4) and scenarios (Section 5) in the studies are discussed; and finally, observations from this review are concluded with suggestions for further work (Section 6).

## 2. A systematic review

In this paper, the real case studies making use of MAMs for applications related to urban climate are examined. A systematic approach is required to review a subject that involves such vast literature. First, 343 potentially relevant articles (document type “ar”) published since 2000 (as of end-November 2019) are identified from the Scopus database using the advanced search query string “ALL (“mesoscale atmospheric model” OR “mesoscale meteorological model”) AND ALL (“urban climate”) AND (LIMIT-TO (DOCTYPE, ‘ar’))”. Next, the articles are checked to see whether full texts can be accessed by the authors and whether they are in English. The abstracts of the studies are then read to filter out those which are not numerical studies (e.g. observational studies, reviews), those in which a MAM has not been employed (e.g. UCMs run offline, microscale modelling with CFD techniques), and those where the study area is not over a city. Li et al. (2019b) stressed the importance of conducting thorough evaluations against observations to ensure the trustworthiness of model results and their implications. Therefore, studies that do not report model evaluation against observations to corroborate the reliability of results are disregarded.<sup>1</sup> Idealized experiments that focus on investigating specific physical or chemical urban atmospheric processes and those which only conducted simulations for future or hypothetical scenarios are also not included in the scope of the current review, which focuses only on real case studies. Out of the remaining 126 studies, 24 of them are further removed because they focus only on technical model development and do not present a clear application on urban climate issues. Finally, 102 articles fulfilling all the selection criteria are shortlisted for review under the scope of this paper. The study selection process can be summarized by the flowchart in Fig. 1.

<sup>1</sup> Studies that pass this filter all reported reasonable model performance compared to observations. However, the assessment of measurement data quality and siting representativeness is out of scope for this review.

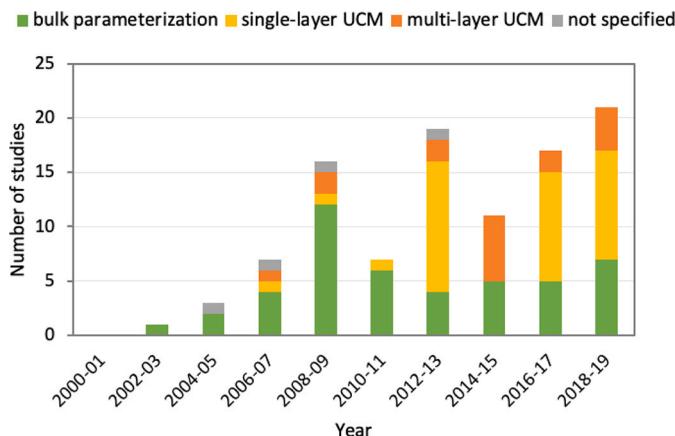


**Fig. 1.** Selection process of studies reviewed.

### 3. General trends from selected studies

#### 3.1. Summary of studies

Overall, there has been an increasing number of urban climate modelling studies conducted in the last two decades (Fig. 2), with almost three-quarters of the selected studies published since 2010. This is likely driven by the growing awareness about climate-induced risks in cities and the demand for mitigative solutions. At the same time, this is a reflection of the progress in model development and the increasing availability of data and resources. The selected studies demonstrate a good variety of case studies conducted in cities with different climates and urban settings for different simulation periods and seasons. More importantly, there is a great diversity in model configuration and precision, as well as a comprehensive coverage of urban climate phenomena/issues discussed and scenarios/experiments investigated. The sample size is also deemed sufficient to portray some recent trends and patterns in model choices and urban databases, capture the preferences and interests of the modern urban climate modelling community, and identify the potential gaps and biases for further work. Nevertheless, it should be acknowledged that this collection of studies reviewed is by no



**Fig. 2.** Number of selected studies with different urban parameterizations in each two-year period from 2000 to 2019. If two or more kinds of urban parameterizations have been employed in a study, the urban parameterization of higher complexity is counted. See Section 3.3 and Table A3 for further description and the list of models belonging to bulk parameterization, single-layer UCM, and multi-layer UCM.

means exhaustive, and relevant studies may have been missed if they do not contain the keywords in their titles, abstracts, and other searched fields, or if they have not been archived in the Scopus database (see Section 6.1). Moreover, local studies in developing countries are prone to being underrepresented due to the barriers in language and publication standards (and therefore may not be included in the Scopus database). A summary table of the 102 studies reviewed can be found in the Appendix (Table A1).

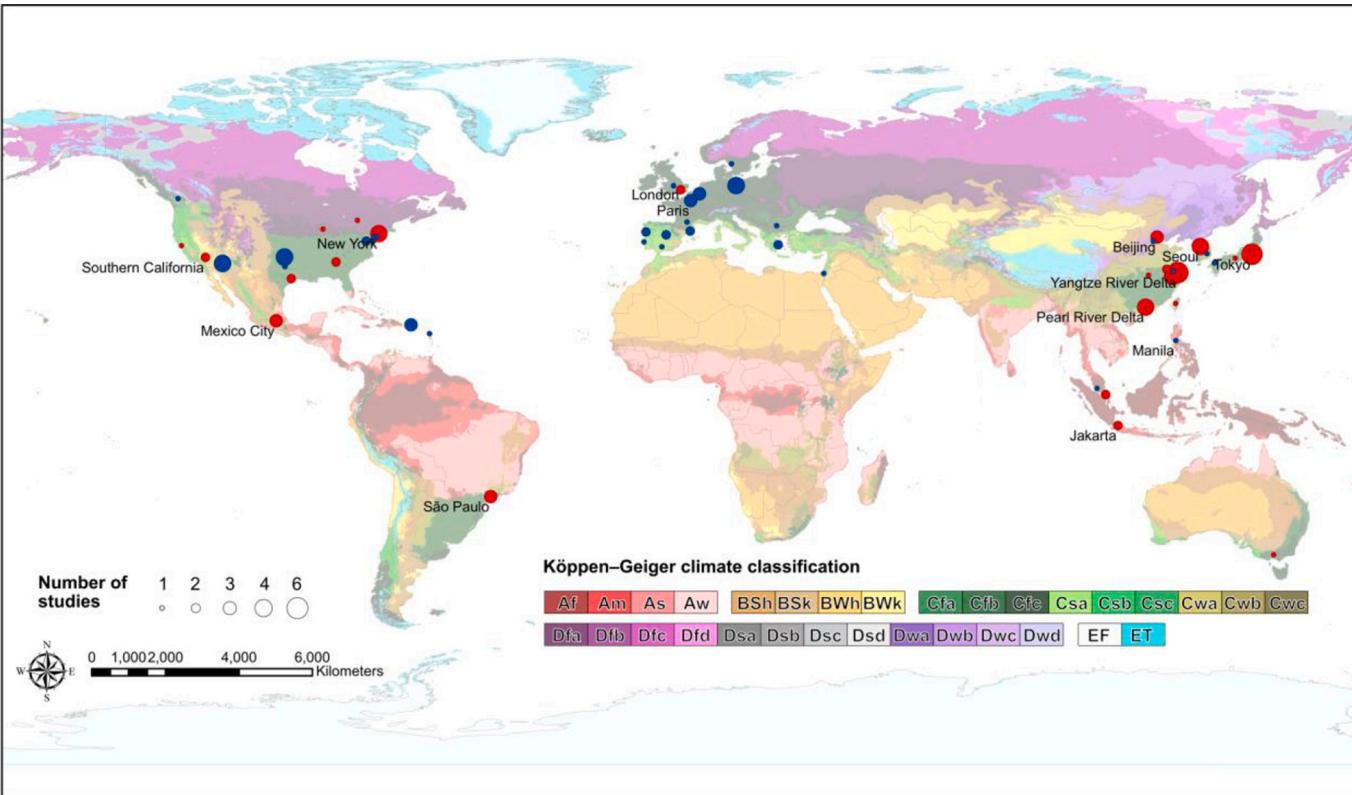
### 3.2. Study locations and periods

Fig. 3 shows a Köppen-Geiger climate map with study locations of the reviewed studies plotted. Despite being distributed across five continents, study locations form three clear clusters in the northern hemisphere, namely western Europe, where most cities studied have a long history of urban development and retain a compact low-rise morphology, east Asia, where most cities studied are modern metropolises with many high-rise buildings (indicated in red in Fig. 3), and North America, where cities studied are more diverse in terms of urban morphology. Considering the total number of cities (in the order of  $10^4$ ) in the world, a disproportionately high number of study locations (~40%) are at one of the 33 present-day megacities (UN, 2018), including those in the rapidly growing Pearl River Delta (PRD) and Yangtze River Delta (YRD) regions in China. A bias is also observed in the climate of study locations, with more than 70% being in warm temperate regions (Köppen-Geiger climate group C; Fig. 4). As Mellinger et al. (1999) have reported a positive relationship between favourable temperate climates (especially 'Cf' zones) and the Gross Domestic Product (GDP; per capita and per  $\text{km}^2$ ), such biases may simply be an indication of the level of economic development, and therefore data and resources available for research, in the megacities and warm temperate regions found in the three identified clusters.

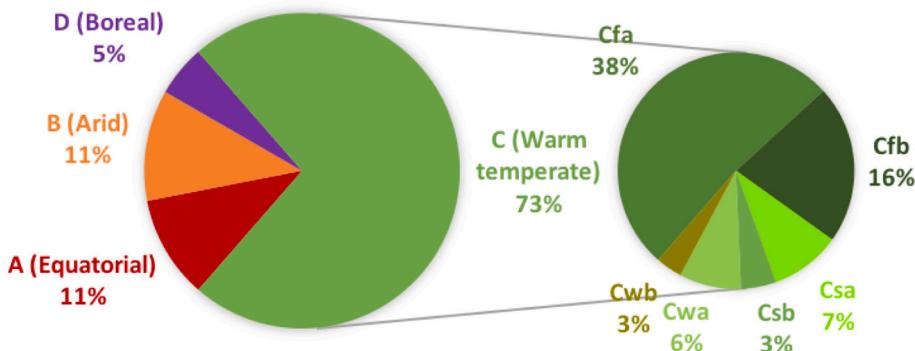
Study periods typically span over a few days to a few weeks, and often correspond to either the representative weather situations of specific cities, or extreme weather events such as heatwaves (e.g. Rosenzweig et al., 2009; Tremeac et al., 2012; Hu and Xue, 2016), heavy precipitation events (e.g., Wan et al., 2013; Ryu et al., 2016; Xing et al., 2019), and high pollution episodes (e.g., Pay Pérez et al., 2014; Cécé et al., 2016). This is in line with the needs of urban climatic information for prevailing and critical conditions in practical applications and decision-making (Ng, 2012). Besides, it is found that summer is the most popularly investigated season in the reviewed case studies, probably due to its relevance to urban heat-related risks and the projected rise in frequency and severity of heatwaves worldwide under climate change. Some study periods coincide with large-scale field campaigns as they provide comprehensive and purpose-oriented datasets for model evaluation and urban climate applications. An example is the Joint URBAN 2003 field experiment in Oklahoma City (Brown et al., 2004), which enabled the evaluation of modelling studies by different research groups and with diverse focuses (Hu et al., 2013; Husain et al., 2014; Kochanski et al., 2015; Nemunaitis-Berry et al., 2017). Similarly, the study periods selected by Miao et al. (2007), Salamanca et al. (2012), and Kwok et al. (2019) fall within the field campaigns GÖTE2001 (Borne et al., 2005), DESIREX (Sobrino, 2009), and CAPITOUL (Masson et al., 2008), respectively, reaffirming the value of observation data in both empirical and numerical studies.

### 3.3. Choice of models and urban parameterization

MAMs and UCMS have undergone active development in the last few decades, giving rise to the many available models for urban climate researchers to choose from. The MAMs employed in the reviewed studies are summarized in Fig. 5 and Table A2 in the Appendix. They share the same fundamental physical conservation laws of mass, momentum, and energy, but may differ in the incompressibility and hydrostatic assumptions, as well as the formulation of equations, the coordinate system, and the available options in parameterization schemes and modules. In the early 21st century, the fifth-generation Pennsylvania State University–National Center for Atmospheric Research Mesoscale Model (MM5; Grell et al., 1994) and the Regional Atmospheric Modeling System



**Fig. 3.** Spatial distribution of study locations in the world and their climate zones. Red circles indicate high-rise cities with more than 100 skyscrapers (building height > 100 m; information from <https://www.emporis.com/buildings>). Labelled cities/regions are/contain megacities (population > 10 million; UN, 2018). The re-analysed Köppen-Geiger climate classification world map at 5 arc minutes is representative for the period 1986–2010 (available at <http://koeppen-geiger.vu-wien.ac.at/present.htm>). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)



**Fig. 4.** Distribution of study locations according to the Köppen-Geiger climate classification.

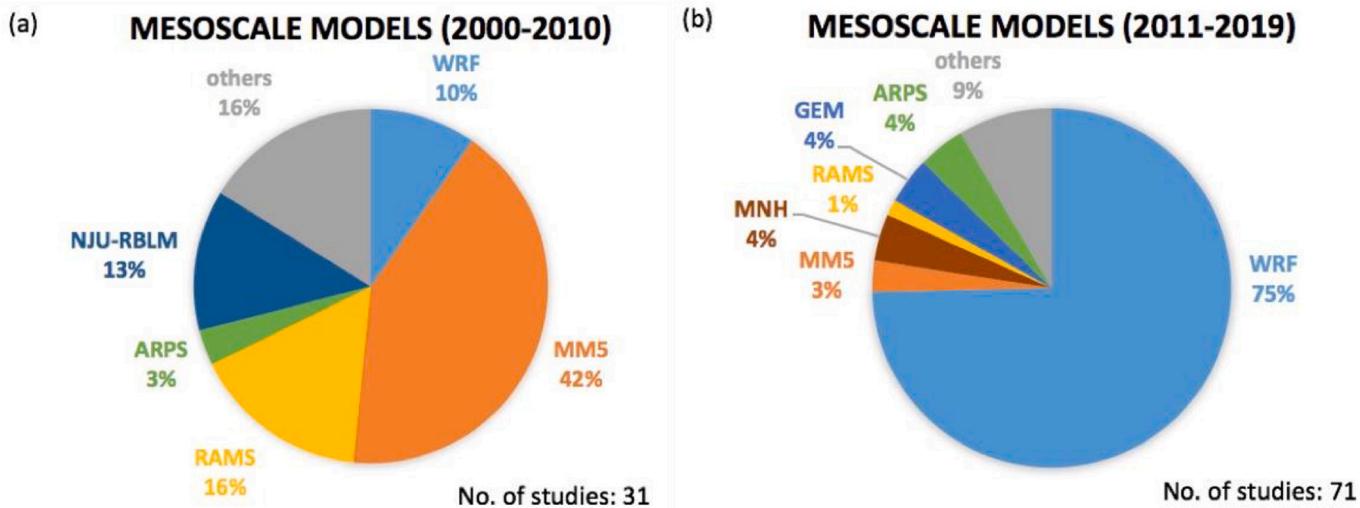
(RAMS; Pielke et al., 1992) were the two most frequently used MAMs in urban climatic studies. In the recent decade, the Weather Research and Forecasting Model (WRF; Skamarock et al., 2008), superseder of MM5, has become very popular thanks to its large collaborative user community, high model reliability, and flexible modular architecture fit for both operational and research purposes on different computing devices and operating systems (Abualkishik, 2018). Some MAMs tend to have preferential applications in certain geographical locations related to the model development teams, for example the Regional Boundary Layer Model developed by Nanjing University (NJU-RBLM; Jiang et al., 2007) in China, the Non-Hydrostatic Mesoscale atmospheric model Meso-NH (MNH; Lac et al., 2018) in France, and the Global Environmental Multiscale numerical model (GEM; Zadra et al., 2008) in Canada.

An atmospheric model requires a land surface model to solve the SEB. There are several approaches to account for the urban-induced thermal and dynamical effects in a MAM. Models adopting a simple bulk parameterization, such as the Noah Land Surface Model (Chen and Dudhia, 2001), make use of an existing vegetation scheme and modify the roughness length, surface albedo, volumetric heat capacity, and thermal conductivity to represent the urban surface characteristics (Liu et al., 2006). A more accurate representation of the three-dimensional urban environment is achieved by UCMs which solve separately the energy budgets for the wall, roof, and road surfaces, and calculate the radiative effects (shadowing, multiple reflection) within an urban canyon. Single-layer UCMs interact only with the lowermost level of the MAM, while multi-layer UCMs apply the drag and thermal effects of building at multiple atmospheric levels. The reader is referred to Grimmond et al. (2010) for a systematic classification of urban land surface models with varied capabilities and degree of complexity. As seen from Fig. 2, the number of studies employing UCMs to model the urban SEB has increased significantly over the recent years. It is interesting to note that some UCMs are usually employed with the same MAM, like the Single-Layer Urban Canopy Model (SLUCM; Kusaka et al., 2001) and the multi-layer Building Effect Parameterization (BEP; Martilli et al., 2002) in the WRF modelling system; whereas other UCMs may be more versatile and easily compatible with different MAMs. An example of such UCM is the Town Energy Balance (TEB; Masson, 2000), which has been coupled to MNH (e.g., Tremeac et al., 2012), GEM (e.g., Leroyer et al., 2014), RAMS (e.g., Freitas et al., 2007), and the operational model 'ALARO-0' (Gerard et al., 2009; e.g., Hamdi et al., 2012). It also serves as the base model for the development of TEB for tropical regions (T-TEB; Karam et al., 2010) and the Canadian Multilayer version of TEB (CaM-TEB; Husain et al., 2013). Other notable features of UCMs include the consideration of urban in-canyon vegetation as in the Vegetated Urban Canopy Model (VUCM; Lee and Park, 2008) and the building energy consumption by a further coupling to building energy models (BEMs; e.g., Salamanca et al., 2010, Bueno et al., 2012). Furthermore, the variation in MAMs and UCMs employed, model configurations, as well as model input data attributes (to be discussed in Section 3.4) and output diagnostics for different studies may be explained with reference to the specific objectives of each study (Baklanov et al., 2009).

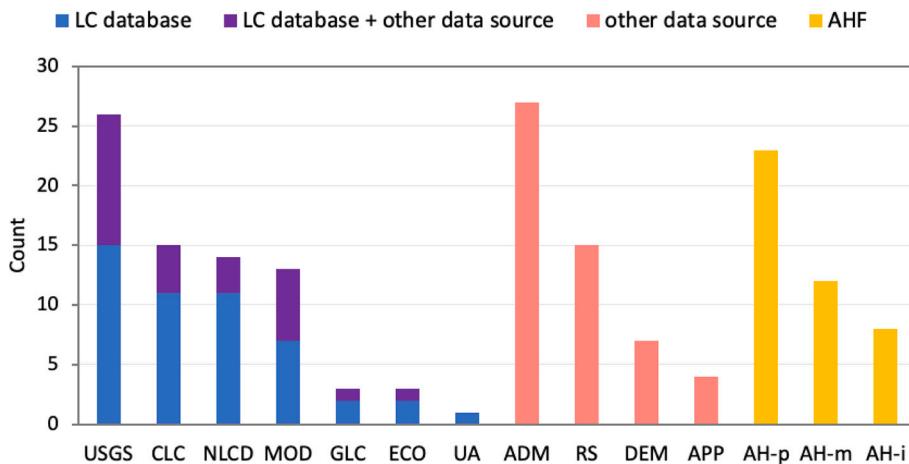
Experiments conducted to test the different urban parameterizations show clear advantages of using an UCM over the simple bulk parameterization (Hamdi et al., 2012; Kusaka et al., 2012; Ryu et al., 2016; Rafael et al., 2019). The UCM is able to capture more accurately the energy partitioning on urban surfaces, i.e. the lower latent heat flux and higher heat storage during the day, and more importantly for the formation of a nocturnal UHI, the sensible heat flux that remains positive in the evening and the radiative cooling of urban materials overnight. As a result, the observed meteorological variables, namely air temperature, relative humidity, wind speed and direction, and rainfall, are much better reproduced when an UCM is employed. In New York City where tall buildings play an important role in modifying the atmospheric flow at multiple levels, it is found that the more advanced BEP-BEM urban parameterization produces more realistic vertical profiles of potential temperature, wind speed, and turbulent kinetic energy (Gutiérrez et al., 2015), as well as flow fields and pollutant dispersion patterns in urban areas (Bauer, 2019).

### 3.4. Urban surface input data sources and model resolution

This section looks into the sources and quality of model input data describing the extent and characteristics of urban environments, and how they could affect the model performance. Needless to say, the most detailed city-descriptive data can be found from administrative databases (ADM in Fig. 6), in which land use is accurately mapped and building geometry is carefully documented by the local government departments. Around a quarter of the reviewed studies have been able to benefit from these high-resolution data, but such data are not always publicly accessible, and may even be non-existent in developing countries.



**Fig. 5.** Mesoscale atmospheric models employed in studies conducted during the periods (a) 2000–2010 and (b) 2011–2019. See Section 3.3 of the main text and Table A2 in the Appendix for model acronyms and references.



**Fig. 6.** Urban surface and anthropogenic heat (AHF) data sources employed in the reviewed urban climate modelling studies. Note that there may be more than one data source for each study and there are 6 studies with no clearly stated urban surface data source (refer to Table A1 in the Appendix for details). LC means land cover in the graph legend. See Section 3.4 of the main text and Table A4 in the Appendix for definitions of acronyms and references.

Seeking ways to overcome this data challenge, researchers have developed methods to obtain the urban surface characteristics through remote sensing techniques. The most commonly employed land cover database among the reviewed studies is the United States Geological Survey's (USGS) Global Land Cover Characterization (GLCC) land use/land cover dataset derived from the Advanced Very High Resolution Radiometer (AVHRR) data collected between 1992 and 1993 (Fig. 6). It has 24 land cover classes at 1 km resolution and is the default database for the MAMs MM5 and WRF. Despite its widespread application in modelling studies, this dataset is criticized for being too coarse and outdated and is therefore often complemented by other data sources for the most urbanized areas (as in Taha, 2008a; Conry et al., 2015; Jänicke et al., 2017). Another commonly used global land cover database is the yearly-updated Moderate Resolution Imaging Spectroradiometer (MODIS) Land Cover Type Product (MCD12Q1) at 500 m spatial resolution (Sulla-Menashe and Friedl, 2018). Both of these databases have only one urban land cover class which may be inadequate in representing the heterogeneity within cities.

As models depart from a bulk urban representation, researchers opt for more detailed descriptions of the urban land cover and surface characteristics. Using a combination of supervised classification of satellite images, semi-automatic mapping technologies, and generalization of high resolution monitoring data, more refined regional resources such as the National Land Cover Database (NLCD; Homer et al., 2015) for the United States and the Coordination of Information on the Environment (CORINE) Land Cover inventory (CLC; Büttner et al., 2004) for Europe are made available. The former contains three urban subclasses with low to high development intensities and the latter has multiple artificial surface covers differentiated by their urban fabric and land use.

An initiative that is worth mentioning here is the World Urban Database and Access Portal Tools (WUDAPT; Ching et al., 2018, 2019). It aims to provide a standardized database on the urban form and function of cities in terms of local climate zones (LCZs; Stewart and Oke, 2012) and their associated values for key urban parameters via a fully open source procedure. The WUDAPT 'level 0' data can now be easily translated into surface inputs for the WRF urban modelling system (Brousse et al., 2016; Martilli et al., 2016). This enabled Mughal et al. (2019), among other more recent studies not included in this review (e.g., Franco et al., 2019; Mu et al., 2020; Patel et al., 2020), to perform a high-resolution, multi-layer simulation of the urban microclimate in Singapore, or any other city of interest. Apart from the aforementioned databases, various satellite imagery (e.g., Landsat, SPOT, IKONOS), the Airborne Thermal and Land Applications Sensor (ATLAS), airborne light detection and ranging (LiDAR) measurements, infrared aerial photography etc. (RS in Fig. 6) have been used for deriving the required urban surface input parameters in the reviewed studies. A few studies also utilized available demographic information (DEM in Fig. 6) on population density and energy use to infer the urban area extent and anthropogenic heat release (e.g. Tokairin et al., 2010; Chen and Zhang, 2018).

Anthropogenic heat flux (AHF) is considered in around 40% of the reviewed studies. In most of these studies, AHF is represented by a prescribed value with a diurnal profile in the model (AH-p in Fig. 6). The averaged AHF for different urban classes are typically taken from global top-down databases (e.g. Flanner, 2009; Dong et al., 2017) or estimated based on statistical models or local knowledge. Some studies obtained AHF model inputs from local/regional emission inventories (e.g. Senoo et al., 2004 for Tokyo (Japan), Lee et al., 2009 for Gyeong-In (Korea), Wang and Wang, 2011 for Guangzhou (China)) and socioeconomic databases (AH-i in Fig. 6). For UCMS that are coupled to BEMs, AHF can be directly modelled given information on building architecture, material properties, occupancy schedules, cooling/heating settings etc. is provided (AH-m in Fig. 6). The importance of taking AHF into account when modelling the urban SEB is emphasized in many studies (more discussion in Section 5.2), and even those which neglected the effects of AHF due to a lack of data, incompatibility of the model, or a different study focus acknowledged this as a major limitation and hence motivation for future works.

Whether the given urban inputs are accurate and representative of the study period can significantly impact the model results and

spatial distribution of simulated meteorological variables, as reported by some of the reviewed studies (Gutiérrez et al., 2015; Kuik et al., 2016; Li et al., 2018). For models which do not allow a grid-specific description of urban parameters and for cities where detailed databases are not available, simulation performances can be improved by increasing the number of urban classes and adopting a fractional area approach to take into account the heterogeneity within urban areas (Chemel and Sokhi, 2012; Sequera et al., 2016). The general principle is that the more detailed the input data, the more accurate the model outputs, with underlying assumptions that model parameters and schemes are appropriately chosen by the user (Grimmond et al., 2011). However, researchers also need to consider the limitations in data availability and computing resources when setting up the most optimized model configuration. As observed from the reviewed studies, default databases with a single urban class are often sufficient for models using a bulk urban representation, while three or more urban classes derived from administrative databases or high-resolution remote sensing methods are usually preferred for simulations with finer grid resolutions ( $\leq 1$  km) and those employing multi-layer UCMS.

In relation to the increased spatial resolution (to sub-kilometre grids) of MAMs in urban climate simulations, a major modelling issue referred to as the ‘grey zone’ or ‘Terra Incognita’ (Wyngaard, 2004) is actively discussed by the modelling community (Martilli, 2007; Ching, 2013; Barlow et al., 2017; Garuma, 2018) but remains unresolved in the past two decades. Due to the heterogeneity over urban surfaces, turbulence is generated at a wide range of length scales during different times of the day. These turbulence effects fall into the problematic transition regime between the explicitly resolved and the parameterized subgrid processes and thus introduce uncertainties to model outputs. Another ‘grey zone’ exists for the representation of buildings within urban grids. At resolutions of a few hundred metres, the canyon assumption for radiative and momentum exchanges in UCMS may break down when modelling bulky structures that occupy a large grid volume. So far, few UCMS take into account the volume occupied by buildings (e.g. Ca et al., 1999), which is an increasingly important consideration at finer grid resolutions, especially for dense cities. Coupling mesoscale models with building-resolving large eddy simulations may be a promising solution (e.g., PALM-4U; Maronga et al., 2019) but the feedback between meso and micro scale atmosphere processes must be handled with caution.

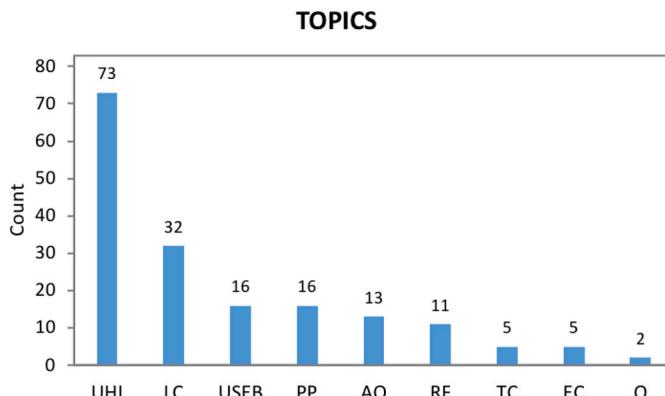
#### 4. Research topics examined in the reviewed studies

In this section, the commonly investigated urban climate topics from the reviewed studies are presented (Fig. 7). The focus here is not on the specific values or findings from individual studies, but the collective understanding on the urban climate issues, processes, and applications gathered from all the different case studies. Having said that, some studies may be highlighted as examples to illustrate certain points of interest.

##### 4.1. Urban temperature studies

The UHI is by far the most extensively studied urban climate phenomenon, both by observational and numerical methods (Mirzaei and Haghhighat, 2010). Unsurprisingly, over 70% of the reviewed urban climate modelling studies examined the UHI or the intra-urban temperature differences (Fig. 7). A simple categorization of these UHI studies in terms of climate zones reveals a geographical distribution that resembles that of all the 102 reviewed studies (Figs. 3 and 4). The largest number of studies have been carried out in American cities, followed by Chinese and Japanese cities.

Arnfield (2003) noted a diversity of UHIs, namely the atmospheric UHI (within canopy and at boundary layer), surface UHI, and sub-surface UHI. All, except one, of the 73 studies examined the near-surface atmospheric UHI. The maximum UHI intensity, typically defined as the urban-rural/preurban near-surface ( $\sim 2$  m) air temperature difference, is found to occur between sunset and sunrise across cities with different urban settings and climates. Examples include, but are not restricted to, the UHI simulated in Tokyo (Kusaka et al., 2012), London (Grawe et al., 2013), Oklahoma City (Husain et al., 2014), Barcelona (García Díez et al., 2016), Israel (Kaplan



**Fig. 7.** Topics discussed in the reviewed urban climate modelling studies. Note that there may be more than one topic for each study (refer to Table A1 in the Appendix for details). The definitions of the acronymized topics are as follows: UHI – Urban heat island/ temperature differences; LC – local circulation; USEB – urban surface energy balance; PP – urban planning/ policy implication; AQ – air quality/ atmospheric dispersion; RF – urban rainfall/ storm; TC – thermal comfort/ heat stress; EC – energy consumption; O – others.

et al., 2017), and São Paulo (Flores Rojas et al., 2018). Within the urban areas, temperature differences are also found, with a stronger intra-urban heat island in zones of high impervious fraction and building density (Kwok et al., 2019; Li et al., 2019a; Mughal et al., 2019). A negative UHI (a.k.a. urban cool island) can occur in the day, especially for cities with a semi-desert surrounding environment (Georgescu et al., 2011) or during dry seasons (Cui and de Foy, 2012).

19 studies (~25% of UHI studies) also reported findings based on land surface/ skin temperature (see Table A1 in the Appendix). Hu et al. (2013) even used land surface temperature as a substitute for air temperature in their UHI spatial analysis. However, though the spatial and temporal distribution in air and surface temperatures may be similar and correlated, there are marked discrepancies between the two, especially during daytime. The land surface temperature rises and falls at a faster rate and is more sensitive to changes in radiation and urban canopy parameters, giving rise to generally higher land surface temperatures, a larger diurnal range, and a greater surface UHI intensity around noon (Miao et al., 2009; Cui and de Foy, 2012; Li et al., 2015; Zhou et al., 2016; Nemunaitis-Berry et al., 2017; Li et al., 2018). Different mitigation strategies are also required to target the reduction of urban air and surface temperatures (Rosenzweig et al., 2009; Chen and Zhang, 2018; more in Section 5.3). For model evaluation, the atmospheric UHI is evaluated against surface meteorological stations, while the land surface UHI can be compared with satellite-derived data.

Fundamentally, the UHI, alongside all other urban climate phenomena, are results of the modified SEB in urban areas. Although energy balance measurements are difficult to obtain in central city locations and high-rise cities (Arnfield, 2003), the different energy flux components can be investigated by simulations. Some of the reviewed studies reported a detailed account of the urban SEB (e.g., Chen and Jiang, 2007; van Weverberg et al., 2008; Georgescu et al., 2009; Nemunaitis-Berry et al., 2017; Flores Rojas et al., 2018; Rafael et al., 2019), which can be summarized as a reduction in the latent heat flux and an increase in the storage and sensible heat fluxes, caused by the lower albedo of urban canyons and the additional AHF due to human activities in urban areas. The heat stored in man-made materials during the day is then released at night as longwave radiation, forming the nocturnal UHI and increasing the planetary boundary layer height.

#### 4.2. Local circulation and air quality

Local circulations over urban areas, mainly the UHI-induced circulations and the land-sea breeze effects, are the second most commonly examined topic among the reviewed studies (Fig. 7). They play an important role in urban ventilation, heat advection, pollutant transport, and moisture mixing processes. The UHI circulation is characterized by convergent flows near the surface, upward flows over the urban heat dome, and divergent upper-level flows. These flows interact with the sea breeze in coastal cities and may accelerate its inflow due to the exacerbated land-sea temperature and pressure differences (Freitas et al., 2007; Li et al., 2015). At the same time, however, frictional effects by buildings can significantly reduce the urban wind speed, causing the sea breeze to stall over the urban areas and inhibiting its penetration further inland (Ryu and Baik, 2013; Flores Rojas et al., 2018; Mughal et al., 2019).

In relation to air quality, the decrease in wind speed has been reported to favour the accumulation of nitrogen oxides (NOx) and alter the surface ozone ( $O_3$ ) concentration (Zhan et al., 2013; Dai et al., 2019). Apart from the physical atmospheric processes, chemical processes, such as the dry and wet deposition, photolytic reactions, secondary production of chemical species, and aerosol forcing, are involved when studying urban pollution. Specific modules like WRF/chem (Grell et al., 2005) are thus frequently employed to model the real-time coupling between chemistry and meteorology (e.g., Kuik et al., 2016; Dai et al., 2019). A comprehensive review of online models used for regional air quality modelling in Europe has been conducted by Baklanov et al. (2014). To obtain a more detailed understanding of the pollutant dispersion pattern in complex urban areas, some studies refine the simulation results by adopting a cross-scale modelling approach to further couple the MAM with a microscale CFD model (Baik et al., 2009; Cécé et al., 2016; Bauer, 2019; see Table A1 in the Appendix). Another important application with high relevance to public health and environmental services is air pollution forecast as investigated by Pay Pérez et al. (2014). In this regard, the reader is also made aware of the international project “Megacities: Emissions, urban, regional and Global Atmospheric POLLution and climate effects, and Integrated tools for assessment and mitigation” (MEGAPOLI; Baklanov et al., 2010), which aims to assess the impacts of air pollution in megacities and quantify the interactions among megacities, air quality, and climate by exploiting multi-scale integrated modelling tools.

#### 4.3. Urban precipitation

Knowing the local precipitation processes are essential for understanding the regional/ global water cycle and assessing the risks of severe rainstorm events. Yet, the influence of cities on precipitation is complex, extensive, difficult to simulate, and not fully understood (reviews by Shepherd, 2005; Han et al., 2014). Two seemingly contrasting effects of urban areas on precipitation have been observed – the amplification of urban rainfall as first noted in the METROMEX experiment (Changnon, 2016) and storm bifurcation due to the building barrier effect as observed in some American (Bornstein and Lin, 2000) and Chinese cities (Dou et al., 2015). Among the reviewed studies, around one in ten investigated the impact of urban areas on precipitation patterns and mechanisms (Fig. 7). The majority of simulations show how cities enhance rainfall mainly by supplying more sensible heat flux and increasing vertical air movement to boost atmospheric convection (Ryu et al., 2016; Zhao and Wu, 2018; Dado and Narisma, 2019), particularly during the initiation of a storm (Xing et al., 2019). The rapid rainwater runoff caused by the conversion of natural land to impervious surfaces also contributes to an increase in urban moisture flux (Zhao and Wu, 2018). Such urban-induced rainfall typically occurs over and downwind of the urban areas, but the formation process and spatial distribution may vary depending on the specific surface characteristics, as well as the local topography (Lin et al., 2008; Comarazamy et al., 2010; Wan et al., 2013; Ryu et al., 2016). However, a conflicting result is found by Hamdi et al. (2012) who reported a significant decrease in summer accumulated precipitation because

urban areas tend to concentrate rainfall locally and lower the moisture availability within the model domain. This shows existing uncertainties in the modelling of urban precipitation which would require further research. Moreover, although observed in several cities, the bifurcation of storms remains less examined (none among the reviewed studies) and challenging to simulate. In future studies, the advancement in urban parameterizations may allow one to reproduce this complex process and to better understand the specific conditions under which storm bifurcation would occur (Dou et al., 2020).

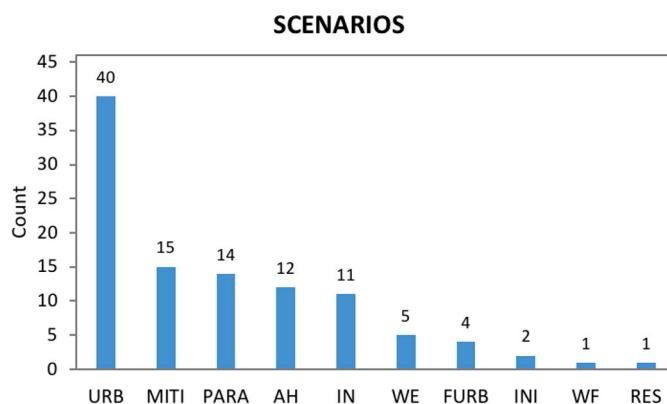
#### 4.4. Urban planning and policy

Having understood the various impacts of urban areas on the natural atmospheric processes, it is crucial to translate the key research findings into practical advice so that cities may respond to the urban climate issues with appropriate urban design and planning policies (Ng, 2012; Hidalgo et al., 2019). While all the reviewed studies reported findings that contain important clues to building more sustainable cities, only 16 of them attempted to make an explicit link between science and practice. For relieving urban heat stress, Kwok et al. (2019) concluded that vegetated and sparsely built settings are more favourable than open mid-rise built environments, based on a case study of Toulouse. Building compact urban zones at strategic locations may also lower daytime heat stress by providing more shading opportunities at local scale. For better air quality, comfort, and health, Rafael et al. (2018) suggested replacing a set of buildings by a green urban area in Porto and reminded planners to consider also the vegetation management and tree species to achieve the optimal outcome. Furthermore, urban climate models are indispensable tools for testing ‘what-if’ scenarios of urban development and mitigation strategies (see Section 5), so that local governments may be informed of the most viable and effective solutions that should be adopted. For example, the effectiveness of the garden city concept in Putrajaya was evaluated by using the coupled WRF-SLUCM to quantify the expected cooling by greenery and waterbodies (Morris et al., 2016). In Melbourne, the increase in UHI intensity, especially during the night, caused by the developments proposed in the Melbourne 2030 plan was simulated and used to persuade planners to implement mitigation strategies (Coutts et al., 2008). In Israel, MAMs are incorporated into planning support systems to provide planning recommendations based on the modelled spatial-temporal impacts of future urban expansion (Kaplan et al., 2017). Nevertheless, it should be noted that numerical experiments may be overly idealistic as the interplay of public perception, implementation costs, interests of different stakeholders, and other practical concerns may not be fully considered simply by an urban climate simulation (Rosenzweig et al., 2009; Ruddell et al., 2012; Li and Norford, 2016).

### 5. Experimental scenarios tested in the reviewed studies

A majority (~80%) of the reviewed studies involve the simulation of scenarios, the results of which are then compared against an evaluated real case reference simulation. Typically, these scenarios are either used to test the performance of different model configurations (e.g., urban parameterization, surface input data, initial conditions, model resolution), or designed to examine the impacts of various parameters relevant to urban climate applications (e.g., land use/land cover changes, AHF, mitigation strategies) (Fig. 8). Since the former has already been discussed in Sections 3.3 and 3.4, this section focuses on the common scenarios in the latter category.

Although outside the scope of this review, a class of modelling studies for future or hypothetical scenarios that cannot be validated (and therefore were not shortlisted for review) deserves a mention here. Such studies make use of MAMs to explore conceptual solutions to increase urban resilience under projected global warming and in turn provide insights on city planning and mitigation strategies (e.g., Silva III and Golden, 2012; Li et al., 2014; Comarazamy et al., 2015; Rafael et al., 2016; Carvalho et al., 2017). Some



**Fig. 8.** Scenarios investigated in the reviewed urban climate modelling studies. Note that 81 of the 102 studies involve the simulation of scenarios, and that there may be more than one type of scenario in these studies (refer to Table A1 in the Appendix for details). The definitions of the acronymized scenarios are as follows: URB – the effect of urbanization/land use/land cover changes; MITI – urban heat mitigation strategies; PARA – the use of different urban parameterization schemes/land surface models; AH – the effect of anthropogenic heat flux/air-conditioning systems and practices; IN – the effect of surface input data precision/urban parameter values; WE – past or future weather scenario; FURB – future urban development scenario; INI – the variation of initialization parameters such as soil moisture; WF – the use of different weather forcing data sources; RES – the effect of model resolution.

other studies perform a series of sensitivity tests to quantify the effects by idealized urban changes on various urban climate phenomena/processes such as the UHI (e.g., Atkinson, 2003; Ryu and Baik, 2012), mesoscale circulations (e.g., Ezber et al., 2015) and extreme precipitation events (e.g., Gero et al., 2006; Pathirana et al., 2014).

### 5.1. The effect of past and future urbanization

Urbanization is a global phenomenon referring to the shift in population from rural to urban areas. As a result, cities grow in physical extent, population density, built-up intensity, as well as economic and industrial activities. To quantify the effects of increasing urban surface covers, buildings, and human activities on the SEB and the atmosphere, many studies have conducted simulations with different land cover compositions or degrees of urbanization (Fig. 8). There are two main ways to construct these scenarios: some studies employ a historical surface input dataset with a lesser extent of urbanization (e.g., Lee and Kim, 2008; Kawamoto, 2017), while others replace the entire urban area with vegetated covers to create the so-called ‘no urban’ scenario (e.g., Ryu and Baik, 2013; Ryu et al., 2016). All of these studies agree that urbanization leads to significantly hotter and drier microclimates. Apart from being the main drivers of the increase in urban temperature, the changes from natural to urban land use also alter the wind circulations, air pollutant levels, and precipitation patterns (see Sections 4.2 and 4.3). The potential impacts of further urbanization are examined in a few studies which simulated a future urban development scenario (Velazquez-Lozada et al., 2006; Coutts et al., 2008; Kaplan et al., 2017; Dimitrova et al., 2019). Besides, the adverse microclimatic effects of urbanization have been and will likely continue to be exacerbated by climate change. Conry et al. (2015) downscaled the global climate conditions of Representative Concentration Pathway 8.5 for 2076–81 to drive the meso to micro scale urban climate simulation of Chicago. Although the future climate conditions may favour the onshore penetration of lake breeze, they revealed a considerable increase in the cooling energy demand and a marked deterioration in pedestrian thermal comfort owing to the heightened daily average air temperature.

### 5.2. The effect of anthropogenic heat flux

Not present in the natural SEB, the anthropogenic heat and moisture fluxes are important components of the urban energy and water balances. Their main sources are from buildings, transportation, industry, and human metabolism (Sailor, 2011). UCMs with an added term for AHF or further coupled to BEMs enable the evaluation of the urban climate effects due to human activities and the simulation of city-scale energy consumption. AHF is found to be a significant driver of the UHI, with contributions varying from around 30% up to nearly 60% (He et al., 2007; Salamanca et al., 2012; Chen and Zhang, 2018; Mughal et al., 2019). It serves as the major heat source for the urban SEB from late afternoon to early morning when solar radiation is weak. For cities with temperate climates, the warming effect of anthropogenic heat release is greater during winter because of indoor heating and the relatively stable atmospheric conditions (Chen et al., 2009; Aoyagi et al., 2012). Ryu et al. (2013) also found that the intensification of AHF could lead to an increase in urban O<sub>3</sub> concentration associated with the dilution of NO<sub>x</sub> in the deepened boundary layer and more advection from the surroundings by the strengthened urban breeze. A few studies focused on the anthropogenic heat due to air conditioning in summer (Tremeac et al., 2012; Wang et al., 2018). The use of wet cooling towers and water-cooled air conditioning systems should be encouraged as such are effective ways to reduce the sensible heat release into the atmosphere while lowering the cooling energy consumption.

### 5.3. Urban heat mitigation strategies

There is a need to mitigate and alleviate the excess heat in cities so to improve thermal comfort and maintain a healthy urban environment (Heaviside et al., 2017). Intensive research efforts have been made recently to find ways to mitigate the urban heat (Aleksandrowicz et al., 2017). Based on the 15 studies which tested mitigation scenarios via mesoscale numerical modelling in this review, two common mitigation strategies, namely the change in albedo of urban surfaces and the increase of urban vegetation, have been identified. City-wide implementation of cool roofs and cool pavements with high albedos can effectively reduce the skin temperature of urban facets, hence the near-surface air temperatures, and for cool roofs, also the building energy consumption (Synnefa et al., 2008; Lynn et al., 2009; Zhou and Shepherd, 2010; Salamanca et al., 2012; Li and Norford, 2016; Chen and Zhang, 2018). The installation and maintenance costs are relatively low, and it is easy to introduce cool materials during retrofitting. However, increasing albedo has little effect on the UHI during the night and may even induce thermal stress for pedestrians in the day due to the high thermal radiation and reflected solar radiation from the roads and pavements (Lynn et al., 2009; Li and Norford, 2016).

As a better alternative, increasing urban vegetation is useful for reducing air temperature throughout the diurnal cycle (Taha, 2008a; Zhou and Shepherd, 2010; Lee et al., 2016; Li and Norford, 2016; Morris et al., 2016). Urban greenery contributes to a lower sensible heat flux, and hence air temperature, by increasing the latent heat flux and reducing the urban heat storage. Besides adding vegetation cover at grade, planting street trees and deploying green roofs are other ways to provide thermal relief and enhance building energy efficiency (Lynn et al., 2009; Rosenzweig et al., 2009; Chen and Zhang, 2018), respectively. It is also possible to cool the city by changing the land cover in its surroundings, such as by suburban reforestation or adding a greenbelt upwind of the city (Chen et al., 2005; Stone Jr et al., 2013). Despite the aforementioned benefits, the implementation of urban greening strategies may cause higher air pollution when the horizontal flow and vertical mixing are reduced owing to the increased roughness and boundary layer stability (Chen and Zhang, 2018; Rafael et al., 2018). Larger amounts of volatile organic compounds released from plants may also enhance ozone production. Finally, an important lesson learnt from the studies is that good urban heat mitigation requires a combination of strategies, tactful urban planning, and coordinated efforts over large areas of a city.

## 6. Conclusion

### 6.1. Limitations of the review

The studies reviewed in this paper have been retrieved from the Scopus database via a search for the keywords “mesoscale atmospheric/meteorological model” and “urban climate” followed by a screening process with seven criteria (described in Section 2). The intent is to achieve a fair sampling and reproducible search, encompass a representative number of relevant articles, while keeping the query string simple. Nonetheless, some studies that do not contain matching keywords or are not found in the Scopus database are inadvertently not included. Upon reflection, the authors could have explored more combinations of keywords, for example “mesoscale model” in place of “mesoscale atmospheric/meteorological model” and “urban climatology” in place of “urban climate”, to reveal an even more comprehensive collection of studies. Notable examples of missing contributions in the current review include investigations on air pollution and land-sea breeze circulations over the complex topography of Hong Kong using MM5 in the early 21st century by Tong et al. (2005) and Lam et al. (2006), one of the first attempts to use WUDAPT LCZ data to refine WRF-BEP urban climate simulations in Madrid by Brousse et al. (2016), and the unique case study on the driving factors and impacts of UHI in a typical Arctic city using CCLM (Varentsov et al., 2018). The integrated meteorology chemistry model Environ-HIRLAM (HHigh Resolution Limited Area Model; Baklanov et al., 2008), which has been coupled with BEP to model the UHI and urban boundary layer over Bilbao (González-Aparicio et al., 2013, 2014), as well as the SUBMESO (model derived from ARPS) with urbanized SM2 employed in studies for Copenhagen (Mahura et al., 2005), are models regrettably not covered in this review. During the course of conducting the review, the authors also noted an emergence of studies on climate scenarios and future impacts which are outside the scope of this review but certainly deserve attention given the urgency of issues associated with global climate change.

### 6.2. Key lessons learnt

In this review, the observed trends in experimental design, topics, and scenarios of 102 practical urban climate modelling studies performed in real cities and published in the first 20 years of the 21st century (2000–2019) have been reported. The major findings can be summarized as follows:

- Study locations tend to concentrate in regions with warm temperate climates, with a disproportionately high number of studies conducted in megacities.
- Simulations are usually a few days to a few weeks in length and represent either typical summer conditions or extreme weather events.
- WRF is the most frequently used MAM in urban climate studies. It is increasingly common to couple it with single- and multiple-layer UCMs for a better urban parameterization.
- Model input data to describe the urban surface are often obtained via remote sensing methods. Given available computing and data resources, the use of more urban categories or real building data from administrative databases are ways to improve the model performance by accounting for the heterogeneity in urban areas.
- The UHI effect is by far the most extensively studied urban climate phenomenon and the urban SEB is well-understood. Modifications in the local circulation, air quality, and precipitation pattern are also examined by numerical modelling methods.
- Researchers are most interested in the impacts of urbanization on the urban microclimate. Numerical experiments can also be used to evaluate the effectiveness of various urban heat mitigation strategies like changing surface albedo and adding vegetation cover.

### 6.3. Outlook and recommendations

However, research in the field of urban climate certainly does not and should not stop here. Standing on the shoulders of giants, the authors noted several research gaps and emerging trends that should be given more attention in future works.

- (1) Future studies should put more focus on the small cities in developing countries and regions with tropical, arid, and cold climates. Such locations lack resources but are experiencing rapid urbanization; they are also among the most vulnerable to climate change.
- (2) Among the urban climate processes and topics identified in the reviewed studies, urban precipitation, outdoor thermal comfort, and building energy consumption are relatively less examined. As Dou et al. (2020) pointed out, the advancement in MAMs and urban parameterizations may facilitate the better understanding of the complex processes involved in the modification of precipitation patterns due to urban areas. The other two topics may serve as links between the scientific understanding and human impact of urban-induced microclimates, and thus should be given no less attention, if not more, than the rest of the topics.
- (3) While studies should continue to provide the pertinent urban climatic information for typical and extreme weather conditions as they have been doing, the Intergovernmental Panel on Climate Change noted a lack of studies on compound events, i.e. the simultaneous or successive occurrence of two or more extreme weather or climate events (Seneviratne et al., 2012). None of the reviewed studies have investigated the impacts of compound events thus far. The causes and spatiotemporal effects of these events, especially with respect to the health and resilience of human ecosystems, may be better understood with the help of urban climate simulations.

- (4) Large-scale urban field campaigns which collect a complete dataset of meteorological, air quality, and energy flux measurements, such as the Joint URBAN 2003 street canyon experiment held in Oklahoma City (Brown et al., 2004), are extremely useful, not only for observational studies, but also for the evaluation and subsequent enhancement of urban climate models. They should therefore be conducted more frequently, for longer durations, and in cities with varied urban settings.
- (5) The choice of MAMs and UCMs has been rather monotonous (most studies use WRF with SLUCM or BEP for good reasons). However, since there is no single model that performs the best in every aspect (Best and Grimmond, 2015), researchers may benefit from working in collaboration with other model development teams to achieve synergistic effects and hence the optimal model results. Moreover, the use of an ensemble simulation approach, as it is commonly adopted for future climate projections (Collins et al., 2012), could be considered. It is found that an ensemble of models is generally able to simulate fluxes of the urban SEB better than any individual model (Grimmond et al., 2011).
- (6) Urban climate processes occur and interact at multiple scales – from city (mesoscale), down to neighbourhood (microscale), and even building scale. A few of the reviewed studies have employed dynamical or statistical downscaling techniques to couple MAMs with CFD models (e.g., Ryu et al., 2013; Conry et al., 2015; Kochanski et al., 2015), making the link between the city and neighbourhood scales, thus facilitating detailed analyses in pedestrian comfort, building energy, and air quality. Although not within the scope of the current review, there have been plenty of microscale and/or offline urban modelling studies that provided useful insights in applications on urban ventilation, pollution, and thermal comfort (e.g. Letzel et al., 2012, Hirano and Fujita, 2016, Sanchez et al., 2017, Nice et al., 2018, Chen et al., 2019, which have been filtered out from the Scopus search results). However, in order to better reproduce the dynamic urban-atmosphere interactions and integrate larger scale environmental influences into finer scale models, there is an increasing need for the development of cross-scale modelling systems.
- (7) As models increase in level of complexity to achieve more accurate simulations in high spatial resolution, they should be matched with appropriate parameterization schemes and urban surface data with a higher level of precision. On the one hand, care needs to be taken in the selection and development of turbulence and urban surface parameterizations when modelling within the turbulence and building ‘grey zones’. On the other hand, more efforts to collect and standardize the description of urban surface characteristics for model input should be encouraged (Masson et al., 2020). For cities in developing countries, data availability could be greatly improved by open source remote sensing methods like the WUDAPT mapping (Ching et al., 2018, 2019); whereas for cities in developed countries, especially those with a complex, high-rise urban form, the acquisition of high-resolution and three-dimensional building data, alongside with parameters influencing the AHF, would be favourable for its application in more advanced multi-layer UCMs and BEMs. Furthermore, enabled by advances in big data and machine learning, novel deep learning approaches have been developed to derive urban spatial parameters from online map and satellite products (e.g. Gong et al., 2018; Middel et al., 2019; Zhang et al., 2020). The potential of applying these data in UCMs has yet to be fully explored.
- (8) The arguably most important aspect of urban climate studies is to ensure knowledge transfer from scientists to architects, urban planners, and policymakers. Only by doing so can the understanding of urban climatic issues be transformed into solutions that ameliorate the living environment and well-being of the urban population. A mere 15% of the reviewed studies have attempted to put their findings into practice while a majority of them could have gone one step further to make the science more accessible and down-to-earth. Building on the prolific scientific literature, more emphasis could be laid upon the practical implications of the different numerical modelling studies to be conducted. Suggestions of topics worthy of further investigation include, but are not limited to, the potential risks of future urbanization under a range of climate scenarios, the holistic cost-benefit analysis of urban heat mitigation strategies, and the design of climate-responsive and sustainable urban systems. In view of the growing multidisciplinary nature of urban climate studies, integrated and collaborative approaches would essentially be the way forward, as demonstrated by the recently commenced synergy project *urbisphere* (<http://www.urbisphere.eu/>).
- (9) At the end of the day, urban climate simulation studies as those reviewed also need to be evaluated with respect to their study objectives and intended applications. Baklanov et al. (2009) provided some guidance and examples on evaluating studies based on ‘fitness-for-purpose’ concepts. This has, regrettably, not been done in the scope of this paper, but should certainly be reflected upon by modellers and researchers in the field for their current and upcoming endeavours. Such model assessments would certainly be a good candidate for further review.

#### **Declaration of Competing Interest**

None.

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## Appendix A

**Table A1**

Summary of the 102 studies using MAMs for urban climate applications reviewed (in reverse chronological order). The climate zones of study locations are taken from the high-resolution Köppen-Geiger map available at <http://koeppen-geiger.vu-wien.ac.at/present.htm>. The duration of simulation periods are categorised into single day (SD), few days (FD) for 2–6 days, weeks (W) for 1–3 weeks, months (M) for periods >3 weeks but <3 months, seasons (S) for periods <3 months but <1 year, and year (Y) for a year-long simulation. Seasons of simulated periods are roughly defined as spring (autumn) in March to May, summer (winter) in June to August, autumn (spring) in September to November, and winter (summer) in December to February for the northern (southern) Hemisphere, except for Singapore (1.35°N, 103.8°E) which is considered to have a summer season all-year round. Note that some studies may have simulated several discontinuous periods from different seasons. Resolution (Res) of the innermost MAM domain is given in metres. Urb-data describes the data sources of urban surface and anthropogenic heat information used as model input. U-cat states whether the model allows the precise input of all urban parameters, urban fraction (UF) or roughness length (Z0) in each grid; otherwise, it states the number of urban categories considered. Note that in some studies, input data with varied precision are used for different urban parameterisations (UPs). Definitions and references for acronymised MAMs, UPs, urb-data, topics, and scenarios can be found in Tables A1 to A4 of the appendix and the captions of Figs. 6 and 7 in the main manuscript. In the columns UP, urb-data, and u-cat, ‘ns’ means such information is not clearly stated in the study. In the Topic column, ‘UHI(s)’ denotes studies which examine also the land surface temperature in urban temperature studies. Asterisks (\*) mark the urban climate topics or scenarios where the MAM-UCM is further coupled to a microscale model (e.g. CFD).

Reference	Location	Climate	Period	Season	MAM	UP	Res (m)	Urb-data	U-cat	Topic	Scenario
Li et al., 2019a, 2019b	Berlin (Germany)	Cfb	W	summer	WRF	SLUCM	1000	CLC, ADM, RS, AH-p	3	UHI	–
Kwok et al., 2019	Toulouse (France)	Cfa	W	summer	MNH	TEB-BEM	250	ECO, ADM, RS, AH-m	precise	UHI, TC, PP	–
Dai et al., 2019	Pearl River Delta (PRD) (China)	Cwa	M	summer, winter	WRF/ chem	SLUCM	3000	GLC, RS, AH-i	precise	AQ, USEB	IN
Xing et al., 2019	Xiong'an City (China)	Bsk	SD	summer	WRF	SLUCM	1000	RS	1	RF	URB
Dimitrova et al., 2019	Sofia (Bulgaria)	Cfb	W	summer	WRF	bulk	500	CLC, NLCD	4	UHI, PP	FURB
Rafael et al., 2019	Porto, Aveiro (Portugal)	Csb	S	autumn	WRF	SLUCM, bulk	1000	CLC, AH-p	3	USEB	PARA
Teixeira et al., 2019	Lisbon (Portugal)	Csa	FD	summer	WRF	BEP, SLUCM	1000	CLC, AH-p	3	O	PARA
Bauer, 2019	New York City (USA)	Cfa	FD	summer	WRF	BEP-BEM, SLUCM, bulk	500	NLCD, ADM, AH-m	3	AQ*	PARA
Mughal et al., 2019	Singapore	Af	M	summer	WRF	BEP-BEM	300	RS, AH-m	10	UHI, USEB, LC	AH, URB, WF
Dado and Narisma, 2019	Metro Manila (Philippines)	Am	S	summer	MM5	bulk	1670	RS	1	RF	URB, WE
Li et al., 2018	Berlin (Germany)	Cfb	W	summer	WRF	bulk	1000	USGS, CLC, UA	precise	UHI(s)	IN, URB
Zhao and Wu, 2018	Beijing, YRD, PRD (China)	BSk, Cfa, Cwa	Y	all	MM5	bulk	3300	USGS, RS, ADM, DEM	1	RF	URB
Rafael et al., 2018	Porto (Portugal)	Csb	FD	autumn	WRF	SLUCM	1000	CLC	1	AQ*, PP	MITI*
Calderón- Ezquerro et al., 2018	Mexico City (Mexico)	Cwb	S	winter, spring, summer	WRF	bulk	3000	MOD	1	AQ	–
Huang et al., 2018	Hangzhou (China)	Cfa	FD	summer	WRF	bulk	4000	GLC	1	RF	–
Hughes and Veron, 2018	Delaware (USA)	Cfa	S	summer	WRF	bulk	2000	USGS	1	LC	–
Dehghan et al., 2018	Greater Toronto Area (Canada)	Dfb	M	summer	GEM	TEB	250	ns	ns	LC	–
		Cfa	FD	summer	WRF	SLUCM	2000		3		

(continued on next page)

**Table A1 (continued)**

Reference	Location	Climate	Period	Season	MAM	UP	Res (m)	Urb-data	U-cat	Topic	Scenario
Chen and Zhang, 2018	Yangtze River Delta (YRD) (China)							RS, DEM, AH-p		UHI(s), PP	AH, URB, MITI
Pereira, and J. L., and Karam, H. A., 2018	Tokyo Metropolitan Area (Japan)	Cfa	S	summer	ARPS	T-TEB	1000	APP, AH-p	1	UHI, LC, RF	-
Flores Rojas et al., 2018	São Paulo (Brazil)	Cfa	SD	winter	ARPS	T-TEB	3000	USGS, APP, AH-p	1	UHI(s), LC, USEB	PARA
Wang et al., 2018	Hong Kong (China)	Cwa	FD	summer	WRF	BEP-BEM	500	ADM, AH-m	2	UHI, LC, EC	AH, MITI
Bassett et al., 2017	Birmingham (UK)	Cfb	M	summer	WRF	BEP	1000	CLC, ADM	3	UHI, LC, PP	URB
Kaplan et al., 2017	Israel	Csa, BSh, BWh	M	summer	WRF	SLUCM	1000	MOD, ADM	1	UHI, USEB, PP	FURB
Jänicke et al., 2017	Berlin-Brandenburg (Germany)	Cfb	M	winter, spring, summer	WRF	BEP, SLUCM, bulk	2000	USGS, CLC	3/ precise UF	UHI	PARA
Nemunaitis-Berry et al., 2017	Oklahoma (USA)	Cfa	FD	summer	WRF	SLUCM	1000	NLCD	3	UHI(s), USEB	-
Kawamoto, 2017	Fukuoka-Kitakyushu Area (Japan)	Cfa	M	summer	WRF	bulk	1000	ADM	precise UP	UHI, LC	URB
García Díez et al., 2016	Barcelona (Spain)	Csa	S	summer	WRF	SLUCM	1100	CLC	3	UHI(s)	-
Kuik et al., 2016	Berlin-Brandenburg (Germany)	Cfb	S	summer	WRF/ chem	SLUCM	1000	CLC, ADM	3	AQ	IN
Wouters et al., 2016	Belgium	Cfb	M	summer	CCLM	bulk	2800	ECO, GLC, AH-p	precise UP	UHI(s)	IN
de Morais et al., 2016	São Paulo (Brazil)	Cfa	FD	winter	BRAMS	TEB	1000	RS, AH-p	4	UHI(s), PP	PARA
Cécé et al., 2016	Guadeloupe	Am	FD	winter	WRF	bulk	111	CLC	1	AQ*	-
Lee et al., 2016	Seoul (Korea)	Dwa	FD	winter	WRF	VUCM	333	ADM, AH-p	2	UHI	MITI
Morris et al., 2016	Putrajaya (Malaysia)	Af	FD	autumn	WRF	SLUCM	300	RS	3	UHI, PP	URB, MITI
Sequera et al., 2016	SC, San Francisco (USA)	BSk, Csb	W	autumn	WRF	bulk	1000	MOD, RS	5	UHI, LC	IN
Li and Norford, 2016	Singapore	Af	M	summer	WRF	SLUCM	300	ADM, RS, APP	3	UHI, PP	URB, AH, MITI
Hu and Xue, 2016	Dallas-Fort Worth (USA)	Cfa	W	summer	WRF	SLUCM	800	NLCD	3	UHI(s), LC	-
Ryu et al., 2016	Baltimore-Washington (USA)	Cfa	FD	summer	WRF	PUCM, bulk	1000	NLCD	3	RF	URB, PARA
Zhou et al., 2016	Wuhan (China)	Cfa	FD	summer	WRF	bulk	500	USGS	1	UHI(s)	URB
Conry et al., 2015	Chicago-Illinois (USA)	Dfa	FD	autumn	WRF	BEP-BEM	333	USGS, NLCD, AH-m	3	UHI, LC, TC, EC*	WE
Gutiérrez et al., 2015	New York City (USA)	Cfa	FD	summer	WRF	BEP-BEM, bulk	1000	NLCD, ADM, AH-m	3	UHI	IN, URB, PARA
Li et al., 2015	Yangtze River Delta (China)	Cfa	W	spring, summer, autumn	WRF	bulk	4000	MOD	1	UHI(s), LC	URB
Kochanski et al., 2015	Oklahoma (USA)	Cfa	FD	summer	WRF	BEP, bulk	1330	MOD	ns	LC*	PARA
Chow et al., 2014	Metropolitan Phoenix Area (USA)	BWh	M	summer	WRF	BEP-BEM	1000	NLCD, AH-m	3	UHI, EC	-
Pay Pérez et al., 2014	Barcelona, Madrid (Spain)	Csa	W	spring	WRF	bulk	1000	USGS	1	AQ	-

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**Table A1 (continued)**

Reference	Location	Climate	Period	Season	MAM	UP	Res (m)	Urb-data	U-cat	Topic	Scenario
Giannaros et al., 2014	Athens (Greece)	Csa	M	summer	WRF	bulk	2000	CLC	4	UHI, TC	-
Ohashi et al., 2014	Tokyo Metropolitan Area (Japan)	Cfa	S	summer	WRF	CM-BEM	1000	RS, ADM, AH-m	precise	TC	-
Husain et al., 2014	Oklahoma City (USA)	Cfa	FD	summer	GEM	CaM-TEB	1000	ns	12	UHI, LC	INI
Kang et al., 2014	Shanghai, Kunshan (China)	Cfa	SD	summer	WRF	SLUCM	500	MOD, AH-p	1	UHI, LC	URB
Leroyer et al., 2014	Vancouver (Canada)	Cfb	FD	summer	GEM	TEB	250	RS, AH-p	12	UHI(s), LC	RES
Ryu et al., 2013	Seoul (Korea)	Dwa	SD	summer	WRF	SNUUCM	1000	RS, ADM, AH-i	2	AQ, LC	AH
Grawe et al., 2013	London (UK)	Cfb	FD	summer	METRAS	BEP	1000	RS	2	UHI, PP	URB
Stone Jr et al., 2013	Atlanta metropolitan region (USA)	Cfa	M	summer	WRF	bulk	4000	NLCD	1	UHI, PP	URB, MITI
Ryu and Baik, 2013	Seoul (Korea)	Dwa	SD	summer	WRF	SNUUCM	333	MOD, ADM, AH-p	2	UHI, LC	URB
Wan et al., 2013	Yangtze River Delta (China)	Cfa	FD	summer	WRF	SLUCM	4000	MOD	1	UHI, LC, RF	URB
Comarazamy et al., 2013	San Juan (Puerto Rico)	Af	S	spring	RAMS	bulk	1000	RS	1	UHI	URB, WE
Zhan et al., 2013	Shanghai (China)	Cfa	FD	summer	MetPho Mod	ns	500	ADM	precise	AQ	URB
Hu et al., 2013	Oklahoma City (USA)	Cfa	FD	summer	WRF	SLUCM	500	NLCD	3	UHI(s), LC	-
de Munck et al., 2013	Paris (France)	Cfb	FD	summer	MNH	TEB	250	ADM, AH-m	precise	UHI	AH
Salamanca et al., 2012	Madrid (Spain)	Csa	FD	summer	WRF	BEP-BEM	333	CLC, AH-m	3	UHI, EC	MITI, AH
Kusaka et al., 2012	Tokyo Metropolitan Area (Japan)	Cfa	M	summer	WRF	SLUCM, bulk	4000	ADM, AH-p	1	UHI, USEB	PARA
Aoyagi et al., 2012	Kanto-Koshin (Japan)	Cfa	M	summer, winter	JMA-NHM	SPUC	4000	ADM, AH-p	precise	UHI	URB, AH
Chemel and Sokhi, 2012	London (UK)	Cfb	FD	spring	WRF	BEP-BEM, SLUCM bulk	1000	MOD, RS, AH-m	1/3	UHI, LC	IN, PARA
Cui and de Foy, 2012	Mexico City (Mexico)	Cwb	W	all	WRF	SLUCM, bulk	3000	MOD	1	UHI(s)	IN
Hamdi et al., 2012	Belgium	Cfb	M	summer, winter	ALARO-0	TEB, bulk	4000	ECO	precise	UHI, LC, RF	PARA
Ruddell et al., 2012	Phoenix metropolitan area (USA)	BWh	FD	summer	WRF	SLUCM	1000	USGS, RS, AH-p	3	UHI, PP, O	-
Carter et al., 2012	Houston (USA)	Cfa	FD	summer	WRF	SLUCM, bulk	1100	USGS, RS	3	UHI(s), LC	URB, PARA
Tursilowati et al., 2012	Jakarta (Indonesia)	Af	FD	summer	WRF	bulk	1000	USGS, RS	1	UHI	URB
Tremeac et al., 2012	Paris (France)	Cfb	FD	summer	MNH	TEB	250	ADM, AH-m	precise	UHI	-
Zhang et al., 2011	Baltimore-Washington (USA)	Cfa	FD	summer	WRF	SLUCM	500	USGS, NLCD	3	UHI(s), LC	URB
Sarkar and De Ridder, 2011	Paris (France)	Cfb	W	summer	ARPS	bulk	1000	CLC, AH-p	3	UHI	-
Georgescu et al., 2011	Phoenix metropolitan area (USA)	BWh	M	summer	WRF	bulk	2000	USGS, NLCD	3	UHI	URB, WE
Lin et al., 2010	Pearl River Delta (China)	Cwa	M	autumn	MM5	bulk	3000	USGS, MOD	1	UHI(s)	URB
Tokairin et al., 2010	Jakarta (Indonesia)	Af	FD	summer	MM5	bulk	3000	USGS, DEM	1	UHI, LC	URB

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**Table A1 (continued)**

Reference	Location	Climate	Period	Season	MAM	UP	Res (m)	Urb-data	U-cat	Topic	Scenario
Comarazamy et al., 2010	San Juan (Puerto Rico)	Af	W	winter	RAMS	bulk	1000	RS	6	UHI, LC, RF	URB
Zhou and Shepherd, 2010	Atlanta (USA)	Cfa	FD	summer	WRF	bulk	2000	USGS	1	UHI	MITI
Rosenzweig et al., 2009	New York City (USA)	Cfa	W	summer	MM5	bulk	1300	USGS, RS, ADM, DEM	1	UHI(s), EC, PP	MITI
Baik et al., 2009	Seoul metropolitan area (Korea)	Dwa	FD	summer	MM5	bulk	1000	USGS	1	AQ*	-
Miao et al., 2009	Beijing metropolitan area (China)	BSk	FD	summer	WRF	SLUCM	500	ADM, AH-p	3	UHI(s), LC, USEB	URB
Lynn et al., 2009	New York metropolitan area (USA)	Cfa	W	summer	MM5	bulk	1330	ns	precise UP	TC, PP	MITI
Georgescu et al., 2009	Greater Phoenix region (USA)	BWh	M	summer	RAMS	bulk	2000	NLCD, MOD, RS	1	USEB	URB, WE
Holt et al., 2009	Tokyo Metropolitan Area (Japan)	Cfa	FD	summer	WRF	LANL, SLUCM	1670	USGS, APP, AH-p	1	UHI, LC, AQ	IN
Jiang et al., 2009	Pearl River Delta (China)	Cwa	FD	autumn	MM5	bulk	1000	USGS	1	UHI	-
Chen et al., 2009	Hangzhou (China)	Cfa	SD	summer, winter	NJU-RBLM	ns	1000	ADM, DEM, AH-i	precise	UHI	AH
van Weverberg et al., 2008	Brussels (Belgium)	Cfb	W	winter, spring, summer	ARPS	bulk	1000	CLC, RS	3	UHI, USEB	URB
Lee and Kim, 2008	Daegu metropolitan area (Korea)	Cwa	FD	summer	LCM	bulk	360	ADM	1	LC	URB
Coutts et al., 2008	Melbourne (Australia)	Cfb	M	summer	TAPM	bulk	1000	ADM, DEM, AH-i	4	UHI, PP	FURB
Synnefa et al., 2008	Athens (Greece)	Csa	SD	summer	MM5	bulk	670	USGS, RS, AH-p	9	UHI	MITI
Wichansky et al., 2008	New Jersey (USA)	Cfa	M	summer	RAMS	bulk	2000	NLCD	1	UHI, RF, USEB	URB
Taha, 2008a	Houston-Galveston (USA)	Cfa	FD	summer	MM5	DA-SM2-U	1000	USGS, RS, ADM, AH-p	precise	UHI	MITI
Taha, 2008b	Southern California (USA)	BSk, BWh, Csb, Csa	W	summer	MM5	bulk	4000	USGS, RS	7	AQ	MITI
Lin et al., 2008	Taiwan	Am, Aw, Cfa, Cfb, Cwa	SD	summer	MM5	bulk	3000	USGS	1	LC, RF, USEB	URB
Miao et al., 2007	Göteborg (Sweden)	Cfb	W	spring	MM5	bulk	2000	USGS	1	UHI	PARA
He et al., 2007	Nanjing, Hangzhou (China)	Cfa	FD	summer, winter	NJU-RBLM	ns	1000	ns, AH-i	2	UHI	AH
Chen and Jiang, 2007	Nanjing area (China)	Cfa	SD	summer	NJU-RBLM	bulk	1000	USGS, RS, AH-i	1	USEB	URB
Freitas et al., 2007	São Paulo (Brazil)	Cfa	FD	winter	RAMS	TEB	4000	RS, AH-p	2	LC	URB
Tokairin et al., 2006	Tokyo (Japan)	Cfa	FD	summer	Kondo	CM	2000	ns	2	UHI	URB, AH
Velazquez-Lozada et al., 2006	San Juan (Puerto Rico)	Af	FD	winter	RAMS	bulk	1000	DEM	1	UHI, USEB	URB, FURB
		Cwb	FD	spring	MM5	bulk	3000		1	UHI(s)	IN, INI

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**Table A1 (continued)**

Reference	Location	Climate	Period	Season	MAM	UP	Res (m)	Urb-data	U-cat	Topic	Scenario
de Foy et al., 2006	Mexico City (Mexico)							MOD, RS			
Fan and Sailor, 2005	Philadelphia (USA)	Cfa	FD	summer, winter	MM5	ns	2000	USGS, AH-p	1	UHI	AH
Chen et al., 2005	Beijing (China)	BSk	FD	summer, winter	NJU-RBLM	bulk	4000	ADM	1	UHI, USEB, PP	MITI
Hirano et al., 2004	Tokyo Metropolitan Area (Japan)	Cfa	FD	summer	CSUMM	bulk	2000	RS, AH-p	precise UF	UHI, USEB	IN
Ohashi and Kida, 2002a, 2002b	Osaka-Kyoto (Japan)	Cfa	SD	summer	DryARD	bulk	2000	ns, AH-i	4	LC, AQ	URB

**Table A2**

Mesoscale atmospheric models in the reviewed studies.

Acronym	Name/Description	Reference
ALARO-0	a revised version of the Action de Recherche Petite Echelle Grande Echelle–Aire Limitée Adaptation Dynamique Développement International (ARPEGE–ALADIN) operational limited-area model	Gerard et al., 2009
ARPS	Advanced Regional Prediction System	Xue et al., 2000
BRAMS	Brazilian developments on the Regional Atmospheric Modeling System	Freitas et al., 2017
CCLM	a version of the Consortium for Small-Scale Modelling (COSMO) model for Climate Limited-area Modelling	Rockel et al., 2008
CSUMM	Colorado State University Mesoscale Model	Pielke, 1974, Kessler and Douglas, 1992
DryARD	Dry Atmospheric Regional Demonstrations	Ohashi and Kida, 2002a, 2002b
GEM	Global Environmental Multiscale numerical model	Côté et al., 1998, Zadra et al., 2008
JMA-NHM	Japan Meteorological Agency Non-Hydrostatic Model	Saito et al., 2006
Kondo	the National Research Institute for Pollution and Resources (NIPR) mesoscale model	Kondo, 1989, Kondo, 1990
LCM	a Local circulation model	Kimura and Arakawa, 1983
MetPhoMod	METeorology and PHotochemistry MODEl	Perego, 1999
METRAS	MEsoscale TRAnsport and Stream model	Schlünzen, 1988
MM5	the community fifth-generation Pennsylvania State University–National Center for Atmospheric Research (PSU–NCAR) Mesoscale Model	Grell et al., 1994
MNH	Non-hydrostatic mesoscale atmospheric model Meso-NH	Lafore et al., 1997, Lac et al., 2018
NJU-RBLM	Regional Boundary Layer model developed by Nanjing University	Jiang et al., 2007
RAMS	Regional Atmospheric Modeling System	Pielke et al., 1992
TAPM	The Air Pollution Model	Hurley et al., 2005
WRF	Weather Research and Forecasting Model	Skamarock et al., 2008, Chen et al., 2011
WRF/chem	an extended version of WRF including atmospheric chemistry	Grell et al., 2005

**Table A3**

Urban parameterization used in the reviewed studies.

Type	Acronym	Name/Description	Reference
Bulk	bulk	land surface model with a simple bulk parameterization for urban areas	(e.g. Noah LSM described in text)
Single-layer UCM	PUCM	Princeton Urban Canopy Model	Wang et al., 2013
	SLUCM	Single-Layer Urban Canopy Model	Kusaka et al., 2001
	SNUUCM	Seoul National University Urban Canopy Model	Ryu et al., 2011
	SPUC	an extended single-layered urban canopy scheme based on TEB and SLUCM	Aoyagi and Seino, 2011
	TEB	Town Energy Balance	Masson, 2000
	TEB-BEM	TEB coupled with a Building Energy Model	Bueno et al., 2012
	T-TEB	Tropical Town Energy Budget	Karam et al., 2010
Multi-layer UCM	VUCM	Vegetated Urban Canopy Model	Lee and Park, 2008
	BEP	Building Effect Parameterization	Martilli et al., 2002
	BEP-BEM	BEP coupled with a Building Energy Model	Salamanca et al., 2010
	CaM-TEB	Canadian Multilayer version of Town Energy Balance	Husain et al., 2013
	CM	a multi-layered urban Canopy Model first developed by Kondo and Liu (1998)	Kondo et al., 2005
	CM-BEM	CM coupled with a Building Energy Model	Kikegawa et al., 2003
	DA-SM2-U	detailed urban and rural canopy parameterization using the drag-force approach and a modified 3D version of the soil model SM2-U	Dupont et al., 2004
	LANL	Los Alamos National Laboratory urban model	Brown and Williams, 1998

**Table A4**

Urban surface input data sources of the reviewed studies.

Acronym	Name/Description	Reference
ADM	administrative database	NA
APP	set by approximation/ based on author's experience	NA
CLC	Coordination of Information on the Environment (CORINE) Land Cover inventory	Büttner et al., 2006; <a href="https://land.copernicus.eu/pan-european/corine-land-cover">https://land.copernicus.eu/pan-european/corine-land-cover</a>
DEM	inferred from demographic/ census data	NA
ECO	ECOCLIMAP database	Champeaux et al., 2005
GLC	Finer Resolution Observation and Monitoring (FROM) of Global Land Cover (GLC) map	Gong et al., 2013
MOD	Moderate Resolution Imaging Spectroradiometer (MODIS) Land Cover Type Product	Sulla-Menashe and Friedl, 2018; <a href="https://lpdaac.usgs.gov/products/mcd12q1v006/">https://lpdaac.usgs.gov/products/mcd12q1v006/</a>
NLCD	United States National Land Cover Database	Homer et al., 2015; <a href="https://www.mrlc.gov/">https://www.mrlc.gov/</a>
RS	derived from remote sensing methods other than the common land use databases	NA (examples in the main text)
UA	Urban Atlas	Prastacos et al., 2011
USGS	United States Geological Survey's Global Land Cover Characterization (GLCC) land use/land cover dataset	<a href="https://doi.org/10.5066/F7GB230D">https://doi.org/10.5066/F7GB230D</a>

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