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Modelling Urban Heat Islands for Resilient Cities: From Building Energy Models to Standards and Policy Frameworks

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Abstract: Urban Heat Island (UHI) effects are increasingly recognised as a major challenge for climate resilience, urban sustainability, and public health. Buildings play a dual role: they are highly vulnerable to overheating while simultaneously contributing to urban heat through energy use and anthropogenic emissions. This review explores the modelling of UHI phenomena across scales, from single-building dynamic energy simulations to Urban Building Energy Models capable of capturing interactions between the built environment and the urban microclimate. Particular attention is given to the drivers of UHI formation, the development of modelling tools such as Urban Weather Generator (UWG), and the growing need for harmonised methodologies and standards, including recent World Meteorological Organization (WMO) guidance. The article highlights the link between scientific evidence and regulatory frameworks, from European climate adaptation strategies to national and regional policies promoting passive cooling, reflective materials, and climate resilience planning. By bridging fundamentals, modelling advances, and policy implications, the paper aims to provide an integrated perspective on how UHI research can inform effective mitigation strategies and support the transition toward sustainable, resilient, and carbon-neutral cities.

Keywords: Urban Heat Island; Urban microclimate modelling; Urban climate resilience; Standards and policy frameworks; Climate adaptation and mitigation

1 Introduction and Fundamentals

Nowadays, over half of the world’s population lives in urban areas, where the air temperature can be consistently higher than in their surroundings. This phenomenon is called the Urban Heat Island (UHI) effect. According to the World Meteorological Organization (WMO) [1], the UHI is defined as the “observed difference in temperature between an urban area and its surrounding non-urban areas under comparable synoptic conditions.” WMO distinguishes several types of UHI considering the atmospheric layer and the relevant variable measured, which include: the surface UHI based on land-surface temperature; the canopy-layer UHI, representing air temperature differences within the urban canopy where people live; and the boundary-layer UHI, referring to air temperature contrasts up to about 1–2 km above the ground. These correspond respectively to the Urban Canopy Layer (UCL), the Roughness Sublayer, and the Urban Boundary Layer, which together form the lower part of the Planetary Boundary Layer (Figure 1).

The UHI spreads horizontally at a variety of spatial dimensions, ranging from micro-scale impacts on individual surfaces and street canyons to local, meso-scale, and regional patterns that cover whole metropolitan areas (Table 1). This classification demonstrates that the UHI is a continuum of temperature contrasts that fluctuate in both vertical and horizontal dimensions, rather than a single phenomenon.

Within the UCL, people directly experience microclimatic variations linked to building height, street orientation, and vegetation density, while the boundary-layer UHI affects regional airflows. The cumulative result is a persistent temperature difference between urban and rural zones (so-called UHI intensity), often strongest at night when stored heat is released. Global satellite analyses across 419 major cities show that the average surface UHI intensity is about 1–2°C, although individual cities display large differences, with values ranging from negative in some desert regions to over 7°C in others [2]. The UHI intensity also varies over time according to several studies: it tends to be relatively low on summer afternoons when convection and latent heat flux dissipate heat. Besides, it peaks during calm, cloudless nights in winter, sometimes exceeding 8°C, and in subtropical cities has reached values of more than 7°C after sundown [3, 4]. These findings highlight the importance of understanding and modelling the UHI phenomenon for developing effective mitigation and adaptation strategies. In this context, the aim of this paper is to provide a comprehensive overview of UHI modelling approaches, linking physical fundamentals, methodological developments, and emerging policy frameworks at international and national levels. A narrative and scoping review approach was used to analyse and synthesise the existing literature.

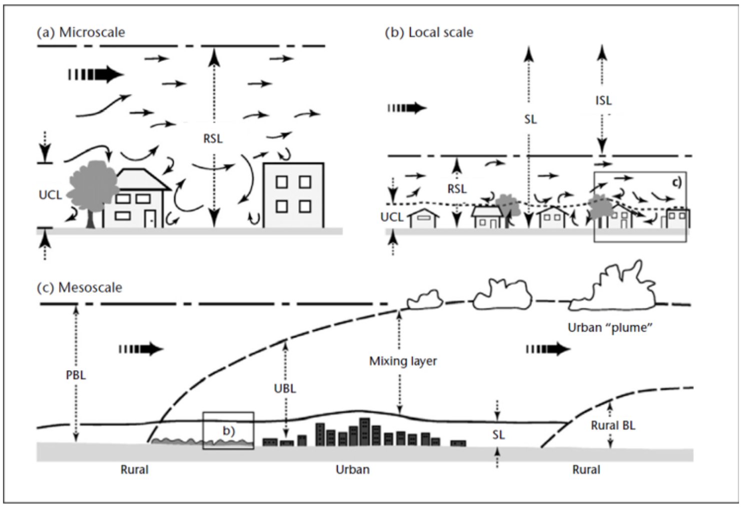

Figure 1. Vertical extent of atmospheric layers across different horizontal scales of urban form: (a) Microscale; (b) Local scale; and (c) Mesoscale

Note: The schematic illustrates the Urban Canopy Layer (UCL), Roughness Sublayer, Surface Layer, Inertial Sublayer, Urban Boundary Layer, and Planetary Boundary Layer. Source: World Meteorological Organization (WMO) [1], adapted from Bailey [5]

Table 1. Characteristic scales of urban form and atmospheric phenomena

Scale	Urban Form	Horizontal Length	Vertical Extent
Micro	Facet (roof, wall, road)	1–10 m	Urban Canopy Layer (UCL)
	Building	>10 m	UCL
	Street, canyon	30–200 m	UCL
Local	Block (bounded by canyons, interior courtyards)	300–500 m	Roughness Sublayer
	Neighbourhood	1–2 km	Roughness Sublayer, Inertial Sublayer
Meso	Urban area (city centre to low-density residential areas that are contiguous)	10–100 km	Urban Boundary Layer
Regional	Region (urban and non-urban surroundings)	>100 km	Planetary Boundary Layer

Source: World Meteorological Organization (WMO) [1], adapted from Cleugh and Grimmond [6], and Oke et al. [7]

The formation of UHI is driven by multiple physical and anthropogenic mechanisms that alter the urban surface energy balance. The local energy balance of cities comprises net radiation, sensible heat, latent heat, storage heat, anthropogenic heat, and advective fluxes. Altering any term—for example, by increasing building density, decreasing vegetation, or intensifying energy use—shifts the balance and modifies UHI intensity [8]. By reviewing several articles, the driving forces can be categorized into four main groups: (1) surface and material properties, (2) land surface state, (3) urban geometry, and (4) anthropogenic heat.

The first represents the physical properties of the materials of the surfaces. The use of impervious surfaces such as dark roofs, asphalt roads, and concrete pavements is very common in urban areas. Due to their low albedo and high heat capacity, these materials absorb large amounts of solar radiation during the day and release the stored energy gradually as longwave radiation later. This increases the overall sensible heat flux within the urban canopy. According to the findings, pavement and roofing materials can become 27–50°C warmer than the ambient air on sunny days, producing potent local heat sources [9, 10].

The land surface state, including vegetation and water bodies, is the second driving force. By altering the amount of solar energy absorbed and promoting natural cooling through latent heat exchange with the atmosphere, vegetation moderates both surface and air temperatures within urban areas. Additionally, it affects UHI through evapotranspiration, albedo, and shading. According to a forest statistical analysis conducted in Xi'an, China, compact local climate zones (LCZs) were roughly 3°C hotter than open zones, and fractional vegetation cover is the single most significant predictor of land-surface temperature [11]. A comparative simulation-based analysis in Brisbane showed that the lack of vegetation raises nighttime temperatures by as much as 1.88°C when compared to scenarios with medium-density vegetation [7]. Furthermore, the presence of water bodies, such as rivers and lakes, further enhances cooling by increasing local humidity and evaporation, which can lower nearby surface temperatures and reduce daytime heat accumulation [12, 13].

The third driver is urban geometry. Narrow street canyons, deep courtyards, and tall buildings reduce the sky-view factor and trap long-wave radiation, which results in decreasing convective cooling. Dense and enclosed geometries intensify surface heating, as demonstrated by a study conducted in Xi'an, China. It was found that compact urban forms with higher building density and smaller sky-view factors were up to 3°C hotter than open configurations [11]. Analytical experiments also show that reducing heat accumulation can be achieved by widening streets, integrating vegetation, orienting buildings for cross-ventilation, and increasing the sky-view factor [9].

The last driver is anthropogenic heat emissions. The surrounding air and surface temperature increase directly due to the waste heat from air conditioning units, vehicles, and industrial activities. Anthropogenic heat can greatly intensify UHI, as evidenced by modelling experiments conducted during Sydney's 2017 heat wave, which found that raising anthropogenic heat release to 266.5 $W{\cdot}m^2$ increased surface temperature by 8.1°C and ambient air temperature by 2.1°C. Anthropogenic heat is especially significant at night and in the winter [13, 14].

The main driving forces for UHI are summarized in Table 2. In addition, it should be noted that meteorological and climatic factors act as modulators, influencing when and where UHI intensity peaks.

Table 2. Main driving forces of the Urban Heat Island (UHI)

Driving Force	Associated Impact on UHI
Surface and material properties	Greater absorption of solar radiation and heat reemission by low-albedo, high heat-capacity materials (e.g., asphalt, concrete).
Land surface state (vegetation and water bodies)	Reduced evapotranspiration and shading due to vegetation loss and sealed surfaces.
Urban geometry	Trapping of longwave radiation and restricted airflow in dense building layouts like narrow street canyons.
Anthropogenic heat emissions	Release of waste heat from buildings, vehicles, and industrial activities.

The consequences of UHI extend far beyond thermal discomfort. Higher ambient temperatures increase building energy need by raising cooling loads. A meta-analysis of global case studies found that UHI can increase cooling energy consumption by a median of 19% and reduce heating energy by 18.7% [15]. Empirical data from Asian cities indicate that a 0.5 K urban–rural difference raises monthly cooling energy by 0.17–1.84 $kWh{\cdot}m^2$ and cuts heating by 0.06–1.19 $kWh{\cdot}m^2$. An electricity penalty of about 0.7 $kWh{\cdot}m^2$, or 21 W per person, can be imposed annually for every additional degree of UHI [16]. Another study in India similarly shows an increase of 2 to 4 percent in electricity consumption for every 1°C of outside temperature rise [17]. Besides, considering the combination of UHI and heat waves is necessary as it can disrupt transport, power networks, and other critical infrastructure, compounding the vulnerability of low-income communities and the elderly [18]. In this regard, addressing UHI is crucial and requires integrating mitigation and adaptation strategies into urban planning to enhance resilience.

2 Modelling Urban Heat Islands: Classifications and Representative Models

Determining the intensity and dynamics of the UHI is critical, as it directly affects human thermal comfort, public health, energy demand, and adaptation strategies [19–21]. While field measurements provide essential evidence, observational data are often scarce, discontinuous, or geographically limited, which makes modelling an indispensable complement for assessing current conditions and exploring future scenarios [22]. To structure UHI modelling, the WMO [1] distinguishes three broad families of urban climate models: (i) statistical/empirical approaches, (ii) obstacle-resolving models, and (iii) numerical weather prediction (NWP) models with urban-canopy schemes. Starting from the WMO classification, this section examines how these categories are used in literature. It reviews representative models and tools within each family and summarizes their underlying principles, required inputs, strengths, and limitations.

2.1 Statistical/Empirical Approaches

Statistical (or empirical) UHI models rely on observational data to establish relationships between urban–rural temperature differences and meteorological as well as morphological variables. They are characterized by low computational cost and are particularly useful for analysing large numbers of cities or exploring multiple scenarios. However, they are strongly dependent on the availability, representativeness, and quality of long-term urban and rural datasets. The following paragraphs present the tools developed within the statistical and empirical framework, outlining their underlying principles, required inputs, and main areas of application.

The first tool developed within the statistical/empirical modelling framework is the Urban Weather Generator (UWG) [23]. It transforms a rural weather file into a weather file that reflects local UHI effects. UWG links the energy balance of the urban canopy with that of the boundary layer, incorporating simplified representations of radiation exchange, anthropogenic heat release, and advective processes. It reads a standard EnergyPlus Weather File and an XML file describing the urban district, then iteratively solves hourly energy balances to calculate urban air temperature and humidity [24]. Since UWG is a downscaling tool, it cannot reproduce site-specific microscale effects (such as shading from individual buildings or trees, or temperature variations between adjacent streets), yet other studies show that it is fast enough to be integrated into building simulations and is reliable and efficient for representing UHI effects. A study in Boston demonstrated the practical advantage of UWG for building performance studies, showing that UWG-derived weather files narrowed the gap between rural and urban building energy predictions [25].

Another statistical/empirical tool is the Surface Urban Energy and Water Balance Scheme (SUEWS), a process-based model that simulates the coupled energy and water exchanges of urban surfaces. SUEWS is designed to operate at the neighbourhood or local scale (hundreds of meters to a few kilometres) with a time step of 5 minutes to 1 hour, allowing simulations from short-term events to multi-year periods. It is computationally efficient and requires commonly measured meteorological variables such as air temperature, humidity, wind speed, radiation, and precipitation, together with surface cover fractions representing paved areas, buildings, vegetation, bare soil, and water. For each surface type, it estimates evaporation, interception, and runoff by solving a single-layer soil-moisture balance and linking water and energy fluxes to compute sensible and latent heat. Evaluations in different climates, including Vancouver, Los Angeles, and UK cities, have shown that SUEWS reproduces the observed diurnal and seasonal patterns of urban radiation and heat fluxes, with acceptable root-mean-square errors (25–47 $\mathrm{W{\cdot}m^2}$) [25, 26]. These evaluations indicate that SUEWS is well-suited to model UHI, as it captures the key energy and water exchanges that drive variations in local urban climates. In practice, SUEWS has also been applied in planning contexts, such as the Brighton & Hove Climate Risk & Vulnerability Assessment & Adaptation Action Plan, where it was used to derive spatial patterns of near-surface air temperature and UHI intensity to inform adaptation strategies [27, 28].

A third statistical/empirical approach relies on empirical frameworks and regression models to estimate UHI intensity from land cover, building geometry, and socio-economic factors. One of the most widely used frameworks is the LCZ classification, which provides a standardized, physically based description of urban and rural landscapes. The LCZ system, proposed by Stewart and Oke [29], distinguishes 17 classes defined by parameters such as building height, street width, surface cover, and thermal properties. These classes can be used to derive statistical relationships between UHI intensity and urban form, with regression models based on LCZ fractions explaining much of the spatial variability of UHI. This makes LCZ-based methods valuable for urban planning and climate services. The classification has been standardized within the World Urban Database and Access Portal Tools initiative, which provides a globally consistent and culturally neutral database of urban form and function [30]. However, LCZ is constrained by its fixed class definitions: While this ensures comparability across cities, it simplifies complex urban realities and limits flexibility for future change.

2.2 Obstacle-Resolving Models

Obstacle resolving models—also named microscale models—explicitly represent buildings, trees, and other obstacles in three dimensions and solve radiative transfer, convective heat exchange, and, in some cases, airflow. They provide detailed micro climate information, but at a high computational cost. These models are particularly useful for evaluating pedestrian comfort and the local impacts of mitigation strategies. The limitation of these models is extensive input data and short simulation periods. The following paragraphs present representative tools within this family, including ENVI-met, SOLWEIG (Solar and Longwave Environmental Irradiance Geometry), RayMan, and PALM-4U [30–34], as well as general-purpose computational fluid dynamics (CFD) solvers, outlining their principles, applications, and main constraints. A comparative summary of the main tools included in this category is presented in Table 3.

ENVI-met is a microscale CFD model that resolves buildings, vegetation, and ground surfaces on a 3D grid (typical resolution between 0.5 to 5 m). It uses the Reynolds-averaged Navier–Stokes equations coupled with energy and mass conservation to simulate wind fields, air temperature, humidity, and pollutant dispersion. WMO classifies ENVI-met as one of the most widely used obstacle-resolving tools. Considering that ENVI-met is computationally demanding, it is often applied to neighbourhoods or single street canyons. The model was first introduced by Bruse and Fleer [35] who demonstrated how a finite-difference grid can represent exchanges of momentum, heat, and moisture between building surfaces, vegetation, and the atmosphere. More recently, Eingrüber et al. [36] evaluated ENVI-met over a 16-ha urban area in Cologne to analyse how sensitive the model is to wind direction.

They tested sensitivity to wind direction forcing and showed that the reference run (with measured wind direction) reproduced observed air temperatures accurately (Nash–Sutcliffe Efficiency = 0.91), while scenarios with constant wind directions produced larger errors (Nash–Sutcliffe Efficiency = 0.15–0.62). Local air-temperature deviations reached up to 4 K, underscoring the importance of accurate boundary conditions when applying ENVI-met to urban climate studies.

SOLWEIG is a radiation model embedded in the Urban Multi-scale Environmental Predictor toolbox. It estimates spatial variations of mean radiant temperature by calculating shortwave and longwave radiation fluxes from six directions (up, down, north, east, south, west). Inputs that are required include direct, diffuse, and global shortwave radiation, air temperature, relative humidity, geographical coordinates, and high-resolution urban geometry. Vegetation and ground-cover data can also be added to consider shadowing and radiative exchange. The model has been validated in different urban contexts. For instance, in Göteborg, Sweden, SOLWEIG reproduced observed mean radiant temperature with high accuracy ($R^2 \approx 0.94$, RMSE $\approx$ 4.8 K) [37]. A subsequent update of the tool (SOLWEIG 2.0) improved algorithms for vegetation shadow casting, sky-view factors, and longwave flux estimation, reducing errors in simulated mean radiant temperature [38]. These enhancements make SOLWEIG particularly useful for mapping outdoor thermal comfort and assessing the effects of vegetation and urban design on human heat exposure. In comparison with ENVI-met, which resolves airflow and turbulence using CFD, SOLWEIG focuses on radiative exchange and shading, making it computationally lighter and better suited for large-scale assessments of thermal comfort.

Table 3. Comparison between tools included in the obstacle-resolving models' category

Tool	**Fundamentals**	**Application Scale**	**Spatial Resolution and Time Step**	**Main Advantages**	**Main Disadvantages**
ENVI-met	Microscale computational fluid dynamics (CFD) model, coupling vegetation, soil, buildings in mass and heat transfer models.	From microscale (e.g., street) to local scale (e.g., neighbourhood)	From 1 m to 10 m spatial resolution. Typical time frame of 24–48 h, time step from 1 second to 1 hour.	Good level of detail. Many physical phenomena considered (heat transfer, evapotranspiration, etc.).	Computationally intensive. Less suited for very large areas.
SOLWEIG	Model estimating spatial distribution of longwave and shortwave radiation, considering shadowing and radiative exchange.	From microscale to local scale	Spatial resolution of 10 m or lower. Hourly (or subhourly) time steps.	Computationally light. Capability of assessing complex urban geometries. Manageable input data.	Limited in modelling dynamic phenomena (e.g., fluid dynamics).
RayMan	Stationary and point-based model suitable for thermal comfort assessment in urban settings.	Microscale	Small point-based areas (spots). Hourly time steps.	Computationally light. Simple to be run, with low input data required.	Limited in modelling dynamic phenomena. Limited spatial capability.
PALM-4U	High-resolution urban climate model coupled with biometeorology (e.g., assessing heat stress for humans) for advanced urban climate research.	From microscale to mesoscale (e.g., region)	From 1 m to 10 m spatial resolution. Time frame from hours to days.	Very detailed and accurate. Good to be coupled with mesoscale models.	Computationally intensive, with high performance computing requirement. High demand of input data.

The next obstacle resolving model is RayMan, which calculates short- and long-wave radiation fluxes, including the influence of clouds. It can handle complex urban structures and provides outputs such as mean radiant temperature—since it is a key input for human energy-balance models—and shaded areas. RayMan is designed for micro- to regional-scale applications and has been widely used in applied climatology and tourism climatology. Validation studies, for example, in Freiburg, Germany, demonstrated that simulated mean radiant temperature values align well with field measurements. In addition, the model is designed to have a user-friendly and accessible interface for users like architects and urban planners [38–40].

Turning to the limitations of the model, RayMan is a stationary, point-based model and does not explicitly simulate airflow or three-dimensional radiation fields, which limits it to resolve microclimatic variations in detail. Compared to the other obstacle-resolving models, RayMan is best suited for quick, location-specific assessments of outdoor thermal comfort.

PALM-4U is an open-source urban climate model that applies large-eddy simulation, which resolves dominant turbulent eddies while parameterizing smaller ones, to represent the transport of heat, momentum, and moisture in urban environments. It has been developed to support municipal employees, architects, and urban climatologists in testing adaptation measures and identifying heat-stress hot spots before implementation [41]. The PALM model system version 6.0 [42] features a modular architecture that couples the atmospheric large-eddy simulation core with urban surface, building, vegetation, and radiation schemes. It implements improved numerical algorithms and has been validated against observations for urban turbulence, energy balance components, and thermal comfort indices [42]. Dedicated user interfaces and simplified workflows allow PALM-4U to be operated by non-experts in planning contexts, making it a practical tool for scenario comparison and stakeholder communication. However, PALM-4U remains computationally demanding, and high-resolution large-eddy simulation runs require significant computing resources, which may limit its use in routine planning.

In addition, general-purpose CFD solvers such as OpenFOAM and ANSYS Fluent are also widely used to study street-canyon and neighbourhood microclimates. These tools solve the three-dimensional Navier–Stokes and energy equations with user-defined boundary conditions, and they can incorporate turbulence and radiation schemes. Built-in flexibility allows researchers to simulate coupled heat and moisture exchanges, airflows, and pollutant dispersion under different urban geometries [43]. Their main strength lies in flexibility and accuracy, but they require expert knowledge in fluid dynamics and numerical methods, and their high computational demand makes them less practical for large-scale or long-term simulations.

2.3 Numerical Weather Prediction Models with Urban Canopy Schemes

The third family of UHI models is represented by NWP models equipped with urban-canopy schemes, which were originally developed for weather forecasting and climate studies. Regional and global NWP models are increasingly equipped with urban canopy schemes that represent the bulk effects of buildings and streets on surface energy and momentum exchange. These models can simulate city-scale UHIs and provide meteorological boundary conditions for building energy models. Their main advantage is capturing the interactions between cities and regional climate, making them particularly useful for forecasting, long-term simulations, and climate change projections. The following paragraphs highlight some widely used NWP systems.

The Weather Research and Forecasting model is one of the most widely used mesoscale weather models for UHI analysis. Its single-layer urban canopy model represents a street canyon with roofs, walls, and roads; surface energy fluxes are calculated separately for these facets, including effects of shading and radiation trapping. More advanced schemes include the Building Effect Parameterisation (BEP), which introduces multiple vertical layers and thermal inertia for walls and roofs, and BEP coupled with a Building Energy Model (BEP + BEM), which simulates indoor–outdoor exchanges, air-conditioning need, and associated waste heat. An evaluation of Weather Research and Forecasting Model coupled with an Urban Canopy Model. for Delhi compared different land-use datasets and showed that including updated land-use data together with the urban canopy model reduced near-surface temperature errors (RMSE decreased from 6.3°C to 3.9°C) and improved the index of agreement for mean UHI from 0.4 to 0.7. The study also found that the urban canopy increased the heat index by about 2.0–2.5°C at densely built-up stations [44]. The unified WRF/urban modelling system, described by Chen et al. [45], integrates single-layer urban canopy model, BEP, and BEP + BEM with the Noah land-surface model. It also incorporates anthropogenic heat and radiative trapping parameterisations, forming a comprehensive framework to capture interactions between urban surfaces, building energy use, and the atmosphere. Turning to its limitations, Weather Research and Forecasting Model coupled with an Urban Canopy Model remains limited by its mesoscale resolution, which cannot reproduce street-level variations, and by the simplifying assumptions in its canopy schemes. It is also computationally demanding and highly dependent on accurate land-use and building datasets.

The next model is Town Energy Balance (TEB), a physically based single-layer urban-canopy model designed to simulate the exchanges of energy and water between cities and the atmosphere. It generalizes the street-canyon concept by representing roofs, walls, and roads separately, with multi-layer heat conduction through these surfaces. TEB accounts for radiative trapping and shading, interception and evaporation of rainfall, snow accumulation on roofs and roads, and turbulent exchanges in the UCL [46]. To reduce computational demand, TEB treats the city as a long street with identical buildings and averages over building orientations. To represent building energy demand and anthropogenic heat fluxes, Bueno et al. [24] integrated a simplified Building Energy Model (BEM) into TEB. This version (BEM-TEB) represents buildings as single thermal zones with thermal mass, solar gains, conduction, infiltration, ventilation, internal loads, and air-conditioning systems, while also allowing passive strategies such as shading and natural ventilation. Evaluation showed that BEM-TEB reproduces city-scale building energy consumption while retaining computational efficiency. Later developments included TEB-Veg, which incorporates the cooling and hydrological benefits of vegetation. By explicitly representing interception and evapotranspiration from green roofs, lawns, and street trees, TEB-Veg can simulate how irrigation or stormwater capture influences latent heat fluxes and canopy temperature [47]. However, TEB remains limited by its canyon-based geometry and averaging assumptions, which limit its ability to capture microscale variability across heterogeneous urban morphologies. Although extensions such as BEM and TEB-Veg expand their scope, the model requires careful parameterisation of building and vegetation characteristics.

Consortium for Small-scale Modelling–Climate Limited-area Model (COSMO-CLM) is a non-hydrostatic regional climate and weather model widely used in Europe. For urban applications, it incorporates the TERRA-URB scheme, a bulk urban-canopy parameterisation derived from the semi-empirical urban canopy parametrization approach [48], which represents the average effects of buildings and impervious surfaces on radiation, heat, and momentum exchanges. TERRA-URB modifies the land-surface input data to represent buildings, streets, and impervious surfaces, translating detailed canopy characteristics into aggregated bulk parameters while maintaining low computational cost. In its implementation within COSMO-CLM, TERRA-URB updates radiative albedo and emissivity, turbulent drag, ground heat capacity, and evaporation schemes. Precipitation over impervious surfaces is treated as direct runoff, and a constant anthropogenic heat flux is added to represent human activity. A very high-resolution downscaling experiment over Italy demonstrated the model's ability to include urban effects at 2.2 km grid spacing, using a tiling approach that distinguishes between urban canopy and natural land cover and adjusts soil and water fluxes for each grid cell. Because of its computational efficiency, COSMO-CLM with TERRA-URB is particularly suited for multi-decadal regional climate projections that account for urbanisation. However, the bulk formulation means that it cannot resolve detailed street-canyon processes or building-scale variability. Its anthropogenic heat parameterisation is highly simplified, and results strongly depend on the quality of land-use and urban morphology datasets [48].

3 Standards and Policy Frameworks

3.1 Technical Standards

Although the topic has been widely studied, no specific technical standards currently exist for UHI modelling. As outlined in the previous section, a range of established methods, data sources, and widely used tools are available for measuring, modelling, and monitoring UHI intensity. Among these, the WMO Guidance [1] stands out as the most comprehensive and authoritative reference.

At the international level, both ISO/TC 268 "Sustainable cities and communities" [49] and CEN/TC 465 "Sustainable Cities and Communities" [50] address the development of requirements, frameworks, guidance, and supporting tools to assist cities and community decision-making and to promote their sustainable development. Within this context, it is worth noting that a new standard on terminology and classification of nature-based solutions is currently under development.

Also relevant is CEN/WS 107 "Mitigation of UHI effects with cool materials" [51], which focuses on supporting the uptake of cool materials by cities to reduce UHI effects. The recently published CWA 17890:2022 [52] provides terminology relating to cool materials, together with a guide to implementing cool surfaces in building envelopes as a means to mitigate urban overheating.

3.2 European Legislation

The EU addresses UHI through broader climate and environmental policies, aiming at achieving climate neutrality by 2025 and requiring a 55% reduction in net energy greenhouse gas emissions by 2030.

Among the different actions, it is worth mentioning the EU Adaptation strategy [53], which aims to help citizens, cities, businesses, and countries adapt to the unavoidable impacts of climate change and become climate-resilient, and the Covenant of Mayor's Cities Refresh campaign [54], which invites local governments to rethink urban spaces in response to rising temperatures and frequent heatwaves.

Cities in the EU are encouraged to use UHI data to develop strategies for climate change adaptation and urban resilience. This involves incorporating UHI modelling into urban planning and development processes to identify hot spots and implement mitigation measures. The data from UHI modelling inform the promotion of green infrastructure (e.g., parks and cool surfaces) and "cool roofs" (light-coloured, reflective roofs) to reduce urban temperatures and the need for air conditioning.

3.3 National Implementation

By taking Italy as an example, the Integrated National Energy and Climate Plan [55] sets out a series of actions for urban settlements, classified into non-structural (soft) actions, ecosystem-based (green) actions, and infrastructural (grey) actions. Among the long-term actions to be implemented in urban settlements are the expansion of urban green areas, the promotion of urban gardens, the development of infrastructural works for the protection against hydraulic and geomorphological risks, and the replacement of asphalted areas with permeable materials.

The adoption of specific technologies is also promoted by the Minimum Requirements Decree [56], which mandates a cost–benefit analysis of the use of high solar reflectance materials for roofs (cool roofs) and of passive cooling technologies, such as ventilative cooling and green roofs.

In Italy, for certain categories of infrastructure projects, a so-called "climate check" is mandatory. This assessment aims to ensure the resilience of the infrastructure to the impacts of climate change and its alignment with emission reduction and climate neutrality objectives. The process involves evaluating the vulnerabilities of the infrastructure, identifying climate-related risks (both physical and transition-related), and integrating mitigation and adaptation measures from the earliest stages of design.

A study coordinated by the Italian National Research Council–Institute of BioEconomy, aimed at supporting the planning of temperature mitigation measures at the national level, quantified the UHI phenomenon across the regional capitals of Italy [57].

3.4 Local Initiatives

Many local administrations (regions, cities) conduct their own UHI assessments and integrate them into their local climate action plans and urban development guidelines.

In Italy, only a few regions have so far adopted a formal climate change strategy. A larger number of regions explicitly consider (UHIs) in their policies or regulations. It is worth mentioning, for example, the UHI vulnerability maps produced by some regional environmental protection agencies.

In the Piedmont region, local climate zoning of the urban area was carried out within the framework of the Mapping and Monitoring of UHIs in Piedmont project [58], co-funded by the Italian Space Agency.

4 Conclusions

UHIs represent a key challenge for building energy performance, public health, and urban resilience. This paper has reviewed the fundamental drivers of the phenomenon—ranging from material properties and urban geometry to vegetation cover and anthropogenic heat—and has discussed their cumulative impacts on microclimate and energy demand. It has also examined the main families of modelling approaches, from empirical and statistical tools to obstacle-resolving and mesoscale models, highlighting their complementary roles in understanding urban thermal dynamics across scales. Moreover, it has outlined current efforts toward standardisation and policy integration, including recent WMO guidance, emerging European and national frameworks, and the increasing use of UHI modelling to inform local adaptation plans.

Taken together, these strands of research and practice underscore the importance of bridging scientific modelling and policy action. Reliable urban climate modelling provides the quantitative basis needed for effective standards, design guidelines, and mitigation strategies—ranging from cool materials and nature-based solutions to integrated urban planning. Future work should focus on harmonising methodologies, improving data accessibility and interoperability, and coupling building-energy and urban-climate models to capture feedback between indoor and outdoor environments, including open-data initiatives, digital-twin applications, and the integration of Urban BEMs with urban digital platforms. Advancing this integration is essential to support evidence-based decisions and to guide the transition toward more sustainable, resilient, and carbon-neutral cities.

Author Contributions

Conceptualization, V.C. and I.B.; methodology, V.C., I.B., and M.P.T.; investigation, V.C. and M.P.T.; writing—original draft preparation, V.C. and M.P.T.; writing—review and editing, V.C., I.B., and M.P.T.; supervision, V.C. All authors have read and agreed to the published version of the manuscript.

Data Availability

The data used to support the research findings are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflict of interest.

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Nomenclature

BEM	Building Energy Model
BEP	Building Effect Parameterisation
CFD	Computational Fluid Dynamics
COSMO-CLM	Consortium for Small-scale Modelling–Climate Limited-area Model
LCZ	Local Climate Zone
NWP	Numerical Weather Prediction
SLUM	Single layer Urban Canopy Model
SOLWEIG	Solar and Longwave Environmental Irradiance Geometry model
SUEWS	Surface Urban Energy and Water Balance Scheme
SURY	Semi-Empirical Urban Canopy Parametrization
TEB	Town Energy Balance
UCL	Urban Canopy Layer
UHI	Urban Heat Island
UWG	Urban Weather Generator
WMO	World Meteorological Organization