Guidance on Measuring, Modelling and Monitoring the Canopy Layer Urban Heat Island (CL-UHI)

2023 edition

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EDITORIAL NOTE

METEOTERM, the WMO terminology database, may be consulted at https://public.wmo.int/en/meteoterm.

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Chair, Publications Board
World Meteorological Organization (WMO)
7 bis, avenue de la Paix
P.O. Box 2300
CH-1211 Geneva 2, Switzerland

Tel.: +41 (0) 22 730 84 03
Email: publications@wmo.int

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PREFACE

Urban areas modify the surface energy exchanges in comparison with non-urban areas and generally exhibit higher night-time air temperatures and similar or lower daytime air temperatures compared with the surrounding rural areas, a phenomenon called the urban heat island (UHI) effect. The UHI in the lower part of the atmospheric canopy layer, the canopy layer UHI (CL-UHI), is directly experienced by humans. The heat burden in cities induced by the UHI is an additional signal on top of the climate warming that cities experience. Urbanization continues in almost all WMO Members, thus the additional urban-induced warming from the CL-UHI will increase, becoming an additional burden for the population in cities.

Despite the importance of the CL-UHI, WMO has not issued guidance on assessing the CL-UHI. At its eighteenth session, the World Meteorological Congress emphasized the importance of this issue and approved Resolution 32 (Cg-18) – Advancing Integrated Urban Services and Resolution 61 (Cg-18) – Integrated and Coordinated WMO Research to Serve Society. These request WMO technical commissions, the Research Board and other relevant bodies to develop science-based technical guidance on the measuring, modelling and monitoring of the CL-UHI effect to support Members' service delivery needs and planning efforts to mitigate the impacts of CL-UHI to support the advancement and development of integrated urban hydrometeorological, climate and environmental services, also referred to as an integrated urban service (IUS). Resolution 61 (CG-18) calls for the long-term expertise of the WMO GAW (Global Atmosphere Watch) Urban Research Meteorology and Environment (GURME) project as well as the World Weather Research Programme (WWRP) to be used in this effort. The Congress also urged:

> Members to improve connections among [National Meteorological and Hydrological Services], research institutions, academia, stakeholders and end-users of services on a national level to ensure that research responds to requirements for the development of new and improved services, and that advances in research are appropriately included in operations;

This connection between research and operations is an example of the "value chain approach" promoted by WMO.

Developed in response to the request from the World Meteorological Congress, the present guidance provides an overview of and recommendations for measuring, modelling and monitoring the CL-UHI, which is based on temperature information at about 1.5 m above ground. Other UHIs, such as the boundary layer, surface or subsurface types, have no direct influences on human health and are therefore only briefly addressed here. CL-UHI information is one component of an IUS. These services may be provided directly by National Meteorological and Hydrological Service (NMHS) operations, in cooperation with stakeholders or partners, or indirectly through stakeholders or partners in cities or public and private agencies. Concepts for these services are explained in *Guidance on Integrated Urban Hydrometeorological, Climate and Environmental Services* (WMO-No. 1234), Volume I: Concept and Methodology, and Grimmond et al. (2020). Detailed examples of integrated services in several demonstration cities are found in *Guidance on Integrated Urban Hydrometeorological, Climate and Environment Services* (WMO-No. 1234), Volume II: Demonstration Cities, and in Baklanov et al. (2020).

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Coordinating lead authors: K. Heinke Schlünzen (Universität Hamburg, Germany), Sue Grimmond (University of Reading, United Kingdom of Great Britain and Northern Ireland), Alexander Baklanov (WMO).

Lead authors: Alberto Martilli (CIEMAT, Spain), Valéry Masson (Météo France), Shiguang Miao (IUM CMA, China), Chao Ren (The University of Hong Kong), Matthias Roth (National University of Singapore), Iain D. Stewart (Global Cities Institute, Canada).

Contributing authors: Felix Ament (Universität Hamburg, Germany), Lee Chapman (University of Birmingham, United Kingdom), Lesley Choo (NEA Singapore), Andreas Christen (University of Freiburg, Germany), Anurag Dipankar (NEA Singapore), Evyatar Erell (Ben-Gurion University of the Negev, Israel), Clare Heaviside (University College London, United Kingdom), Jorge Gonzalez (City College of New York, United States of America), Guido Halbig (DWD, Germany), Peter Hoffmann (GERICS, Germany), Meinolf Kossmann (DWD, Germany), Scott Krayenhoff (University of Guelph, Canada), Stephen Po-wing Lau (Hong Kong Observatory), Humphrey Lean (UK Met Office, United Kingdom), Glenn McGregor (Durham University, United Kingdom), Gerald Mills (University College Dublin, Ireland), Negin Nazarian (University of New South Wales, Australia), Paulo Saldiva (University of São Paulo, Brazil), Vivek Shandas (Portland State University, United States), Stefan Smith (University of Reading, United Kingdom), Jianguo Tan (Shanghai Institute of Meteorological Science, CAMS, China), Oksana Tarasova (WMO), James Voogt (University of Western Ontario, Canada).

REVIEWERS

Benjamin Bechtel (Ruhr-University Bochum, Germany), Edmilson Dias de Freitas (University of São Paulo, Brazil), Paul Joe (ECCC, Canada), Hunter Jones (NOAA, United States), Feng Liang (Beijing Meteorological Service, China), Juerg Luterbacher (WMO), Yves-Alain Roulet (Meteo Swiss, Switzerland), Marcus Thatcher (CSIRO, Australia), Alberto Troccoli (World Energy & Meteorology Council (WEMC), United Kingdom), Helen Ward (University of Innsbruck, Austria).

EXECUTIVE SUMMARY

The urban heat island (UHI) is one of the earliest documented effects on air temperature observed in urban areas. It results from differences in the surface energy balance between urban and rural areas, caused by the interaction of urban surfaces with atmospheric processes. The focus of this guidance is the canopy layer UHI (CL-UHI). The CL-UHI is concerned with near-surface air temperatures differences (~1.5 m above ground) between urban and rural areas. With more than half of the world's population living in cities, these temperature effects are directly experienced by many humans and can be linked to changes in human comfort, public health and human activities. Exposure to high temperatures can increase morbidity and mortality, especially during heat waves and at night, when urban CL air temperature can be elevated compared with the rural surroundings. Other types of UHIs, such as the boundary layer, surface or subsurface types, have less direct influences on human health and are therefore only briefly addressed in the present guidance.

The scientific background needed to understand the processes creating and influencing the CL-UHI is presented in the present guidance, with examples of different agencies and services that need information about the CL-UHI. Critical to this is understanding the role of scale and the link to urban form. Guidance is provided on the parameters required to characterize urban areas at microscale and local scale, and the ways in which they influence the CL-UHI are discussed.

The guidance reviews the "ideal" weather conditions (calm, clear days and nights) for development of large CL-UHI intensities, and the influences of meteorological factors, topography and urban features. It introduces different approaches to measure the CL-UHI using sensors placed in different locations, for example a pair of sites, traverses, meteorological networks and opportunistic sensing, with discussion of site and sensor selection criteria. Similarly, modelling approaches, including statistical, obstacle-resolving and numerical weather prediction models, are compared, along with their advantages and limitations for determining CL-UHI values. Measurements can support CL-UHI assessments and enable robust evaluations of model outputs. Models performing satisfactorily for their intended applications can be used for simulating CL-UHIs for current and future scenarios such as city development and climate change. Monitoring the CL-UHI requires both observations and modelling. Key to monitoring are long-term maintenance and documentation of changes, for example, of site and instruments (that is, metadata). Mitigation and adaptation efforts to reduce the effects of CL-UHIs are discussed, such as efforts to reduce heat stress, air pollutant concentrations and energy use.

The guidance is written for WMO Members, National Meteorological and Hydrological Services (NMHSs) and their many potential partner agencies and stakeholders undertaking activities in cities that are impacted by weather and climate across a wide range of time and space scales. Information on CL-UHIs is one part of an IUS and may be part of multi-hazard early warning systems and high-resolution weather prediction systems for urban areas.

CHAPTER 1. INTRODUCTION

The present guidance focuses on urban-induced heat effects. The guidance uses the term "**urban**" for populated areas that are built-up, with increased density of built structures such as houses, commercial buildings, roads, industrial facilities and other urban forms. Towns, cities or suburbs are all referred to as urban areas. Non-urban areas outside the urban area are called "**rural**" in the present guidance.

Urban areas have modified surface energy balances and frequently exhibit higher night-time air temperatures and lower daytime near-surface air temperatures compared with the surrounding rural area, a phenomenon called the urban heat island (UHI) effect. An UHI with negative intensities – thus exhibiting urban air temperatures below the rural ones – can be referred to as an "urban cool island". In the present guidance, the term urban heat island is used to discuss the phenomenon whether the air temperatures are elevated or reduced.

The UHI in the lower part of the atmospheric canopy layer, the canopy layer UHI (CL-UHI), is directly experienced by humans. In some situations, the CL-UHI effect poses a threat to public health: more than half of the world's population now lives in cities, and exposure to high temperatures can increase morbidity and mortality, especially during heat waves. With temperature values elevated at night, the CL-UHI directly influences human well-being. Therefore, one major reason to assess the CL-UHI effect is to improve forecasts provided by an IUS (*Guidance on Integrated Urban Hydrometeorological, Climate and Environmental Services* (WMO-No. 1234), Volume I: Concept and Methodology and *Guidance on Integrated Urban Hydrometeorological, Climate and Environment Services* (WMO-No. 1234), Volume II: Demonstration Cities). In contrast to the CL-UHI, the surface UHI (S-UHI) is based on surface temperature values. It has its maximum during daytime, when humans can better deal with heat through behavioural changes than at night when trying to sleep; the focus of the present guidance is thus on the CL-UHI.

The CL-UHI is a type of urban-induced warming first recognized more than 200 years ago by Howard (1818). It is one of the most evident direct atmospheric signatures of humans' alteration of the Earth's surface. The characteristics of CL-UHIs differ between cities, within cities, with rural surrounding type and with time. In addition to their influence on short-term weather, health and human comfort, CL-UHIs have major implications for energy demand and urban climate adaptation policies. Urbanization continues in almost all WMO Members, and the heat burden in cities induced by the CL-UHI is an additional signal that cities experience especially at night – in addition to warming caused by climate change. Urban planning measures can help to reduce CL-UHI intensities, where beneficial.

This guidance provides general information on the CL-UHI (Sections 2.1–2.5) and on other types of UHIs (Section 2.6) as well as CL-UHI effects on the surroundings (Section 2.7). The Section 2.8 summary provides a general orientation that can be quickly read. Selected applications are provided in Chapter 3, including their integration in multi-hazard early warning systems (Section 3.5). Chapter 4 explains in detail how urban areas need to be characterized to determine the CL-UHI, with the main aspects briefly summarized in Section 4.6. Observational approaches (Chapter 5), use of models (Chapter 6) and monitoring (Chapter 7) are introduced in detail with their respective challenges summarized in the last section of each chapter. Chapter 8 discusses mitigation measures typically used and their influence on the CL-UHI, as well as challenges (summarized in Section 8.6). In Appendix 1 an example application is provided to highlight how the CL-UHI is influenced by the rural surroundings. Typical misunderstandings of the CL-UHI are clarified in this example application. Examples of observation set-ups (Appendix 2) and monitoring (Appendix 3) are provided. The publications cited in the main text (References) are supplemented with a Bibliography for further reading organized by the different aspects addressed in this guidance.

Table 1.1 summarizes the structure of the present publication with respect to processes, applications needing CL-UHI information, methods for CL-UHI determination and mitigation of the CL-UHI.

Table 1.1. Main elements of this document

Overview of processes relevant to CL-UHI	**Chapter 2:** – Urban scales – Definition of CL-UHI – Metrics for CL-UHI – Processes related to the genesis and development of CL-UHI – Other types of UHI **Appendix 1:** Application example illustrating information of Chapter 2
Applications needing CL-UHI	**Chapter 3:** Where CL-UHI information is needed **Appendix 1:** Application example illustrating influences on CL-UHI
Methods to determine CL-UHI	**Chapter 4:** Characterization of the urban area and its surroundings **Chapter 5:** Observations **Chapter 6:** Modelling **Chapter 7:** Monitoring **Appendix 2:** Observational networks **Appendix 3:** Examples of monitoring CL-UHI
Mitigation of CL-UHI	**Chapter 8:** How to mitigate CL-UHI effects

CHAPTER 2. GENERAL INFORMATION ON THE CL-UHI

2.1 HISTORICAL BACKGROUND

Some of the earliest documented urban effects on air temperature were published by Luke Howard. From 1806 to 1830, Howard analysed data from a small network of thermometers across London (United Kingdom) and its surroundings, and surmised that London's climate was warmer than the surrounding rural areas. He suggested that this warmth was caused by radiation trapping and airflow interference by building walls, heat release from domestic and industrial combustion processes, and lack of evaporation from built surfaces. Howard's account of the anomaly is remarkably accurate considering the few instruments that were available at that time. Studies in other cities soon followed Howard's ground-breaking work, each with a similar outcome. In 1897 this inspired Julius Hann, the pioneer of modern meteorology, to formally label the recurring warmth in large cities the "city temperature" effect. Several decades later, the thermal anomaly became known as the "urban heat island" effect, owing to the innovative work of Austrian and German researchers using motorcars to carry thermometers through city streets and record air temperatures in hundreds of locations. Their approach uncovered thermal spatial patterns in cities that resembled "islands" of heat when plotted on a map. The patterns were clearly relatable to the built form of the urban area and were relevant to local concerns about air pollution, weather forecasting, settlement design and human health. The combined use of motorcar surveys and climate observatories eventually enabled researchers to study the spatial and temporal characteristics of heat islands in individual cities.

Scientific understanding of the CL-UHI has advanced based on this foundation. The controls, spatial and temporal patterns, as well as the meteorological and societal implications of heat islands are now well understood (Oke et al., 2017). Assessments and predictions of CL-UHI effects can now be made with reasonable accuracy in most cities.

2.2 HORIZONTAL SCALES AND VERTICAL LAYERS IN URBAN AREAS

In the present guidance, horizontal scales are defined as a function of the horizontal extent of urban form (Table 2.1, column 1). This follows the nomenclature used in several urban climate publications. For those more familiar with Orlanski's (1975) definition of horizontal scales for atmospheric phenomena, we also 'translate' the two scales (Table 2.1): with column 2 listing urban forms and column 6 containing the corresponding horizontal length of atmospheric phenomena. Urban forms create atmospheric phenomena that may have the horizontal length of the urban form or its facets, such as a roof vortex, or larger such as a wake downwind of a building. Thus, the resulting atmospheric phenomena are multi-scale. The present guidance uses horizontal scales derived from urban form. When it deviates from this and uses the Orlanski (1975) scales, this is explicitly mentioned in the text.

The focus of this publication is the UHI in the lower part of the **urban canopy layer** (UCL), defined as the air volume between buildings and trees (Figure 2.1a, b). The vertical extent of the UCL is from the ground to the top of the buildings and trees. The horizontal extent is across the urban area (10–100 km, Figure 2.1). Critically, this is the region where people are exposed to the environment, including the effects of the CL-UHI, both indoors and outdoors.

The urban form has facets consisting of walls, roofs and ground (Table 2.1). Within the UCL, **microscale** heating and cooling processes at timescales of seconds to days dominate. In compact neighbourhoods with closely spaced buildings and small amounts of vegetation, the surfaces are predominately impervious with bluff bodies having sharp edges. The facet's arrangement results in complex radiative interactions. These include shadowing, multiple reflections, horizon screening by building walls and thereby lowered sky view factors, as well as

Table 2.1. Characteristic scales for urban form based on surface characteristics

Scale	*Urban form*	*Horizontal length (HL)*	*Vertical extent*	*Related parameters*	*Atmospheric phenomena HL scale*
Micro	Facet (roof, wall, road)	1–10 m	UCL	Materials	Microscale γ
	Building	10+ m	UCL	H	Microscale γ
	Street, canyon	30–200 m	UCL	H, W	Microscale β
Local	Block (bounded by canyons, interior courtyards)	300–500 m	RSL	λp, H_{max}, σ_H	Microscale α
	Neighbourhood	1–2 km	RSL, ISL	λp, H_{max}, σ_H	Microscale α
Meso	Urban area (city centre to low-density residential areas that are contiguous)	10–100 km	UBL	λp, H_{max}, σ_H	Mesoscale γ, Mesoscale β
Regional	Region (urban and non-urban surroundings)	>100 km	PBL	λp, H_{max}, σ_H	Mesoscale β, Mesoscale α

Note: The vertical extent (Figure 2.1) is influenced by the nature of urban form, where H: building/urban canyon height; W: street/urban canyon width; λp: plan area fraction of buildings; H_{max}: maximum H; σ_H: standard deviation of H; UCL: urban canopy layer, RSL: roughness sublayer, ISL: inertial sublayer, UBL: urban boundary layer, PBL: planetary boundary layer.

Source: Modified from Cleugh and Grimmond (2012) and Oke et al. (2017). Atmospheric phenomena characteristic scales based on Orlanski (1975).

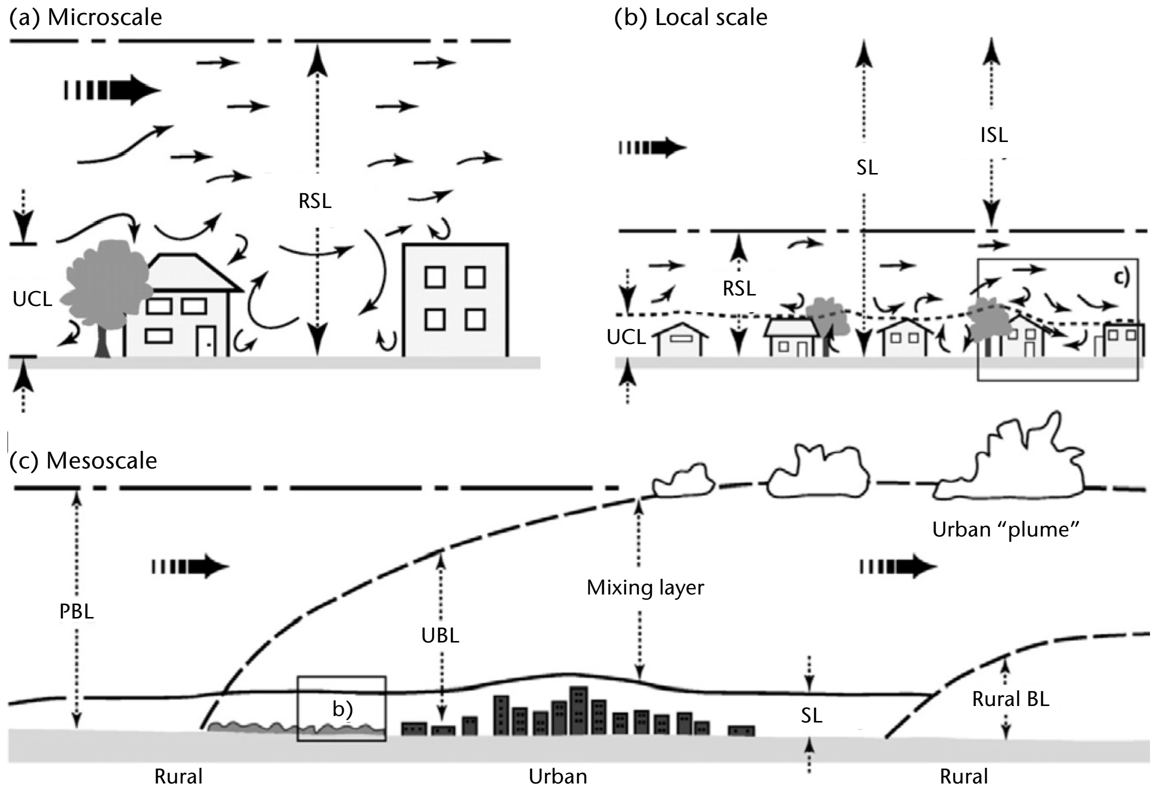


Figure 2.1. Vertical extent of atmospheric layers for (a–c) different horizontal scales of urban form. UCL: urban canopy layer; RSL: roughness sublayer; SL: surface layer; ISL: inertial sublayer; PBL: planetary boundary layer; UBL: urban boundary layer.

Source: Adapted from Oke (1997).

airflow effects like channelling, blocking, wakes and flow vortices. Buildings, the basic structural unit of every urban area, are commonly organized along streets, and in densely-built areas create "urban canyons".

The UCL is part of the **roughness sublayer** (RSL); this is the volume of air that is directly influenced by individual surface roughness elements like buildings or trees (Figure 2.1). This layer may extend to 2–5 times the height of the roughness elements, with the spacing of roughness elements and individual tall buildings having an influence on its depth. The depth of the RSL further varies with thermal stratification. Within the UCL and RSL, there is a three-dimensional (3D) time-dependent variation in the atmospheric characteristics over short distances (1–100 m).

Above the RSL there is an **inertial sublayer** (ISL), or constant flux layer (Figure 2.1). Within this layer, the influence of individual roughness elements is blended so that there is a small variability in atmospheric characteristics in the horizontal direction. For an ISL to form, there needs to be an area of similar fetch below, for example, neighbourhoods with similar building shape, building layout, construction materials and anthropogenic heat emissions. Atmospheric properties in the ISL are referred to as having one-dimensional (vertical) scaling and are **local scale** (on the order of 100 m–1 km) (Table 2.1).

Combined vertically, the RSL and ISL make up the surface layer (SL) of the **urban boundary layer** (UBL) (Figure 2.1). The UBL, influenced by the rough and heated urban surfaces, has dynamic vertical dimensions that vary both diurnally and seasonally. On clear days with strong solar irradiance, the UBL may reach 1–2 km in the afternoon, before falling to 100 m (or less) by night as a nocturnal inversion forms. In large cities the UBL is regarded as a mesoscale feature (Table 2.1) that is affected by the geographic setting, for instance orography or large water bodies (Subsection 2.5.5), and impacts the region as winds can advect the UBL downwind of the urban area for tens or hundreds of kilometres as an elevated urban plume (Figure 2.1c). All these features are within the planetary boundary layer (PBL), where all atmospheric processes are influenced by the surface.

2.3 DEFINING THE CL-UHI

The CL-UHI is a microscale to mesoscale atmospheric warming effect associated with cities. The CL-UHI is usually estimated from synchronous differences in near-surface air temperatures between urban and non-urban areas. The typical measurement height is about 1.5 m above ground level (AGL) for both areas. The present guidance uses the term "**urban**" for areas that are built-up with increased density of structures such as houses, commercial buildings, roads, industrial facilities and city parks. Towns, cities and suburbs are all referred to as urban areas. Areas surrounding urban environments are called "**rural**" in the present guidance. Rural areas may include both natural areas, where human changes to the landscape are minimal or not evident, or anthropogenically modified areas, such as agriculture and forestry areas. Rural areas can also include water bodies.

Ideally, the CL-UHI would be based on near-surface temperature differences at the same place with and without urbanization. However, observed values would be separated in time and therefore include the climate signal, making the true urban effect difficult to isolate. Modelling studies can simulate urban and pre-urban effects; however, it is difficult to determine a pre-urban case (Section 6.2). Thus, pragmatically, the urban effect is estimated from the difference in simultaneously observed or simulated temperatures at carefully selected urban and rural sites within the **region of interest.** As the strength of the CL-UHI varies with the urban area, it is important to consider this as well as the upwind rural surroundings that are the reference.

In the urban area, the near-surface canopy layer temperature (CL-T) is taken between the roughness elements (for example, buildings and trees), typically at a height of 1.25–2 m AGL (Subsection 5.4.5). If the rural environment consists of a large grass area, the air temperature is measured within the ISL and not in the very short rural canopy layer. Thus, the CL-UHI refers to the near-surface air temperature difference representing different sizes and patterns in thermal source areas (Subsection 5.4.3).

The CL-UHI intensity is normally defined as a synchronous air temperature difference between one or more urban and rural measurement sites (selection of sites is discussed in Chapter 5). Commonly a temperature difference (ΔT_{u-r}) is measured between the urban (u) location with the slowest cooling (which might be the city centre) and a location in the rural (r) surroundings, to capture the **maximum** urban thermal effect relative to a place where urbanization is absent ("Maximum" metric, Table 2.2, part (a)). This will not account for variations in types of urbanization or changes and heterogeneities in the rural setting. An approach that identifies "hot" and "cool" spots will capture **intra-urban thermal differences**, providing information on local-scale variations ("Spatial pattern" metric, Table 2.2, part (b)) influenced by surface properties. Similarly, using several rural sites and determining average rural values helps to avoid biases resulting from microscale effects at a selected rural site (Section 5.2). Note, the CL-UHI intensity is a temperature difference and is not indicative of the actual air temperature at either location (urban or rural).

Table 2.2. CL-UHI metrics based on ΔT_{u-r}, use cases with (a) conditions of likely occurrence and (b) main influences

(a) CL-UHI metric	*Use case*	*Conditions of likely occurrence*
Minimum	AC, CM, EU, HIC, R, WF	During midday hours in urban centres with shaded deep urban canyons or intense vegetation Irrigated urban parks with dense vegetation Cities surrounded by arid or semi-arid rural areas that warm rapidly after sunrise
Maximum	AC, CM, EU, HIH, R, UDP, WF	At night under ideal weather conditions (Subsection 2.5.3) Cold climates with high anthropogenic heat emissions any time of day
(b) CL-UHI metric	*Use case*	*Main influences*
Daily mean	CM, EU, EV, HI, R, UDP, WF	Weather situation, time of year, urban form
Seasonal mean	AA, CM, EU, EV, HI, R	Leaf on/leaf off, anthropogenic heat emissions, sky view factor, soil moisture, synoptic conditions, urban form
Annual mean	AA, CM, EU, EV, R, UDP	Urban form, surface materials, population, urban areal extent, regional climate, inter-annual variability of weather, anthropogenic emissions (depending on cool/warm winters, quality of building insulation)
Spatial pattern: use the other metrics at several sites	AA, AC, CM, EU, EV, HI, HIC, HIH, R, UDP, WF	Urban form, population, urban areal extent, terrain, surface materials, land use

Note:
AA – agricultural applications such as urban horticulture, city parks and green spaces (Section 3.4);
AC – atmospheric chemistry (Section 3.2);
CM – climate monitoring (Section 3.5);
EU – energy use (Section 3.3);
EV – ecology and vegetation, for example, assessing earlier spring and later autumn onset compared to rural phenology (Section 3.4);
HI – health impact (Section 3.1);
HIC – health impact cold, such as cold waves and extreme weather (Section 3.1);
HIH – health impact hot: emergency response, for example, heat stress and heat warning due to high temperatures (Section 3.1);
R – research;
UDP – urban design and planning (smart city applications) (Chapter 8);
WF – weather forecasting (Section 3.5).

2.4 CL-UHI METRICS

Table 2.2 provides a list of CL-UHI metrics and corresponding use cases. The maximum CL-UHI intensity may be of interest to those concerned with public health and heat stress at night (Section 3.1). The highest reported value in any city is about 12 K, assuming larger-than-normal anthropogenic heating is not a factor (Oke et al., 2017). Minimum values can be small but positive, and negative values can also occur, indicating an urban cool island, where the urban location is cooler than the rural one.

Daily, seasonal or annual means include a time definition (day, season, year), but time averaging can be done, for example, over several days or over several years. Similarly, the minimum or maximum metrics might be used to determine average values for specific synoptic situations in order to better understand the impact of the climate or weather patterns on the CL-UHI development (Subsection 2.5.4). Average intensities are always smaller than maximum intensities measured under ideal weather conditions for individual nights (Subsection 2.5.3). For any metric, the temporal averaging (or sampling method) needs to be specified to properly interpret the intensities.

Each metric can be applied to one site or to multiple sites. Using multiple sites provides information on the spatial pattern. However, averaging the CL-UHI intensity over several urban sites will reduce the CL-UHI intensity for the urban area. Therefore, not only the temporal but also the spatial averaging needs to be specified and documented in each application. The metric and averaging to apply will differ depending on the end-user applications (Chapter 3).

2.5 DEVELOPMENT OF THE CL-UHI

2.5.1 Surface influences

The physical causes of the CL-UHI are well known. As urban populations grow, more buildings are erected, often replacing vegetated landscapes that include meadows, forests or fields with 3D impervious surfaces that store heat due to their thermal properties, emit heat associated with human activities, and, in general, alter the surface energy exchanges. The CL-UHI is fundamentally a thermal anomaly that results from differences in the energy balance in urban and surrounding rural environments. In the UCL, the relevant energy exchanges occur at different heights within the **canopy volume** (Figure 2.1). These urban-induced changes to the energy balance compared to rural areas result in differences in cooling and heating rates between the two areas. This creates the distinct thermal environment of urban areas. The alterations to the radiative, thermal, moisture and roughness properties in cities, together with emissions of heat and pollution from human activities, give rise to the four main causes of the CL-UHI (Oke, 1982):

- **Thermal properties**: Building materials often have greater heat capacity than open vegetation and store heat during daytime that is released at night.

- **Surface state**: Surface waterproofing by buildings and paving reduces subsurface moisture storage and directs available energy into surface heating rather than evaporation. Immediately after rain events, there might be a cooling effect for surfaces and air due to the evaporation of intercepted water.

- **Surface geometry**: The total area of the urban surface (horizontal, vertical and sloped facets) is increased relative to that of the non-urban surface due to its corrugated form. This increase results in: (i) reduced average wind speeds, (ii) multiple reflections and greater absorption of solar radiation, (iii) increased surface area for heat storage, (iv) reduced net energy loss to the atmosphere via longwave radiation in densely built-up areas due to horizon screening during daytime (increased loss at night-time), and (v) reduced heat loss by convection and advection in the sheltered UCL.

– **Anthropogenic heat**: The release of heat from fuel combustion and electricity use is much greater in urban areas compared to rural areas.

2.5.2 Interaction of physical processes

The 3D structure (geometry) of the urban surface and the high thermal mass of the materials are the main causes of the nocturnal CL-UHI. The high level of roughness of urban surfaces reduces the wind speed in urban areas (Subsection 2.5.1); thus, the sensible heat fluxes are smaller than in less rough rural areas. In addition, sealed surfaces with less vegetation combined with lower wind speeds than in the rural surroundings also reduce the latent heat fluxes. Thus, the surface energy budget is mainly determined by radiative fluxes and heat storage/release by the 3D urban forms (Table 2.1). Wind speed is a critical influence on heat fluxes and therefore surface–air exchange. In general, stronger wind speeds result in smaller CL-UHI intensities.

After sunrise, rural areas warm rapidly because they are fully exposed to the sun when they have a large sky view factor. The warming is concentrated in a shallow unstable layer of air near the surface, capped by the remnants of a nocturnal inversion. Warming is slower in urban areas because the trees and buildings shade large areas of the UCL and have smaller sky view factors. Thus there is less direct solar radiant energy but more diffuse radiation across the numerous 3D surfaces. This energy is conducted into the urban mass. The nocturnal cooling of the 3D surfaces and near-surface air is comparatively slower in the urban canyons because of reduced sky view factors and the heat stored in the urban fabric. This results in near-surface air temperatures remaining higher in urban areas at night compared to more rapidly cooling surrounding rural areas. The lower rural temperatures result in a more stable atmosphere at night in these areas than in urban areas, which can stay unstable. This impacts air pollutant concentrations (Section 3.2). The CL-UHI intensity rapidly decreases to a minimum near sunrise or even becomes negative a few hours after sunrise.

In some cases, especially for urban areas surrounded by arid or semi-arid landscapes, the lag period in near-surface urban air warming is sufficiently long to reverse the thermal anomaly. In addition, these cities might have more vegetation (or green infrastructure) than the rural surroundings, which might change the surface energy balance in favour of more evapotranspiration than in the rural surroundings, such that the urban area is cooler than the rural surroundings during the middle of the day. This is called an urban cool island (see ″Soil humidity matters″ example in Appendix 1).

As solar day length varies throughout the year, the times that exhibit the greatest differences in heating/cooling rates shift. Therefore, comparative analysis of heating/cooling rates must be normalized relative to solar day length (sunset, sunrise). In addition, the synoptic conditions that favour or suppress CL-UHIs vary with season. Generally, CL-UHI intensities are greatest in summer months for mid-latitude cities, and in dry months for tropical cities (Roth, 2007). This pattern results from the important driving forces of solar radiation, soil moisture and synoptic-scale weather patterns (wind, cloud, precipitation). Seasonal variations in anthropogenic heat inputs, most notably space heating in cold seasons or air conditioning in hot seasons, also increase CL-UHI intensities. An example of the influence of latitude and temperature is given in "Latitude matters" example in Appendix 1.

The intensity of the CL-UHI is often approximated by in situ measurements of air temperature using sensors positioned at or near standard screen-level height of 1.25–2 m above the ground (see *Guide to Instruments and Methods of Observation* (WMO-No. 8), Volume I: Measurement of Meteorological Variables, Section 2.1.4.2.1) at multiple sites within and around the urban area (for observational set-ups see Section 5.3). When the resulting isotherms are mapped, they resemble the altitude contours of an island, with variations corresponding to urban land cover, building morphology, human activity and surface relief characteristics (Figure 2.3).

2.5.3 Ideal weather conditions

These factors (Subsections 2.5.1 and 2.5.2) all contribute to the formation of a CL-UHI. The fundamental processes can be most easily examined under "ideal" weather conditions when the CL-UHI intensity is maximal. These are **calm, clear days** with strong daytime insolation followed by **calm, clear nights**.

With very low wind speeds, turbulent mixing is weak and thus sensible and latent heat fluxes are smaller throughout the day than for clear, slightly windy days. To achieve energy balance, heat loss to the atmosphere must be matched by heat conduction from the surface mass. In these "ideal" circumstances, the CL-UHI intensity primarily depends on the comparative radiative and conductive heat fluxes in urban and rural environments. On calm and clear nights, surface cooling is driven by radiation loss, with the surface-emitted longwave radiation exceeding that received from the atmosphere. The radiative processes are influenced by the sky view factor, which is reduced by trees and building walls. The conductive heat losses are regulated by the properties of the surface fabric such as thermal admittance, which is greater for urban materials.

Maximum CL-UHI intensities develop under ideal weather conditions as defined above. A corresponding diurnal cycle is illustrated in Figure 2.2. Urban and rural areas might exhibit similar daytime air temperatures but distinctly different nocturnal temperatures, with higher values in the urban area (Figure 2.2a). The formation of the nocturnal CL-UHI is associated with a strong cooling rate in rural areas around sunset (Figure 2.2b). The cooling rate in urban areas varies with building density. Differences in evening cooling are magnified when rural areas are dry (such that thermal admittance is low) and heat withdrawal from the subsurface is limited. While the cooling rates are distinct at sunset (SS), the rates start to converge as the night progresses (Figure 2.2b). This results in a characteristic temporal pattern in the CL-UHI intensity, with significant growth in the early evening right after sunset, followed by a relatively constant period through the middle of the night (Figure 2.2c).

2.5.4 Influences of actual weather conditions

The ideal weather conditions resulting in maximum CL-UHI intensities (Subsection 2.5.3) rarely occur. The actual intensity and time/space characteristics of the CL-UHI are controlled by many interdependent factors related to actual weather, as well as city size, surface properties, solar zenith angle and geographic setting. The most relevant meteorological variables for the intensity of the CL-UHI include near-surface wind speed and humidity as well as cloud cover and precipitation.

Wind speed and cloud cover are both inversely related to CL-UHI intensity. As wind speeds increase (if skies are clear and surface moisture is available), sensible and latent heat fluxes will increase because of mixing of the air between the surfaces. Eventually the increasing wind speed reduces both the near-surface air temperatures and urban–rural air temperature gradients. The wind speed at which the CL-UHI intensity falls to below 1 K differs by city and the prevailing atmospheric conditions, such as cloudiness and precipitation. Regional wind may displace warmer isotherms from the city centre downwind. The atmospheric stability within the UCL, UBL and rural PBL all play a role in vertical heat exchange and thus influence CL-UHI development. Cloud type and cloud amount control the CL-UHI intensity by modifying radiative receipt and cooling. Clear skies at night permit stronger radiative cooling of rural than urban air, while a whole day with overcast skies suppresses these differences. Cloud type and cloud altitude moderate this, with high-altitude clouds (for example cirrus) impacting the radiative heat transfer less locally than low-altitude clouds (for example cumulus).

Since the meteorological conditions influence the CL-UHI development, synoptic-scale weather patterns are also important. Weather situations that quickly change are frequently linked to higher wind speeds that reduce the intensity of the CL-UHI due to increased turbulent mixing. In addition, rainfall and snowfall patterns modify soil moisture and thereby water availability for evapotranspiration. The spatial and temporal distribution of dry/wet soils across an urban–rural area influences the diurnal and seasonal expressions of the CL-UHI.

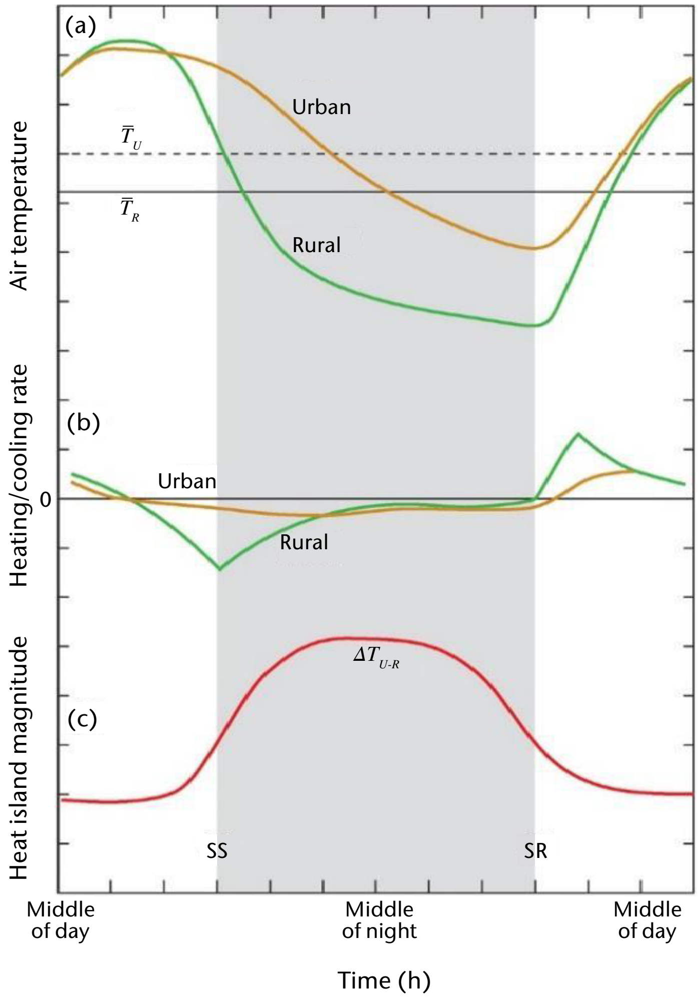


Figure 2.2. Diurnal variation at an urban (brown) and a rural (green) site under favourable meteorological conditions for a CL-UHI (clear skies, high solar radiation, light winds), (SS = sunset; SR = sunrise):

(a) ~2 m air temperatures with daily mean for urban (dashed black, $\overline{T}_U$) and rural (black, $\overline{T}_R$) site; (b) heating/cooling rates; and (c) CL-UHI intensity (red, ΔT_{U-R}). Vertical scale units are approximately (a, c) 2 K and (b) 2 K h^{-1}.

Source: Oke et al. (2017). Reproduced with permission of the licensor through PLSclear.

2.5.5 **Influences of city form and geographic setting**

A third set of controls on the CL-UHI relates to the size of a city, defined by its form and function (Table 4.1) and its geographic setting. Cities with urban areas that have extensive paving and tightly spaced tall buildings tend to exhibit strong CL-UHI intensities in those areas (Figure 2.3a, b). The extent of the urban area influences the CL-UHI given the potential sources of heat for advection across the urban area. Heat, moisture and pollution emissions from human activities vary with socioeconomic and cultural practices both in and out of the city (for example use of irrigation). Industrial areas with many factories and little or no green spaces may experience large CL-UHI intensities. Residential populations may live in tall towers or low-rise, low-density buildings. Population density tells us about the likely urban form, although it is not helpful for the central business district. Population density alone also does not provide information about how city form might change as population grows or shrinks (Oke, 1981). For example, a larger population does not necessarily increase the urban extent, building density, vertical extent or reduce the pervious surface cover.

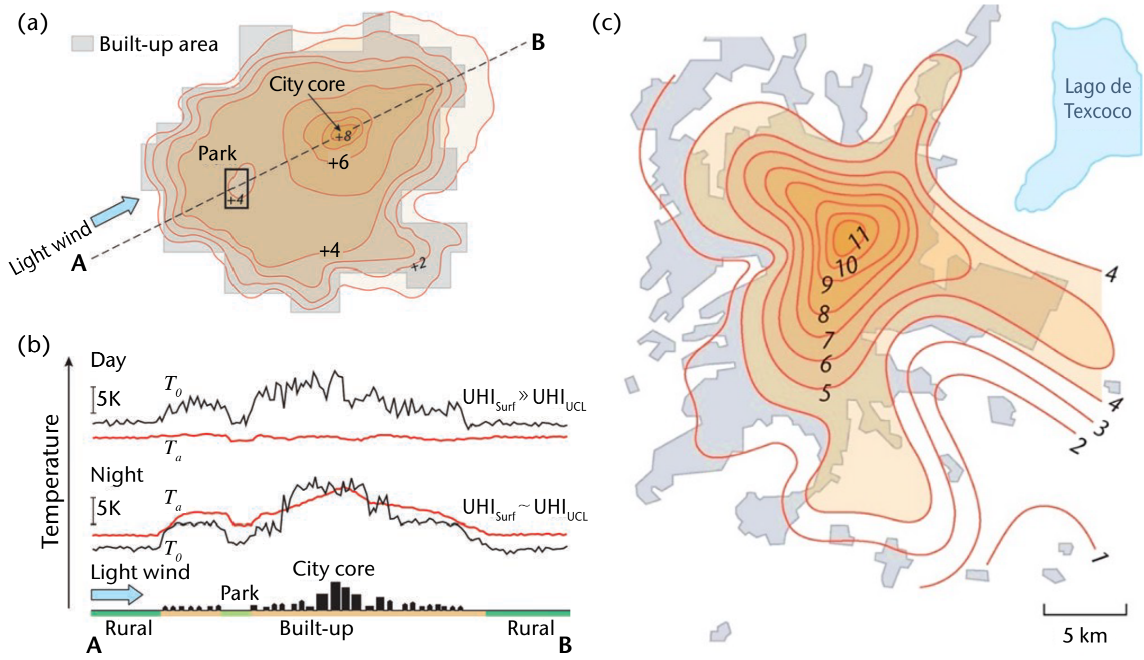


Figure 2.3. Isothermal maps during clear, calm weather.
(a) CL-UHI intensity for a "typical" city with flat terrain 2–3 h after sunset,
with (b) cross-section (A → B in (a)) of building density and temperature.
(c) Air isotherms (thick lines, °C) for Mexico City in the early morning (8 Feb. 1972)
at minimum daily temperature. Urban areas shown by shading.

Source: (a), (b) Oke et al. (2017). Reproduced with permission of the licensor through PLSclear. (c) Oke et al. (2017) based on data from Jáuregui (1973). Reproduced with permission of the licensor through PLSclear.

The topographic setting of a city influences the intensity and spatial characteristics of the CL-UHI. Urban areas in valleys are often warmer during day than their more elevated rural surroundings, since temperatures are generally warmer at lower altitudes above sea level (ASL). This influences the calculated CL-UHI intensity, which is based on urban–rural temperate differences. Therefore, CL-UHI calculations should preferably be based on values taken at the same altitude (Section 5.2).

Mesoscale circulations induced by the geographic setting (valley, basin, coastal, mountain) influence wind fields, causing for instance cold air currents, land–sea breezes or downslope winds. These pre-settlement circulations influence the surface energy budget. Their development is influenced by the urban area, and they may weaken or strengthen the CL-UHI depending on their diurnal and seasonal cycles, the thermal characteristics of the winds and possibly associated cloudiness, as well as the city's location upwind or downwind of major orographic and topographic features (Wanner and Filliger, 1989).

Modest terrain can create upslope flows during the day and downslope flows at night. Cold pools are often formed close to the valley floor during the night by the accumulation of the cool air flowing down the slopes (katabatic flow), but dense urban structures might block these flows. These orography effects can be mixed with the urban-fabric-induced temperature change and affect the CL-UHI intensity. An example is given in Figure 2.3c for Mexico City. During night-time, under clear-sky conditions, cold-air katabatic flows cool the north and west of the city, as shown by the spatial pattern of isotherms at the perimeter of the urban area.

Cities located at higher altitudes may experience larger CL-UHIs as there is more daytime heating of the urban area from the clearer skies (lower optical thickness). If a nocturnal thermal inversion occurs in these elevated areas, the CL-UHI may be enhanced when calculated based on measurements made at rural stations situated at lower altitudes. Apatity, Russian Federation (~60 000 inhabitants) provides an example. During winter, a CL-UHI of ~10 K was observed in the city, which is located on a small hill with the rural station ~50 m lower at a frozen lake. About 50% of the CL-UHI was attributed to anthropogenic heating based on model studies (Varentsov et al., 2018).

The CL-UHI intensity is also impacted by water bodies such as lakes and rivers in the urban area. The daytime CL-UHI can be reduced close to the water body by onshore advection of cool air, but the large thermal mass of water keeps nocturnal water temperatures more constant, resulting in a high CL-UHI intensity at night close to the water body (Schlünzen et al., 2010). The CL-UHI in coastal cities can be strongly modulated by sea/lake breezes. Daytime anthropogenic heat emissions may be transported downwind, causing the peak CL-UHI to be displaced from the densest parts of the city, often historically near the shore, to inland suburban areas. Sea breeze fronts can travel several tens of kilometres inland. The interaction of the moister sea breeze air with the urban thermal structure can initiate thunderstorms as in São Paulo, Brazil (Vemado et al., 2016), or increase rainfall as in Singapore (Doan et al., 2021), which in turn may reduce the CL-UHI because of storage heat loss associated with runoff and evapotranspiration. Similarly, sea breezes can cause clouds (for example in Tokyo or London) over the urban area and increase night-time CL-UHI intensities if the rural area remains less cloudy. However, while coastal areas remain cooler than the inland urban regions by day, if the inland movement of the sea breeze front is hindered by the urban roughness, the opposite occurs at night, as found in Mumbai, India (Maral and Mukhopadhyay, 2015).

The city latitude is an important determinant of the annual and seasonal intensities of solar radiation received depending on the regional climate (in particular the amount of cloudiness). This influences the heat that can be stored in the urban fabric, the demand for energy to heat and cool buildings, and, while also considering socioeconomic conditions, release of anthropogenic heat. Given the greater frequency of cloud and rain in tropical latitudes (excluding deserts), and to some extent different city forms in these regions (high albedos, traditionally lower building heights), it is generally observed that tropical cities experience smaller CL-UHI intensities than temperate cities (*Urban Climatology and its Applications with Special Regard to Tropical Areas: Proceedings of the Technical Conference* (WMO-No. 652); Roth, 2007).

2.6 DISTINGUISHING THE CL-UHI FROM OTHER URBAN HEAT ISLAND TYPES

The CL-UHI is a measure of the temperature response of the UCL atmosphere, and it can be attributed mostly to changes in the energy exchanges at the surface due to the characteristics of the urban environment (Subsection 2.5.2). These characteristics also give rise to other types of UHI, including the following (Oke, 1995):

– **Urban boundary layer UHI** (UBL-UHI): The air above an urban area in the UBL (Figure 2.1) is warmer compared to air at a similar height above the rural area.

– **Surface UHI** (S-UHI): S-UHI is defined as the heat island resulting from the surface temperature difference between urban and rural areas. Sunlit urban surfaces (notably ground, roofs and walls) are mostly warmer during the day than rural surfaces in the surroundings. At night the urban surfaces are in many cases warmer than rural surfaces (see "Large CL-UHI is not necessarily related to high urban temperatures" example in Appendix 1). In cold climate cities, the S-UHI increases the number of frost-free days, and snow is less likely to remain on the ground. The S-UHI does not represent the near-surface air temperature (Stewart et al., 2021).

– **Subsurface UHI** (SS-UHI): SS-UHI is defined as the heat island resulting from the subsurface (in the ground) temperature difference between urban and rural areas. Urban substrate materials (for example soil, rock, groundwater, and city infrastructure such as sewers, subways and building foundations) are often warmer than those in the rural surroundings over long time periods. An example of SS-UHI impacts in Arctic cities is the change in depth of the permanently frozen soil, causing a mass movement of soil in urban areas that can weaken the infrastructure foundation.

Each UHI type is closely linked to the vertical structure of the urban area and the atmosphere above it. These other UHI types have spatial and temporal expressions different from those of the CL-UHI. Some are less studied because of the difficulty of obtaining the observations needed to measure them, for instance above the canopy layer (UBL-UHI) and below the surface (SS-UHI). Observations of the S-UHI have increased with the availability of satellite and aircraft-based infrared sensors, but often using brightness temperatures because of the challenge of obtaining all the surface emissivities.

The different UHI types share the same fundamental energy balance origins. Differences between the types reflect the scale and medium (air/solid) under investigation. The S-UHI responds nearly immediately to insolation and quickly reacts to changes in cloud cover, for example. If cloudiness differs at the urban and rural sites, the cloudiness effect is also part of the S-UHI signal. Apart from that, the characteristics of each facet (Section 2.2) determine the surface temperatures and thus the S-UHI. As it is based on the difference in the temperatures of surfaces (for instance at top of the trees), the values are not directly relevant for human health or urban planning. The CL-UHI response to the surface temperature depends upon molecular diffusivity and convection to transport heat from surfaces to the near-surface atmosphere and the atmospheric turbulence close to the surfaces. The CL-UHI blends contributions of proximate surfaces and anthropogenic heating/solar energy removal within the UCL with contributions advected and turbulently mixed from microscale, local scale and larger scales.

Understanding these distinctions between CL-UHI and S-UHI is critical in evaluating policies that are designed to mitigate the CL-UHI (Chapter 8). Often, satellite-derived S-UHI is confused with the CL-UHI based on near-surface air temperature differences, despite the fact that they represent different thermal responses at different spatial and temporal scales. The CL-UHI should be viewed as one expression of the urban thermal effect relevant for several applications (Chapter 3). Addressing its causes and mitigating its effects (Chapter 8) will affect the urban-induced warming and impact the development of the other UHI types.

2.7 CL-UHI EFFECTS ON METEOROLOGICAL AND CLIMATOLOGICAL CONDITIONS

When there are light regional winds, the heat exchange from surfaces including roof and wall facets (this is the net contribution of wall and ground surfaces to the atmosphere) can initiate a thermodynamic circulation called the "country breeze". It is caused by lower air pressure above the warmer urban area. This leads to updrafts in the warm centre, resulting in a horizontal flow convergence there, and return flows in higher layers to the rural surroundings with subsidence there. The circulation is potentially important to the CL-UHI as a self-regulating mechanism moderating its intensity: urban temperatures are limited by the inflow of cooler air from the surroundings, while rural cooling rates are partly compensated by the subsidence of warmer urban air from aloft (Haeger-Eugensson and Holmer, 1999).

The updrafts created by an intense CL-UHI may increase convection in the overlying air and contribute to cloud development, lightning strikes and extreme precipitation. The upper UBL often contains higher concentrations of pollutants, many emitted from within the UCL. These might provide additional cloud nuclei.

Radiative fog formation occurs under conditions that also favour high CL-UHI intensities. The slower urban cooling rate means cities are more likely to remain fog-free under such conditions, and with the warmer temperatures the urban relative humidity is likely to be less than in the rural surroundings. The warmer nocturnal urban temperatures reduce the spatially variable dew formation on surfaces. Reduced urban dewfall may be a contributor to the observed nocturnal urban moisture excess, where absolute humidity shows increases at night as in London (Lee, 1991) or Belgrade (Unkašević et al., 2001), unlike relative humidity. Anthropogenic emissions of water vapour, from combustion processes, air conditioning, or evaporation after street cleaning or irrigation, also contribute to the moisture excess in cities.

The CL-UHI creates a longer growing period and earlier greening of trees in the spring along with a later leaf fall. The UBL-UHI contributes to mixing emissions into a larger volume of air than in the rural areas, especially at night, and the elevated temperatures influence temperature-dependent chemical transformation of pollutants. For more details see Chapter 3.

2.8 THE CL-UHI IN BRIEF

The CL-UHI is a microscale to mesoscale atmospheric warming effect associated with the characteristics of the urban environment. It describes near-surface air temperatures that are higher in urban areas than in the surrounding rural areas, particularly at night. It is one of four UHI types that also include the boundary layer UHI (UBL-UHI), the surface UHI (S-UHI) and the subsurface UHI (SS-UHI). The CL-UHI is observed in the airspace between buildings and extends to the height of building roofs and treetops (the urban canopy layer – UCL). The present guidance focuses on the CL-UHI at near-surface levels (1.5 m).

When mapped across the urban landscape, isotherms take the form of an "island" with values increasing from the outskirts towards the centre of the urban area. The CL-UHI intensity is greatest under clear skies and with weak winds following a short dry period; the highest intensities typically last for several hours after sunset. The energetic basis for its formation is as follows:

- **Urban fabric** permits greater storage of heat during the day which is released at night.
- **Urban surface geometry** obstructs the sky view by its complex 3D form, thus impeding ground cooling by multiple wall and street facets within the UCL.
- **Urban imperviousness** reduces subsurface water for evaporation and directs available heat into sensible rather than latent heat energy exchanges.
- **Anthropogenic heat** adds an additional source to the CL heat energy balance resulting from human activities related to the industries, buildings and transportation.
- The **meteorological situation** influences exchange processes at surfaces (especially heat and radiative fluxes).

CHAPTER 3. URBAN SERVICES NEEDING CL-UHI INFORMATION

Information on current and future CL-UHIs helps to improve forecasts provided by an IUS (*Guidance on Integrated Urban Hydrometeorological, Climate and Environmental Services* (WMO-No. 1234), Volume I: Concept and Methodology and *Guidance on Integrated Urban Hydrometeorological, Climate and Environment Services* (WMO-No. 1234), Volume II: Demonstration Cities). The forecast, either itself or in combination with a statistical model (Section 6.4), can consider the CL-UHI in the total temperature, CL-T, to be provided to citizens. Cities, mostly in cooperation with NMHSs, provide several services to their citizens, including those linked to health (Section 3.1), air pollution (Section 3.2) and energy use (Section 3.3). The latter also impacts the CL-UHI, for example through anthropogenic heat emissions, while the atmospheric composition has significant implications for human health (WHO, 2021). The CL-UHI can modify vegetation's phenology (Section 3.4), which influences the health of those sensitive to pollen, while vegetation in turn impacts the CL-UHI intensity (Chapter 2). The CL-UHI may also be important in early warning systems for extreme weather and emergency management operations (Section 3.5). Depending on the application, one or many metrics (Table 2.2) may be relevant.

Newly planned urban forms and designs can intentionally or unintentionally impact the CL-UHI intensity. Assessments can be made in advance by using models (Chapter 6). Dedicated urban planning and design may mitigate CL-UHI intensities (Chapter 8).

3.1 HEAT STRESS INFORMATION AS A SERVICE – CL-UHI IMPACTS ON HEALTH

Elevated heat stress is particularly problematic for vulnerable groups, for example children, adults with certain pre-existing medical conditions and outdoor workers (*Heatwaves and Health: Guidance on Warning-System Development* (WMO-No. 1142)). As noted (Chapter 2), the CL-UHI characterizes the urban temperature deviation compared to the rural temperature signal, with higher temperatures in urban areas, especially at night. Maximum CL-UHI values are a good metric to assess the intensity of nocturnal extremes (Table 2.2). This can be used in combination with forecasts to determine night-time CL-T (Section 6.4).

Human thermal comfort is estimated by many thermal indices that combine various environmental factors (Subsection 3.1.1). The WMO Commission for Weather, Climate, Water and Related Environmental Services and Applications (SERCOM) Study Group on Integrated Health Services, together with the World Health Organization (WHO), is considering the impacts of heat stress on health, and the two organizations have provided guidance on warning-system development (*Heatwaves and Health: Guidance on Warning-System Development* (WMO-No. 1142)). See also Subsection 3.1.2.

3.1.1 Thermal comfort assessment

Elevated skin and body temperatures, heart rate or sweating are all manifestations of heat strain arising from heat stress. Heat-related illnesses, in increasing order of severity, include heat rash, heat oedema, heat syncope, heat cramps, heat exhaustion and life-threatening heat stroke. Even moderately high temperatures are known to be associated with increased all-cause population mortality (Basu, 2009). However, although studies have linked mean, minimum and maximum CL-T at different timescales with mortality and morbidity in cities, the effects of temperature extremes in the urban canopy on heat- and cold-related mortality also depend on non-climate factors such as the demographic profile of each city. This is considered in thermal indices that depend on a combination of environmental factors, including temperature, humidity, ventilation (wind), and solar and longwave radiation, as well as personal factors such as metabolic heat, age and clothing insulation. Numerous thermal comfort-related bio-meteorological indices with different complexity exist (see reviews such as de Freitas and Grigorieva (2017), and Fischereit and Schlünzen (2018)).

Daily and monthly CL-UHI maps vary across a city (use cases HI, HIC and HIH in Table 2.2). When combined with background temperature data and social and economic characteristics, spatial heat-risk maps can identify potentially vulnerable groups. Heat-related mortality can be estimated using time-series and epidemiological methods. Furthermore, recommendations can be given regarding places where citizens can go to cool off.

As exposure to wind and mean radiant temperature can vary over metres, using the CL-UHI (or CL-T) as a proxy for thermal comfort in an urban canopy might be misleading. However, the heterogeneity of the CL-T may influence indoor air temperatures, particularly in poorly insulated buildings, contributing to indoor overheating and risk.

3.1.2 Heat-health outcomes and early warnings

The CL-UHI is only one contributor to heat stress in urban areas. However, as the CL-UHI is a nocturnal phenomenon it may result in poor sleep quality, with consecutive hot nights causing greater health risks than hot days. Therefore, monitoring and providing CL-UHI information is important in early warning systems for predicting and informing the public about heat waves and heat stress events in urban areas (*Heatwaves and Health: Guidance on Warning-System Development* (WMO-No. 1142); *Multi-hazard Early Warning Systems: A Checklist*; *Guidance on Integrated Urban Hydrometeorological, Climate and Environmental Services* (WMO-No. 1234), Volume I: Concept and Methodology).

3.2 AIR POLLUTANT CONCENTRATION INFORMATION AS A SERVICE – CL-UHI IMPACTS ON ATMOSPHERIC COMPOSITION

With increasing urbanization, a larger proportion of the world's population is exposed to concurrent urban environmental risks such as overheating and poor air quality that may have independent or synergistic impacts. During heatwaves with high air pollution, mortality rates increase in cities; therefore, the combined effects need to be considered. Anthropogenic heat fluxes (Section 3.3) modify the CL-UHI, and the urban microscale to local-scale heterogeneity can increase turbulent mixing within the UCL and above, both increasing the UBL height. With deeper UBLs the near-surface concentrations of constituents like aerosols are reduced. The CL-UHI may cause modifications of the physical (for example moisture, wind, temperature, aerosols), biological (for example pollen, viruses, spores, plant diversity) and chemical (for example air quality, particle formation) state of the urban air. These in turn can impact the health of the citizens. A higher CL-T will accelerate air chemical processes such as night-time chemical reactions and daytime photochemistry. For example, the rate constants of the chemical reactions responsible for the formation of ozone increase with air temperature and solar radiation. These processes are indirectly impacted by the CL-UHI since the urban fabric influences the CL-T and shortwave radiation pattern in a city. The CL-UHI in turn influences the circulation (see description of "country breeze", Section 2.7).

The relations between the CL-UHI and pollutant concentrations are complex and pollutant dependent. Therefore, it is important to include information on CL-UHI values in assessments of air quality as well as in any mitigation plan. Changes in vertical mixing, horizontal transport, temperatures, shading as well as 3D urban forms directly influence near-surface concentrations.

3.3 ENERGY PROVISION AS A SERVICE – CL-UHI IMPACTS OF AND ON ENERGY USE

The amount of energy used to keep indoor environments comfortable depends on the energy balance of the building envelope, ventilation rates, solar gain and the demographics of the occupants. The energy balance of the building envelope is a function of air temperature, wind speed, the amount of radiation exchanged with the environment, the building's shape, building materials, airtightness, internal sensible and latent heat loads resulting from, for instance, cooking or lighting and the density of people in a room (100–200 W per person). Cities with different building designs and construction standards, and different socioeconomic characteristics (for example air-conditioning usage patterns) will differentially impact or be impacted by CL-T. For example, major increases in space cooling can increase energy demand, and the resulting anthropogenic heat emission can amplify at microscale the night-time CL-UHI by 0.5–1 K (de Munck et al., 2013) and thereby CL-T. However, the CL-UHI reduces winter energy demands in moderate to large cities in cold climate regions (Varentsov et al., 2018).

Energy use associated with buildings and transport is a major anthropogenic heat source in urban areas that needs to be accounted for in the urban energy balance and can affect the CL-UHI. The amounts and spatial distribution of this heat will change with the decarbonization of the energy sector. This is dependent on political, technical and social changes at different spatial scales. Within cities, there are moves towards shared/common energy distribution networks to reduce energy waste, with a shift to greater use of renewable energy sources to overcome intermittency in supply. The technological changes associated with energy transitions, whether replacement technology (for instance replacing combustion boilers with electric heat pumps) or new technology (for example photovoltaic solar panels), have shifted energy considerations from being predominantly focused on large-scale supply management to a model where distributed production and consumption has increased relevance. Balancing energy demand with supply is requiring more sensitivity to microscale and local-scale conditions that, when combined with varying social influences across a city, are giving greater weight to the argument that automated and "smart" controls are critical.

Climate change (global warming) will increase demand for summer cooling at higher latitudes than today. Demand profiles will differ vertically and horizontally within the UCL (Hertwig et al., 2021a). Knowledge of the high-resolution annual and seasonal CL-UHI values, as well as diurnal and extreme values, will help to facilitate the basic engineering tasks of system sizing and design. Modelling (Chapter 6) and monitoring (Chapter 7) of the CL-UHI provide an opportunity for more informed ventilation and heating/cooling control that is particularly relevant to buildings with mixed-mode strategies and for maintaining critical infrastructure (for example cooling demand in data centres).

Shared energy networks, such as those for buildings and transport, face operational constraints at the local scale and microscale. In urban areas with pronounced CL-UHIs, for instance, increases in need for cooling might coincide with higher energy demands for electromobility, requiring intelligent system management and control of energy by end users. The stress placed on existing energy networks from an expectation of increased demand at peak times is leading to new energy services where data and knowledge on the CL-UHI has a part to play. Such services include the consolidation of energy end- user ability/capacity to shift energy demand (in time) through demand-side management programmes and new business models with an emphasis on "service" rather than "energy" provision, for instance by contracts/payment for guaranteeing building indoor comfort rather than energy use. Approaches for assessing the viability of these services are beginning to be explored where differentiation in the CL-UHI will add value in assessing the capacity of weather-sensitive energy infrastructure, for instance through local zone classification (Section 4.3), CL-UHI measurements (Chapter 5), modelling (Chapter 6) and monitoring (Chapter 7).

Temporal and spatial dynamics of energy use are not only influenced by the heterogeneity in design, built features (Section 2.2, Table 2.1) and societal variance (Sections 4.1, 4.2), but also by movement and transport characteristics. Incorporating CL UHI data into traffic management procedures may impact behaviour and thus place and time of energy demand. These dynamics are beginning to be considered in relation to energy and CL-UHI modelling (Capel-Timms et al., 2020).

3.4 URBAN VEGETATION AS A SERVICE – CL-UHI IMPACTS ON AND FROM VEGETATION

Urban vegetation not only provides ecosystem services, but also helps to influence CL-UHI patterns (Subsection 2.5.2) and is thus a relevant urban climate service. It provides shade that reduces radiant temperatures (Section 3.1) and cultural services, as green spaces contribute to human well-being (Chang et al., 2017; von Szombathely et al., 2017). The CL-UHI can extend the frost-free season by several weeks each year, affect temperatures during individual freeze events and provide warmer habitats. Thereby, the CL-UHI can influence plant composition and diversity, with those needing higher temperatures found in areas that often have larger CL-UHI intensities (Figure A3.2). In addition to plant composition, the growing season and thus the period of active photosynthesis is influenced by the CL-UHI: it is longer in mid- and high-latitude urban areas than in their surroundings, with an earlier flowering time, a later end of the growing season and an increase of growing degree days. As one result, the total length of the pollen-allergy season is longer. Furthermore, the higher temperatures may allow exotic plants to grow, introducing new allergens or causing ecological issues. There is evidence that pollen in polluted urban areas has a higher allergenicity, with several reasons for this effect (D’Amato et al. 2007).

Urban vegetation clearly impacts CL-T and hence the CL-UHI through increased latent heat fluxes which reduce the turbulent sensible heat flux. Street trees also provide shade, which reduces daytime temperatures and can trigger a cool island (Subsection 2.5.2). Urban vegetation can reduce CL-UHI intensities by 0.5 °C–4.0 °C at microscale. Urban gardening and green roofs or façades may also increase latent heat fluxes and thereby reduce the CL-UHI intensity; however, sufficient water needs to be available. In addition, some vegetation may improve urban air quality by absorbing gases and particles (Section 3.2), and vegetation provides water retention areas for rainfall, and modifies the thermal mass and, therefore, heat storage. Cities may reduce the CL-UHI by implementing sustainable urban agriculture policy and zoning interventions such as promoting the concept of intensive production and creating “edible urban landscapes” by building green roofs and greenways, and encouraging vertical farming. The CL-UHI may assist in colder regions, making it possible to grow vegetables within the urban area when not possible in the cooler surroundings.

3.5 MULTI-HAZARD EARLY WARNING SYSTEM – CONSIDERATION OF THE CL-UHI

Knowledge about the CL-UHI is relevant to delivery of an IUS, being included in daily forecasts and multi-hazard early warning systems that provide air quality data and thermal comfort indices. The time-dependent pattern of CL-UHI intensity will vary with the meteorological situation. This information can help to derive city-wide temperature patterns supported by measurements (Section 5.2) or by model results (Section 6.2). CL-UHI information may also be a valuable input for issuing targeted warnings based on large-scale weather forecasts (Subsection 6.4.2) or for assessing thermal comfort using climate projections (Subsection 6.4.3).

It should be remembered that the CL-UHI intensity indicates the difference in temperature in an urban area relative to a nearby rural area. Thus, changes in rural surface cover (for instance wildfire, rural flooding) influence the CL-UHI intensity without necessarily resulting in higher or lower temperatures in the urban area.

CHAPTER 4. CHARACTERIZATION OF THE URBAN AREA AND ITS SURROUNDINGS

Given that the CL-UHI is defined as the difference between CL-T values in different areas (Section 2.3), the characterization of the region of interest (urban and rural areas) is essential for understanding, measuring, modelling, monitoring (Chapter 5, Chapter 6 and Chapter 7, respectively) and mitigating (Chapter 8) the CL-UHI. Several parameters are needed for characterizing feature types at urban and rural sites in order to provide more complete urban services (Chapter 3). To determine the intensity, location and timing of the maximum CL-UHI, it is advisable to characterize the whole urban area and its surroundings (region of interest, see Section 2.3). As the methods to obtain these parameters require expertise and regular updating, there is an associated cost in terms of time and money.

4.1 TYPES OF PARAMETERS NEEDED

The numerous features to characterize the urban area and its surroundings can be subdivided into four types (Table 4.1) related to: (1) built form, (2) vegetation and other land cover forms, (3) function (human activities), and (4) geographic setting. The parameters vary between and within different cities.

The level of detail should ensure that local-scale variability within the urban area is captured and that for observation sites the microscale variations are monitored over time to ensure appropriate interpretation of observations (Chapter 5). For modelling applications (Chapter 6), this characterization is needed at least at the grid resolution, preferably with more detailed information within each grid cell to estimate the parameter's variability and to provide correct parameters to the model. Without the correct parameters, the model physics cannot provide reliable output. Given the dynamic nature of cities and nearby rural areas, the characteristics must be updated regularly.

4.2 DETAILED PARAMETERS AT MICROSCALE

For characterizing the immediate measurement site surroundings (Section 5.6) or for obstacle-resolving modelling (Subsection 6.1.2) or similar applications, several parameter values (Table 4.1) are needed to reliably describe both the 2D land cover and 3D form as well as the materials. Table 4.2 gives an overview of data sets typically used and possible data sources

Table 4.1. Characteristics to describe urban and rural areas

Feature type	*Built form*	*Vegetation and other land cover forms*	*Function*	*Geographic setting*
Related parameters	Morphology (heights, shape, density, surface covers, roughness) Materials (heat capacity, diffusivity, albedo, emissivity, soil texture)	Morphology (e.g. tree structure) Phenology Soil Water	Land use Emissions (heat, water, aerosols, gases) Human behaviour (e.g. mobility patterns) Transport (e.g. car, motorbike, train)	Terrain (elevation, slope, orientation) Major water bodies Latitude

Table 4.2. Data sources typically used to determine parameters for built, vegetated and other land cover forms at microscale

Built, vegetated and other land cover form (urban form)	*Data sets*	*Data sources*
Morphology – of roughness elements: – Wall area density or frontal area density – View factors – Distance between roughness elements (e.g. width between buildings/trees) – Street directions	– Building inventories – Derived from heights and spacing between roughness elements	– City administration – City planning departments – City parks agencies – Tree advocacy groups (vegetation) – Transport departments (street trees) – City and regional planning GIS
Heights – of roughness elements: – Buildings – Trees – Other	– Stereographic images – LIDAR – Synthetic aperture radar	– City administration – City planning departments – City parks agencies – Tree advocacy groups (vegetation) – Transport departments (street trees) – National agencies
Surface cover: – Horizontal plan area fraction – Impervious: buildings, paved, rocks – Pervious: vegetation (e.g. trees, crops, grass), water, soil	– Satellite or aerial photography – City land use and cover inventories – Google street view	– Cartography departments – City administration
Materials: – Fraction of wall occupied by windows – Radiative characteristics – Thermal characteristics	– Architectural information database – Spectral libraries – Planning regulations by period – Building information systems – Building archetype – Analysis of street-level, aerial or satellite images (e.g. material properties)	– Planning department
Vegetation: – Leaf area index – Phenology – Type	– Satellite or aerial observations – Ground surveys	– City parks agencies – Tree advocacy groups – Crowdsourcing
Soil: – Type – Moisture (dynamic, initial conditions)	– Satellite images – Measured in situ soil profiles	– City database – Model databases
Hydrology: – City water drainage and sewage systems	– Modelled sewage system/ water retention map	– City planning department – Flood planning/protection agencies – Wastewater disposal service of the city

Note: GIS – geographical information system, LIDAR – light detection and ranging.

providing these parameter values. Built, vegetated and other land cover forms are mixed in urban areas (for example street trees) and together shape the urban form (Figure 2.1). While data sets for built form and vegetation are quite different, the data sources are often the same.

In many cities, the planning departments have detailed geographical information systems (GISs) with much of the 3D information needed, so collaboration is mutually beneficial to ensure the urban form information used is current and correct. Many of the morphometric parameters needed can be approximated from existing parameters, using empirical relations for example. If no detailed information is available, parameters need to be taken from the literature, ideally taking the local context into account.

More challenging than obtaining morphology or height data (Table 4.2) is obtaining the material characteristics which influence radiative characteristics (for example albedo, emissivity) and thermal characteristics (for example thermal conductivity, admittance, density) at microscale resolution. Information exists for many new buildings today. However, the construction process may cause, for example, thermal contacts, or maintenance may result in building surfaces being cleaned or not cleaned, so that the existing information is not fully applicable to the existing building. Furthermore, surface characteristics, most importantly albedo, may be changed by deposition of aerosols and dust. At the building scale, large window fractions and their thermal properties (for example, heat transfer coefficient and emissivity) impact heating, cooling and ventilation. Several methods can be used to estimate architectural information (Masson et al., 2020). One example is the use of street-level, aerial or satellite remote sensing images to determine materials like thermal and radiative properties, which can benefit from crowdsourcing (for example, as done in Tunis, Tunisia (Mhedhbi et al., 2019)). Table 4.3 gives an overview of how people's activities influence the functioning of cities and the data sets typically used to capture these.

Despite their local-scale resolution (Table 4.4), land-use data provide some information about when and how an area is likely to be occupied (for instance residential versus commercial). Microscale data are preferable, but often not available. Other issues to consider for determining parameters at the microscale include the following:

- Vegetation data tend to be biased by their sources. For example, the city GIS may have a good record of large street and park trees but lack data for private properties. Required urban vegetation parameters are similar to those for buildings (for example heights, areal extent by type), but leaf area index and phenology are additionally required. Similar techniques are used for the built form (Table 4.2).

- Timing is important (such as of crop rotations, typical work days and times, snow clearing patterns).

- At middle and high latitudes, anthropogenic heat emissions due to space heating may be larger than the energy input by net all-wave radiation in winter.

- In cities with extensive air conditioning, extraction of heat from buildings and emission to the urban atmosphere can increase the CL-UHI intensity by ~1 K (Takane et al., 2019).

- Some industries inject large amounts of heat into the atmosphere.

- Heat release from transport can be important near large roads or at local openings of metro lines.

- Water removal from impervious surfaces after rainfall events may result in large amounts of heat being moved to the storm water and sewage infrastructure. With nature-based solutions (see Section 8.2) being advocated, new rainwater retention areas are created influencing latent heat fluxes in urban areas. As this adaptation approach for cities to climate change is increasingly applied, the areal extent and location of the nature-based solutions need to be regularly updated, for instance in city GIS databases, and used.

Table 4.3. Data sources typically used to determine parameters to account for human activities that can characterize urban function. These need to be determined for the appropriate scale.

Function	*Data sets*	*Data sources*
Land use	– City and regional planning maps	– City administration – Agricultural department (rural crops) – Copernicus, USGS for regional
Anthropogenic emissions – Energy use – Heat emission	– Fuel consumption data – Building construction data – Socioeconomic characteristics	– Energy department/companies – Transport department/companies
– Gas and particle emissions to air or water	– Emission inventory	– Government/local agencies with different responsibilities which may vary with source type (e.g. industrial, residential, transport) – Environmental agencies, which may mandate activities
– Water	– Emission inventory	– Companies or local government agencies that supply water – Government agencies, which may limit permitted uses (e.g. hose-pipe or irrigation bans or restrictions)
– Building usage (offices, homes) – Heating and air conditioning (usage pattern) – Ventilation	– People's activity patterns – Census data (home, work population) at small spatial units – Typical work/home/ recreation patterns – Building information systems – Work related activities	– Crowdsourcing – Planning department – Energy regulators – Public transport providers
Transport – Public transport (bus, subway, etc.) – Car (types) – Biking – Walking	– Fuel consumption data – Socioeconomic characteristics – People's activity patterns	– Energy department/companies – Transport department/companies – Crowdsourcing – Planning department

Note: CORINE – Coordination of Information on the Environment (European Union programme), USGS – United States Geological Survey.

Table 4.4. Data sources typically used to determine parameters for functions at local scale

Function	*Data sets*	*Data sources*
Land use	– City and regional planning maps – CORINE land cover data (Europe) – Copernicus Global Land Cover – USGS maps – LCZ	– City administration – Agricultural department (rural crops) – https://land.copernicus.eu/pan-european/corine-land-cover – https://land.copernicus.eu/global/content/annual-100m-global-land-cover-maps-available – https://www.usgs.gov/search?keywords=Land%20Cover – https://www.wudapt.org/lcz-maps/
Anthropogenic heat emission	Statistical data: – Energy consumption – House types – House insolation status	– National/county/city administration data sets – National/county statistical offices
Further data:	– Table 4.3	– Table 4.3

Note: LCZ – Local Climate Zone (Figure 4.1).

– Microscale data should be updated if major changes occur, and should be checked at least every 5 years, if not rapidly changing, but more frequently in periods of development and gentrification.

For the rural surroundings, similar data are required as for the urban area (Table 4.2), but the potential partner agencies may use different techniques to gather these data. The proportion of individual land cover types will vary throughout the year and from year to year, and with that, the heights of roughness elements such as crops and trees that are essential to characterize the microscale. In these areas, the most critical parameters are likely related to vegetation (type, phenology, leaf area index), soil type, soil moisture condition and water bodies.

Water balance modelling accounting for both precipitation and irrigation can provide soil moisture conditions. Spatial and seasonal variations of soil moisture impact both urban and rural areas, and both urban and rural soils may or may not be irrigated depending on human activities. For example, in very dry regions the urban area may have moist soils, while the rural region may be more spatially variable in terms of humidity conditions, resulting in very different CL-UHIs depending on the rural reference used.

4.3 CHARACTERIZATION AT THE LOCAL SCALE

A useful starting point for characterizing the region of interest at local scale may be to map the urban area and its surroundings into areas with similar characteristics using one of the many existing classifications for urban and rural areas. For example, land use, such as residential, commercial, agriculture, forest, transportation (Table 4.4), is frequently used for this purpose (land use is one of the functions in Table 4.1). The attributes derived from a classification depend on the intended use of the data. The data are one input for mesoscale models (Subsection 6.1.3). Many global maps of land use only have one urban class, whereas others may provide several classes, for example the Urban Atlas (European Environment Agency, 2021).

To estimate anthropogenic heat emissions at local scale (Table 4.4), two general approaches are used (Sailor, 2011):

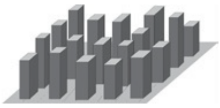
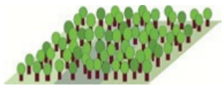
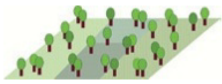
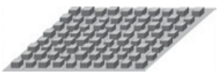
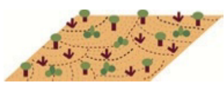
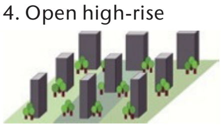
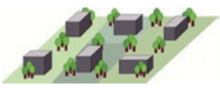
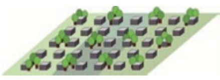
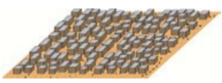
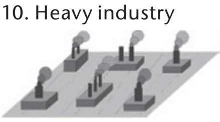
– **Top-down inventories**: Large-scale (mesoscale or larger) energy consumption information is disaggregated to local scale using ancillary data. These may be building data or local-scale annual consumption data. The large-scale data may be available for the whole urban area or the country with time intervals such as 30 min allowing for example assessment of heating/air conditioning responses to regional temperatures.

– **Bottom-up inventories**: Components (buildings, vehicles, people) are individually simulated and then aggregated to the desired scales (Capel-Timms et al., 2020).

Both approaches require data about the structure of the urban area (urban form) and how people use the urban area (function). These data can be challenging to obtain. As data may be different between administrative units, harmonization will likely be required.

One local zone classification scheme designed for UHI studies characterizing urban form and considering urban function is the Local Climate Zone (LCZ) scheme created by Stewart and Oke (2012) (Figure 4.1). The scheme divides urban and rural landscapes into 17 classes, of which seven are land cover types (LCZs A–G) and 10 are built types (LCZs 1–10). Each class describes a relatively uniform landscape with a distinct land cover and built form, though not necessarily a distinct thermal climate.

The LCZ classification is widely used by the urban climate community and interpretable by urban planners and city administration, as it is based on form (built types in Figure 4.1) and function (land cover types in Figure 4.1). The LCZ scheme serves many purposes, of which the main ones are: (i) the general classification of neighbourhoods where meteorological stations are installed (Chapter 5); (ii) the specification of surface parameter values for atmospheric models; and (iii) the exchange of urban climate knowledge with city planners.

Built types	*Definition*	*Land cover types*	*Definition*
1. Compact high-rise 	Dense mix of tall buildings to tens of stories. Few or no trees. Land cover mostly paved. Concrete, steel, stone, and glass construction materials.	A. Dense trees 	Heavily wooded landscape of deciduous and/or evergreen trees. Land cover mostly pervious (low plants). Zone function is natural forest, tree cultivation, or urban park.
2. Compact midrise 	Dense mix of midrise buildings (3–9 stories). Few or no trees. Land cover mostly paved. Stone, brick, tile, and concrete construction materials.	B. Scattered trees 	Lightly wooded landscape of deciduous and/or evergreen trees. Land cover mostly pervious (low plants). Zone function is natural forest, tree cultivation, or urban park.
3. Compact low-rise 	Dense mix of low-rise buildings (1–3 stories). Few or no trees. Land cover mostly paved. Stone, brick, tile, and concrete construction materials.	C. Bush, scrub 	Open arrangement of bushes, shrubs, and short, woody trees. Land cover mostly pervious (bare soil or sand). Zone function is natural scrubland or agriculture.
4. Open high-rise 	Open arrangement of tall buildings to tens of stories. Abundance of pervious land cover (low plants, scattered trees). Concrete, steel, stone, and glass construction materials.	D. Low plants 	Featureless landscape of grass or herbaceous plants/crops. Few or no trees. Zone function is natural grassland, agriculture, or urban park.
5. Open midrise 	Open arrangement of midrise buildings (3–9 stories). Abundance of pervious land cover (low plants, scattered trees). Concrete, steel, stone, and glass construction materials.	E. Bare rock or paved 	Featureless landscape of rock or paved cover. Few or no trees or plants. Zone function is natural desert (rock) or urban transportation.
6. Open low-rise 	Open arrangement of low-rise buildings (1–3 stories). Abundance of pervious land cover (low plants, scattered trees). Wood, brick, stone, tile, and concrete construction materials.	F. Bare soil or sand 	Featureless landscape of soil or sand cover. Few or no trees or plants. Zone function is natural desert or agriculture.
7. Lightweight low-rise 	Dense mix of single-story buildings. Few or no trees. Land cover mostly hard-packed. Lightweight construction materials (e.g., wood, thatch, corrugated metal).	G. Water 	Large, open water bodies such as seas and lakes, or small bodies such as rivers, reservoirs, and lagoons.
8. Large low-rise 	Open arrangement of large low-rise buildings (1–3 stories). Few or no trees. Land cover mostly paved. Steel, concrete, metal, and stone construction materials.		
9. Sparsely built 	Sparse arrangement of small or medium-sized buildings in a natural setting. Abundance of pervious land cover (low plants, scattered trees).		
10. Heavy industry 	Low-rise and midrise industrial structures (towers, tanks, stacks). Few or no trees. Land cover mostly paved or hard-packed. Metal, steel, and concrete construction materials.		

VARIABLE LAND COVER PROPERTIES

Variable or ephemeral land cover properties that change significantly with synoptic weather patterns, agricultural practices, and/or seasonal cycles.

b. bare trees	Leafless deciduous trees (e.g., winter). Increased sky view factor. Reduced albedo.
s. snow cover	Snow cover >10 cm in depth. Low admittance. High albedo.
d. dry ground	Parched soil. Low admittance. Large Bowen ratio. Increased albedo.
w. wet ground	Waterlogged soil. High admittance. Small Bowen ratio. Reduced albedo.

Figure 4.1. Local Climate Zones (LCZs) to characterize the land cover and surface structure of urban and rural areas

Source: Stewart and Oke (2012) © American Meteorological Society. Used with permission.

A popular means to implement the scheme in urban climate work is through LCZ mapping. LCZ maps can be produced in multiple ways but ideally should be comparable when finished. For example, satellite imagery is used by the World Urban Database and Access Portal Tool (WUDAPT) (Ching et al., 2018), while Open Street Map (Coast, 2015; www.openstreetmap.org) is used by other investigators. A global LCZ map produced by Demuzere et al. (2022) is freely available.

It should be noted that characterizations at local scale (Table 4.4) currently do not include spatial detail within the pixel. Calculating all urban parameters in detail as needed for the microscale (4.2), either for characterization of observations (Chapter 5) or for obstacle-resolving models (Subsection 6.1.2), may be difficult or impossible from these data, because of their insufficient resolutions of ~100 m (for example, CORINE Land Cover data for Europe, Copernicus Global Land Cover). In even coarser resolution (~1 km), several additional data sets, such as for leaf area index, can be obtained from Copernicus or the USGS. For characterizing the direct surroundings of a measurement site (Section 5.6) or for obstacle-resolving modelling applications (Subsection 6.1.2) or similar applications, these local data sets provide insufficient spatial accuracy.

4.5 REGIONAL TOPOGRAPHIC CHARACTERIZATION RELEVANT FOR THE CL-UHI

The geographic setting of the city is important and influences the CL-UHI intensity (see description of orography effects in Subsection 2.5.5). This can include relative terrain differences, the presence of large water bodies (including the ocean) and the potential impact of ocean currents. Even small variations in altitude in the region of interest need to be accounted for (Section 5.2). To perform corrections or consider uncertainties induced by the geographic setting when interpreting the CL-UHI, the geographic location of major water bodies and altitudes have to be determined and documented for the whole region of interest. In addition, regional influences of water bodies and topography on air flows and temperature distributions from outside the region of interest should be assessed to ensure that the determined CL-UHI intensities are really caused by an urban effect and not by the topographic conditions.

4.6 MAIN ASPECTS FOR CHARACTERIZING URBAN AREAS IN BRIEF

If the CL-UHI is only determined for a pair of observation sites (urban and rural), only microscale details are needed and the CL-UHI is only assessed for this pair of sites (see information on site selection in Section 5.4). Local-scale information helps to assess if the CL-UHI might have similar values in other parts of the city. On the other hand, when the whole region, with its true spatial variability, needs to be assessed, local-scale spatial data are needed for the whole region of interest. Examples are CL-UHI forecasts (Subsection 6.4.2), assessment of a future climate CL-UHI (Subsection 6.4.3), urban development and the CL-UHI (Subsection 6.4.4), urban services (Chapter 3) or mitigation of the CL-UHI (Chapter 8).

CHAPTER 5. DETERMINING THE CL-UHI FROM OBSERVATIONS

5.1 BACKGROUND ON MEASUREMENTS

As cities expand and the absolute number of people living in cities grows, meteorological stations that provide regular observations of the urban thermal conditions become increasingly important. Given the complexities of the UCL (Section 2.2), it is difficult to make observations in the UCL with a large spatial and temporal representativeness. Most urban stations do not conform to the WMO standard guidelines for site selection and instrument exposure applicable to flat and homogeneous terrain (*Guide to Instruments and Methods of Observation* (WMO-No. 8), Volume I: Measurement of Meteorological Variables); instead, the guidelines for the urban environment need to be considered (*Guide to Instruments and Methods of Observation* (WMO-No. 8), Volume III: Observing Systems, Chapter 9). Despite the complexity and inhomogeneity of urban environments, useful and repeatable observations can be obtained by careful experimental design that reduces uncertainties and thereby enhances the value of observations. The challenge of measuring the CL-UHI and the many aspects to be considered are the focus of this chapter.

5.2 CALCULATION OF THE CL-UHI INTENSITY FROM URBAN AND RURAL OBSERVATIONS

The challenge posed is to isolate the urban effect in the observations. Although CL-UHI intensity appears to be the simple temperature difference between an urban and a rural measurement site (Section 2.3), establishing its intensity accurately requires the removal of several confounding effects. The air temperature is influenced by processes at multiple scales (Chapter 2), including the weather conditions (Subsection 2.5.4) and geographic setting Subsection 2.5.5), which complicate the detection of the urban effect as the CL-UHI, particularly over long time periods in which one or more influencing factors are likely changing.

If the regional climate remained 'constant', the urban influence on temperature could be most directly assessed from a continuous set of synchronous observations at reference sites that respond to urban development. If the measurements began prior to any urban development, then a 'true' urban signal could be obtained. Such opportunities rarely exist and, furthermore, climate changes; thus, temperature values taken in an urban area and compared with values at the same place before urbanization include both the urban and the climate change signal. Thus, pragmatically, the urban effect is estimated from the difference in simultaneously observed temperatures at carefully selected urban and rural sites.

Details on how to choose the sites are provided in Section 5.4. In particular, the use of a rural reference (Subsection 5.4.1) poses some conceptual issues (Oke et al., 2017). From the perspective of the CL-UHI, these include the following:

- Measurements in the rural area are not equivalent to pre-urban values.
- As the rural area is not static, the urban–rural difference can change through time without urban changes.
- Rural stations may be affected by advection of warmer air from the urban area.
- Rural and urban sensors must be exposed to the same regional climate, for example they should be placed at the same distance from the coast.
- Rural and urban sensors should be placed at the same altitude and height above ground.

– At both urban and rural sites, careful consideration of sensor location is required, recognizing that the surface characteristics and wind variabilities that influence temperature at both sites will have spatial variability. This variability is particularly marked in urban areas, resulting in temperatures that generally vary more rapidly in space and time compared to temperatures in a rural environment.

As air temperature decreases in a well-mixed boundary layer without phase changes with a dry adiabatic lapse rate of about 1 K per 100 m, a height-based altitude correction is needed for all the urban and rural reference sensors used to estimate the CL-UHI. This avoids systematic errors while analysing differences between stations at different altitudes.

5.3 MEASUREMENT APPROACHES

Although there are no clear guidelines, the use case and metric under investigation (Table 2.2) largely determine how many stations are required. This section outlines four distinct but complementary approaches. Examples of network layouts are provided in Appendix 2.

5.3.1 Single pair of sites

One way to determine the CL-UHI is to use ground-based **fixed stations**. This allows the assessment of temporal variations on a continuous and long-term basis. Careful consideration should be given to which metrics are needed for the use cases (Table 2.2). If only one pair of sites is to be selected it is critical to acknowledge that an urban site truly representative of the urban area does not exist, as microscale and local impacts always occur (Section 5.4). Reference WMO sites in green spaces, over grass, or at semi-urban locations will at best only partially represent urban effects. Although a site may be maintained for decades with the same microscale exposure (facet-scale, 10 m), there is often no control over changes in the larger area around the site which will affect the observed near-surface temperatures and thus the derived CL-UHI intensities. This highlights the essential need to regularly update station metadata (Section 5.6). Sites with instruments on rooftops exist in some cities, but these locations are too high to monitor the CL-UHI (Subsection 5.4.5).

If the goal is to establish the temporal variations of the maximum CL-UHI in the urban area, one urban station may suffice after appropriate preparatory observations (for example traverses, see Subsection 5.3.2). Classifying neighbourhoods, for example using LCZs (Section 4.3), can provide initial guidance to select possible sites to obtain this metric. Other use cases where a single site may be appropriate include monitoring the impact of a particular neighbourhood, such as the LCZ with the greatest extent in an urban area, assessing a site before and after development or assessing the CL-UHI of a neighbourhood with a population vulnerable to potential excessive heat (Section 3.1). However, one urban station will not capture spatial differences in the CL-UHI, and it will be extremely challenging to justify the representativeness of one site without undertaking traverses or considering measurements at other sites.

5.3.2 Traverse approach

Suitable location(s) to install sensors to measure the CL-UHI can be derived by mobile surveys to identify the spatial variations of air temperature in response to variations in urban and rural characteristics. Any mobile platform can be used for such **traverse approaches**, including a person, bicycle, automobile, truck or public transport vehicle, as long as care is taken that the instrument location on the mobile platform will not introduce unnecessary errors into the measurements (Subsection 5.5.3). Drones are generally not helpful, since a flight level of 1.25–2 m AGL is likely to be difficult and permissions are hard to obtain in cities. However, in rural areas there may be greater opportunity to use them as it will be easier for the pilot to maintain eye contact with the drone.

A common approach is to use an out and back traverse that samples the same route in two directions. Traverse routes can be designed to sample selected neighbourhoods to identify the major features of the CL-UHI with sample points also in the rural surroundings. Using multiple mobile platforms simultaneously allows for greater spatial coverage and better resolution of spatial patterns. Using a single sensor in the traverse approach has the advantage of avoiding inter-instrument comparison issues. It is limited by the need to apply temporal corrections for the temperature changes that occur in the time required to complete the traverse. These might be considerable around sunrise or sunset. The design of traverse routes should limit the total traverse time to approximately 1 hour, otherwise temperature and weather will have changed, potentially making uncertainties and magnitudes of the temporal corrections large compared to the spatial differences of temperature.

A common starting point and end point are essential to allow estimation of a linear rate of change of temperature occurring during the traverse. If the platform speed is approximately constant and the rate of change in temperature with time is linear, the average of the outbound and inbound points provides a simple and sufficiently accurate correction. More complex corrections may use data taken at network stations (Subsection 5.3.3) or be based on repeated measurements of more points over the traverse to determine the temperature changes associated with different land cover types (Section 4.3). After correcting for temporal effects, the data can then be mapped to show the spatial variation of temperature.

When the traverse is carried out using a vehicle, temperature readings must be made with sensors that have a rapid response time, sufficient to register changes caused by spatial variations such as a local park. This is quite difficult to achieve in practice: considering that even at a moderate speed of 36 km hr^{-1} a vehicle covers a distance of 10 m s^{-1}, there are few temperature sensors that can record temperature differences that occur over distances of this order of magnitude.

Each mobile platform type is limited in terms of the locations it can access (for example it may be limited to the road or footpath network), hence many areas may not be accessible to a particular mobile platform (for instance private property). To detect maximum CL-UHI values, traverses are best conducted at night, typically some hours after sunset or before sunrise, when winds are calm and skies are clear (Subsection 2.5.3).

5.3.3 **Meteorological networks**

A network of urban and rural stations can provide information about the spatial character of the CL-UHI. Each site in an urban meteorological network needs to adhere to the guidance in the present publication. It is critical to select sites that are representative (Section 5.4), and that site metadata (Section 5.6) be gathered regularly to ensure appropriate interpretation. With enough sites, the spatial form of the CL-UHI intensity emerges and different metrics can be determined. Weather station costs have decreased markedly over the last couple of decades, making it now possible to deploy relatively dense networks of weather stations across cities provided space is available. There is a growing body of examples of urban meteorological networks now deployed across the world, utilizing a range of deployment strategies (some examples are provided in Appendix 2). However, the ongoing costs of maintenance and governance of large networks have led to opportunistic approaches (Subsection 5.3.4) being explored as an alternative for monitoring. In addition, university research networks were set up in places such as Birmingham (Chapman et al., 2015), Hamburg (Wiesner et al., 2014) or Oklahoma City (Hu et al., 2016). Full weather stations are not required for CL-UHI estimation, and adding more temperature sensors to measure just air temperature can provide useful additional information.

5.3.4 **Opportunistic sensing – crowdsourcing**

Beyond traditional, planned urban meteorological networks, a range of techniques is available for opportunistic sensing (see Muller et al., 2015 for a summary), including crowdsourcing, citizen (or public) science weather stations, connected vehicles and mobile phone data. Each can provide abundant low-cost (effectively free) data potentially with high density compared to traditional meteorological networks. However, they need quality control that includes corrections for instrument and measurement errors (Section 5.5) and attribution of the thermal source area that they measure (Subsection 5.4.3). It is often difficult or impossible to obtain relevant metadata (Section 5.6).

Citizen science stations run by weather enthusiasts arguably provide a viable option for temperature data, though a challenge is often discoverability as there are many companies that provide interfaces to data from their own sensors but not from others. As these free data are collected via multiple platforms, some of which are well maintained and include metadata, they can significantly increase the number of CL-T measurement points in a city (Chapman et al., 2017). Likewise, data from sensors installed as standard equipment in vehicles are increasingly available, but both sensor location on the vehicle and data protection regulations can make some data unusable or inaccessible. For both citizen science weather stations and vehicles, the meteorological community has been actively involved in assessing their utility with efforts to assimilate the data to enhance forecast efforts. There is a potential to estimate air temperatures from mobile phone battery temperature data, but this is arguably the least reliable approach.

Despite the dense spatial coverage, data need to be checked (outliers, noise) and preferably statistically analysed to provide anything meaningful, with the only benefit so far being at city-scale. Geostatistical or machine learning techniques may potentially be transformative in the future and provide usable temperature patterns, but data protection regulations and metadata issues will remain.

At the time of writing of the present publication, the use of crowdsourcing data is recommended only with great caution, and only to complement other sources.

5.4 CHOOSING A SITE

5.4.1 Selection of rural reference sites

As rural reference sites used to assess the CL-UHI also have their own microclimates, their placement needs careful consideration. A siting classification can be found in Annex 1.D of *Guide to Instruments and Methods of Observation* (WMO-No. 8), Volume I: Measurement of Meteorological Variables. The LCZ scheme (Section 4.3) allows rural areas as well as urban ones to be locally characterized. Choosing a site that is representative of one LCZ is challenging, as the spatial variability within one may be as great as within the urban area. Furthermore, agricultural areas undergo seasonal changes that will affect urban–rural differences, as does the vegetation around rural reference sites. In addition, agriculture creates some side effects influencing the CL-UHI, as there is a drastic difference in rural temperatures caused by the varying degrees of vegetation cover, irrigation rates and concentrations of atmospheric aerosols. This will change the apparent urban–rural temperature difference without any changes in the urban area. Information on vegetation type and phenology helps to interpret the measured temperatures. Thus, as in the urban area, the characterization of the rural area needs to be both detailed and regularly updated (see *Guide to Instruments and Methods of Observation* (WMO-No. 8), Volume I: Measurement of Meteorological Variables, Annex 1.F), and include phenology information (Section 5.6).

Rural sites are prone to advection from urban areas. It is impossible to know the exact spatial extent of the downwind urban thermal anomaly, but a rural station may be affected by the advection of warmer air from the urban area (see description of thermal source area in Subsection 5.4.3). Rural sites in the dominant upwind direction are therefore preferred and can be identified using wind rose data derived from long-term data from an operational meteorological station nearby. If selecting multiple sites, locations perpendicular to the prevailing wind direction can also be considered. For coastal cities, rural reference sites are ideally located at a similar distance from the coastline as the urban site to avoid different advective effects arising from sea/land breezes. In more mountainous or hilly areas, reference sites are ideally situated at similar altitudes to that of the urban site. They should not be sited in areas where they would be differentially impacted by topographically influenced winds, exposure to the sun and/or temperature stratifications (Subsection 2.5.5).

Temperature measurements from an urban park may be used to assess intra-urban temperature variability, but urban parks do not qualify as true rural reference sites for determining the CL-UHI. Similarly, an airport sensor must be carefully assessed for its ability to be a true rural reference, as airports are characterized by extensive impervious areas, have anthropogenic activity and often have significant urban-like development surrounding them.

5.4.2 Purpose of the urban station

Site selection requires an initial definition of the **purpose** of the station: the use case has to be clear (Table 2.2). Consideration should be given to the following questions:

- Is the station intended to characterize the greatest impact of the urban area on temperature and the CL-UHI (use cases such as weather forecasting or research)?
- Is the station targeting the area in the city with the highest population (use cases such as energy use or health impact)?
- Is the station intended to represent a block, a neighbourhood or a larger urban area (use cases such as climate monitoring or urban design)?
- Is the station part of a meteorological network intended to define the intra-urban temperature variability for specific neighbourhoods and the associated spatial structure of the CL-UHI (use cases such as health impact or agricultural applications)?
- Is the station targeting a particular site (for instance intended for development or redevelopment) or is it intended to characterize a particular environmental issue or issues (use cases such as ecology and vegetation or atmospheric chemistry)?
- Is the station intended to be in place for a short experiment or for a long period of time (longitudinal study), potentially before and after heat mitigation interventions are put in place (use cases such as urban design and planning or energy use)?

The specific siting of the station should consider the local land cover mix it is intended to represent and the thermal source area (Subsection 5.4.3). Typically, local-scale representativeness is intended (Section 2.2); for this purpose large patches of relatively homogeneous urban development are required, with minimum microscale influences for instance from facets, buildings or urban canyons. In addition, if the aim is to monitor the local urban effects, then mesoscale influences such as cold air drainage, river valleys or shoreline locations must be carefully evaluated. As local-scale cold air drainage effects can exist and influence both urban and rural sites, there is a need to consider whether they should be captured within a site setting, or not. If a potential location is too heterogeneous to derive locally representative values or has anomalous microscale features that may distort the signal, it is advised to find a more homogeneous setting for observations. The station may be classified according to *Guide to Instruments and Methods of Observation* (WMO-No. 8), Volume I: Measurement of Meteorological Variables, Annex 1.D; sites should be preferably restricted to Classes 1–3.

5.4.3 Thermal source areas

The temperature recorded by a sensor depends on the conditions along the back trajectory of air parcels reaching the sensor; this area is named thermal source area. Interactions with various different urban surfaces and facets generate the observed temperature characteristics. Turbulent mixing with ambient air dampens these characteristics and diminishes the effect of distant surfaces. Accordingly, the measured temperature originates from multiple surfaces at an area upstream of the sensor location defined as thermal source area, or footprint (Figure 5.1).

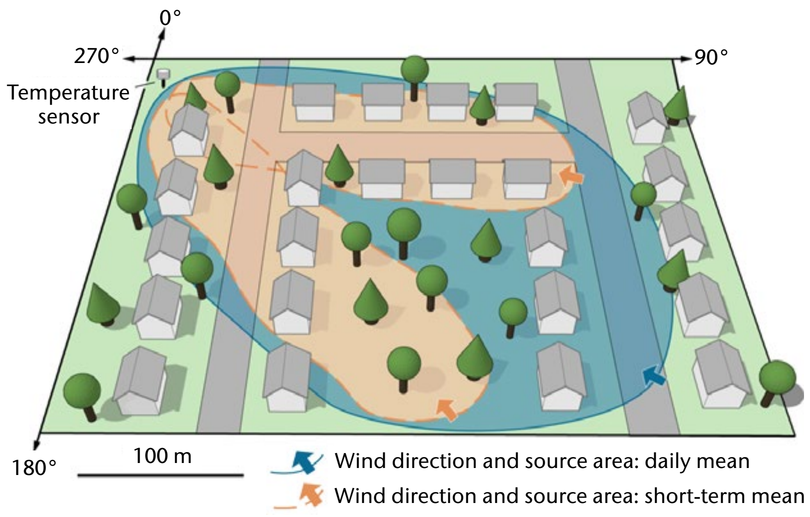


Figure 5.1. Neighbourhood-scale surface projections of hypothetical thermal source areas for a standard screen-level-height temperature sensor. Depicted are two source areas for short-term (<1 h) intervals (orange, dashed lines) and daily mean considering a predominant south-easterly wind direction (blue, solid line).

Source: Adapted from Stewart and Oke (2012). Drawn by K. Van Kerkoerle (University of Western Ontario) with input from J. Voogt and M. Roth.

Conceptually the thermal source area is the total surface area "seen" by the sensor. The size, shape and orientation of the source areas evolve with time and meteorological conditions (turbulent mixing, wind speed and direction). Over short periods (<1 h) the area is roughly elliptical and oriented in the upwind direction from the sensor (orange area in Figure 5.1). Because of temporal changes in wind direction and stability, these areas oscillate around the measurement site so, over time, they form a misshapen "circle" (blue area in Figure 5.1). Surfaces and roughness elements (for instance buildings, trees, street furniture) will also influence the thermal source area, particularly for the near-surface measurements that are needed for determining CL-UHI intensities.

Analytical solutions to quantify the extent of the thermal source area have been developed for homogeneous and isotropic turbulent conditions for the ISL – thus well above the roughness elements (Figure 2.1). These models predict elliptical-shaped source areas with increasing extent for higher wind speed, higher measurement height and more stable conditions. The source areas thus vary with the meteorological conditions, and they are time dependent. The analytical solutions help to determine thermal source areas above the UCL but are not applicable within it as the turbulence is non-homogeneous, and blocking and wakes by buildings substantially modify back trajectories. These effects can only be resolved by computationally demanding obstacle-resolving Reynolds-averaged Navier–Stokes (RANS) or large-eddy simulation (LES) models (Subsection 6.1.2). Their results can be used to calculate more reliable backward trajectories, or they provide information by using an embedded Lagrangian stochastic particle model (LES–LS), or Eulerian passive tracer dispersion model. The resulting source area estimates feature complex structures and will typically differ between nearby positions within an urban canyon and/or among other roughness elements.

Exposing a sensor optimally to monitor effects within one specific neighbourhood, LCZ, or situation of interest is a challenging task. Sufficient upstream fetch with homogeneous and characteristic conditions of the local climate is needed. If no RANS, LES or LES–LS source area calculations are available, analytical models might give some rough guidance. The appropriate orientation of the source area can alternatively also be estimated from long-term wind data for the location, recognizing that the thermal source area size increases with the height of sensor and atmospheric stability. Classification of measured temperature data according to wind direction, wind speed or stability enables a better allocation of the thermal source area. However, the immediate environment of a station remains most important since microscale effects dominate the signal and therefore are an essential part of the metadata (Section 5.6). Sensors located in urban canyons with densely packed buildings have smaller and more poorly defined thermal source areas and smaller areal representativeness compared to those sited in more open zones.

5.4.4 **Sensor positioning for representative measurements of neighbourhoods**

If the thermal modification caused by a particular neighbourhood is of interest, then sites should be surrounded by conditions that are average or typical for the neighbourhood and the microscale setting should be representative of its surface cover, geometry and human activity. The site should be in the centre of an open space where the surroundings' aspect ratio (H/W) is approximately representative of the neighbourhood. To avoid heterogeneous microscale influences in the measurements the following general considerations should be noted (Stewart and Oke, 2012):

– Sensors within the UCL are probably affected by the environment within a radius of up to 500–1 000 m.

– Sensors should be located within a reasonably homogeneous part of the LCZ and away from borders between LCZs with different surface properties.

– Sites with anomalous structure, surface cover, materials or other properties within the thermal source area (Subsection 5.4.3) should be avoided. This applies in particular to unusually moist or dry patches or sites near a concentrated heat source such as a heating plant or an outlet of a heating, ventilation and air conditioning (HVAC) system.

– Sites along a small urban canyon (large aspect ratio H/W) at the same distance from the buildings and with buildings of mostly similar materials (for instance LCZ 1) provide a relatively similar temperature signal, if they are aligned with the street axis and situated on the same side of the street.

– If the site is within an urban canyon, the dimensions (height, width and length) of that canyon should ideally be representative of the surrounding neighbourhood.

– For compact built zones (for instance LCZ 1–3) "representative" implies a sheltered urban canyon with paved ground; for open built zones (for instance LCZ 4–6) it implies an exposed setting with vegetated ground, scattered trees and nearby buildings.

For continuous monitoring, north–south oriented streets are favoured because there is less phase distortion in the temperature signal (from solar radiation), although the daytime course of temperature may be more peaked. However, for some applications, east–west aligned roads might be a better choice to avoid distortions due to prevailing winds or flow channelling effects. If possible, north–south and east–west aligned streets should be observed together.

5.4.5 **Vertical positioning**

For rural stations, the WMO standard screen-level height (see *Guide to Instruments and Methods of Observation* (WMO-No. 8), Volume I: Measurement of Meteorological Variables, Section 2.1.4.2.1) of 1.25–2 m AGL is recommended. Using the same height AGL for urban and rural stations is recommended. As adhering to this guideline may be more difficult in urban areas, it can be relaxed to allow greater heights, considering the vertical character of the temperature gradient in the urban canopy. With the increased turbulence and vertical mixing in the urban environment, often the stratification is neutral with narrow canyons having only slight air temperature gradients (for heights >1 m AGL) through most of the UCL. Therefore, measurement data at 3–5 m AGL are only slightly different from those at the standard screen-level height. In this height range they are beyond easy reach (to prevent vandalism) and are out of the path of vehicles, and they also have a slightly larger thermal source area. The higher measurement heights also ensure greater dilution of vehicle exhaust heat and reduce contamination from dust (see *Guide to Instruments and Methods of Observation* (WMO-No. 8), Volume III: Observing Systems, Chapter 9).

Installing sensors on street poles (such as those holding street lights or road signs) may simplify access, if permissions can be obtained from a single utility provider or authority, and allow a consistent installation height. Some structures may provide access to mains power.

Roofs should be avoided for determining the CL-UHI for most use cases as the sensors installed there do not provide canopy layer temperatures.

5.5 SENSORS

5.5.1 Instruments

There is a wide range of sensors that can measure air temperature (see *Guide to Instruments and Methods of Observation* (WMO-No. 8), Volume I: Measurement of Meteorological Variables, Chapter 2; Foken, 2021), but not all are appropriate to calculate the CL-UHI intensity. Some sensors measure in the wrong part of the vertical structure of the atmosphere (for example radio-acoustic sounding systems (RASSs), microwave radiometers) and/or are too noisy to operate in urban areas without generating complaints from nearby residents (for example sound detecting and ranging (SODAR), RASSs) or do not measure the air temperature (for example LIDAR, satellite measurements of infrared temperature, surface temperature measurements (Section 2.6; Appendix 1)).

Instrument requirements and operation should follow WMO guidelines (*Guide to Instruments and Methods of Observation* (WMO-No. 8), Volume I: Measurement of Meteorological Variables, Chapter 2). Sensors used can include electrical (resistance, semiconductor or thermocouples) or glass thermometers. The latter, while cheap and not reliant on power, can only be operated manually and are therefore not suited for long-term monitoring. Sensors should be calibrated at regular intervals following the guidelines (*Guide to Instruments and Methods of Observation* (WMO-No. 8), Volume I: Measurement of Meteorological Variables, Chapter 2). Calibration in the field when the atmosphere is well mixed, that is, during strong winds, is also acceptable. The response time of the instrument should be sufficient to achieve thermal equilibrium in the environment, but not so long as to mask trends caused by anthropogenic influences.

5.5.2 Radiation shielding and ventilation

Sensors need to be shielded from radiation to permit measurements in the presence of solar radiation. Radiation reflected off sunlit walls, roads or shiny surfaces in the proximity of the sensor can distort the measured signal and hence needs to be effectively blocked out. Since there may not be sufficient space at urban sites to install a Stevenson screen, which is the traditional standard for a naturally aspirated shield, compact radiation shields made of a series of stacked, inverted bowl-shaped plates with an open interior can be used. However, they may introduce differences of up to 2 °C (–1 °C) relative to the Stevenson screen in sunny conditions with light wind (on a calm clear night); smaller sensors are less susceptible to radiant effects than otherwise identical but larger ones (Erell et al., 2005). The shield should also protect the instruments from precipitation while still allowing the free circulation of air.

Since the shield itself can also be a heat source, forced ventilation (or aspiration) is preferred. The latter is important to ensure that the sensor is in equilibrium with the adjacent air. Particularly in sheltered canyon environments when wind speeds may be low, lack of ventilation can result in erroneous readings being caused for instance by radiative errors from nearby sources such as traffic heat or walls. Ideally, sensors should be >3 m from an obstacle to allow for less obstructed airflow. Critically, to avoid sensor-induced biases, similar sensor housings and measurement protocols need to be used across all sites that will be compared.

5.5.3 Mounting and measurement protocol

5.5.3.1 *Fixed sites*

Limited space, numerous regulations and sensor design may restrict mounting options in urban areas. Traditional approaches to protecting stations such as fences may be neither possible nor desirable. If a dedicated space is unavailable, existing urban infrastructure such as street poles can be used to mount small, unobtrusive sensor packages. Care must be taken to avoid mounting options that distort the measured signal. Solar panels, which tend to be prone to vandalism, can be avoided by using a fixed power supply. Free Wi-Fi networks or long-range wide area networks, if available, permit data transfer in real time. Real-time monitoring and automated post-processing allow quick detection of measurement issues, which can help to minimize gaps in the data set.

Measurements should be conducted continuously, if possible. The sampling interval should be at least once every second, and averages should be calculated and reported for 1–10 min periods following the WMO automatic weather station (AWS) guidelines (*Guide to Instruments and Methods of Observation* (WMO-No. 8), Volume I: Measurement of Meteorological Variables, Subsection 2.1.3.3 and Volume V: Quality Assurance and Management of Observing Systems, Subsection 2.1.2). Clearly, for manual systems, longer sampling and reporting intervals are more practical.

Quality control of the recorded data should include tests for step changes to identify and remove erroneous data caused by irregular anthropogenic activities for instance by vehicles stopping at the site, construction work nearby or sun glints from glass at particular times of year at particular solar angles. Real-time or near-real-time monitoring is useful to perform online data quality control and quickly detect issues with the measurements.

Regular maintenance visits should be part of the measurement protocol (Section 5.6), especially if the data are used for monitoring (Chapter 7). The physical condition of the instruments needs to be inspected not only to ensure that they are in their regular operational state but also to check for vandalism. Additional cleaning may be necessary given the prevalence of particulate matter, soot and other air pollution in urban areas that might be deposited onto the sensors and/or radiation shields and thereby affect the readings.

5.5.3.2 *Sensors on mobile platforms*

Sensors mounted on a mobile platform need to avoid heat sources on the scale of facets (10 m) from both the platform and the surroundings such as vehicles or other canopy layer point sources of heat. Detailed wind-tunnel studies, either self-conducted or based on the literature, may be needed to assess appropriate locations on mobile platforms. Mounting sensors to the front, and preferably at some distance out from the platform, should increase the exposure to the ambient air and reduce impacts from platform heat sources (exhaust or motor). A sensor height of 1.5 m or higher avoids the lower-level exhaust emissions from car-type vehicles. Radiation shielding and adequate ventilation are required (Subsection 5.5.2), the latter especially at low vehicle speeds.

The response time of the sensor affects the ability to resolve fine spatial scale temperature differences and their apparent location. A sampling rate of at least once every 1 s using a sensor with a matching response time is recommended; spatial sampling controls are needed to avoid oversampling and a resulting misinterpretation of data when the platform is stopped. Detailed consideration needs to be given to platform speed, spatial heterogeneity and sensor source area. Speeds should not exceed 60 km h^{-1} to avoid dynamic influences on the temperature measurement or these influences need to be corrected.

Traverse data need careful quality assurance and control to check for effects from heat sources linked to the mobile platform that are not representative of the near-surface UCL in general. Temperature spikes might occur associated with vehicle exhaust emissions at intersections when the platform is in proximity (<5 m) to other motorized vehicles. Data analysis needs to consider the sampling frequency in terms of both temporal intervals and the corresponding spatial locations, to consider the representativeness for example of a constant sampling frequency when stopped at a traffic signal. Hence, accurate geo-referencing of the measurements is essential.

5.6 METADATA FOR OBSERVATIONS

Collection and regular reporting of site surroundings metadata is an important part of any measurement programme. Metadata categories are given in *WIGOS Metadata Standard* (WMO-No. 1192) for WIGOS observations. Site metadata describe the location, instrument systems and sensor exposure. They provide the basis to describe the respective urban and rural stations selected to define the CL-UHI as well as for comparisons across different urban and rural sites or to document changes in time with urban development or land use change. Furthermore, metadata are needed to properly interpret CL-UHI intensities across different cities. Metadata are also important for using the data from other agencies or for other urban services, given that there is not always the opportunity to set up new stations, and selection from existing stations may be needed.

Table 5.1 summarizes the recommendations regarding critical quantitative and qualitative metadata that should be collected and updated over time. These relate to the instrumentation, sensor mounting platform and site surroundings at both the microscale and local scale. On all

Table 5.1. Metadata needed to support air temperature measurements for determining the CL-UHI. For all categories, a time series must be collected.

Sensor	*Observing platform*	*Microscale*	*Local-scale*
Manufacturer Model Serial number Maintenance history including cleaning Calibration history Aspiration and shielding Measurement uncertainty, precision and response time of the sensor	Sensor height AGL Sensor distance from the mounting structure Platform location Platform type Platform porosity Sensor orientation Surfaces underlying individual instruments Sky view factor Ground view factor	Height AGL Relation to local-scale area Surface cover (built-up, paved, vegetated, bare soil, water) Structure (dimensions of buildings and spaces between them, street widths and street spacing) Fabric (construction and natural materials) Human activity (emissions of heat, water, pollutants) Vegetation and phenology Short-term changes (e.g. construction activity, road works)	Topographic setting of the site (including altitude) Relation to the larger urban area Distance to major changes in surface character Distance and direction to major geographic features (e.g. water bodies, hills, valleys, swamps, deserts, forests) LCZ class (Section 4.3) Surface cover fractions (built-up, paved, vegetated, bare soil, water) Structure (dimensions of buildings and spaces between them, street widths and street spacing) Fabric (construction and natural materials) Human activity (emissions of heat, water, pollutants) Vegetation and phenology Short-term changes (e.g. construction activity, road works)

site visits, photographs should be taken of the instruments, platform and surroundings so that changes are documented. It may not be until sometime later that an aberrant measurement is discovered, for instance related to a small but influential change in sensor exposure, such as new windows casting a sun glint, vegetation phenology or growth. Photographic records can help to explain why the change likely occurred; however, permanent photography might not be possible due to privacy restrictions. All metadata need to be updated over time, especially after significant changes in the microscale or local-scale surroundings.

5.7 DATA TRANSFER AND AVAILABILITY

Transfer of raw data from the sensor to the storage will ideally be automated but may need to be manual if a data network such as the mobile phone network or Wi-Fi is unavailable. Data stored locally on a data logger should be downloaded regularly (for instance hourly (automatic), daily (automatic), monthly (manual)). Frequent downloads are needed for many IUS and multi-hazard early warning systems (Section 3.5) to allow use of the data in near real time but may be costly. Automated downloads reduce the probability of poor or missing data as real-time checks and quality control can occur, facilitating rapid repair if necessary. In some cases, advanced "edge computing" capabilities may enable data storage, quality control and compression to happen at the station (edge) rather than at a central computer so that processed data can be transmitted more efficiently.

To ease data use, following the variable naming and format in the *Guide to the WMO Information System* (WMO-No. 1061) and the *Manual on the WMO Information System* (WMO-No. 1060) may help to ensure standardization in data, information and communication procedures.

5.8 OBSERVATIONAL CHALLENGES IN BRIEF

The wide range of measurement techniques that exist for measuring atmospheric and other closely linked variables such as those related to soil, hydrology or vegetation are relevant to the urban environment (Foken, 2021) and the rural comparisons site(s) (see Subsection 5.4.1). It is important to choose a suitable type of sensor, with the appropriate type of shielding (see Section 5.5 and *Guide to Instruments and Methods of Observation* (WMO-No. 8), Volume I: Measurement of Meteorological Variables) at the appropriate site (Section 5.4). As noted (Section 5.3), lack of awareness of how a sensor operates and therefore of the thermal source area the sensor will represent (Subsection 5.4.3), or lack of consideration of the original objective in siting a sensor in a particular location (Section 5.4), will lead to results for the CL-UHI values that are not helpful in the use case considered (Table 2.2), even if the sensor is an excellent instrument.

The LCZs (Figure 4.1) were originally designed to allow a global, cross-cultural description of the neighbourhood area surrounding a measurement site to aid interpretation of the CL-UHI observed (Stewart and Oke, 2012). It is essential to consider neighbourhood scale, but the microscale also needs consideration as poor siting (for example, a site with too much influence from close-by facets) will make the LCZ consideration irrelevant. As the atmosphere has larger spatial variability close to the surface, the central task is to ensure good microscale siting for investigating the process of interest (Section 5.4). This is challenging in cities because of the wide range of materials and facets nearby.

There are numerous reasons to undertake observations within urban areas, beyond observing the CL-UHI (for instance wind, humidity, radiation). Some of these additional measurements may be very helpful for purposes related to the CL-UHI including bio-meteorological indices (Subsection 3.1.1), data assimilation (Subsection 6.1.3), model evaluation (Section 6.3), interpretation of CL-UHI data, or for supporting other needs for an IUS (Section 3.5). If the data taken for CL-UHI assessments are to be used for another purpose than that for which they were originally intended, consideration needs to be given to whether the new purpose is an appropriate use of these data. The site selection, sensor, metadata and other details need to be reviewed in light of this. Therefore, metadata are essential (Section 5.6).

CHAPTER 6. DETERMINING THE CL-UHI WITH MATHEMATICAL MODELS

There are three mathematical model types to simulate CL-UHI intensities (Section 6.1): statistical, obstacle-resolving and numerical weather prediction (NWP) models. With many numerical models, numerous processes that cause the CL-UHI can be modelled through time in conjunction with the regional-scale heat, moisture and momentum exchange between surfaces, UCL, UBL and rural PBL. However, like observed data, numerical models have limitations that make these tools only applicable for specific purposes and scales. Not every CL-UHI metric can be calculated with every model type (Table 6.1). Any attempt to simulate the CL-UHI with atmospheric models parameterizing urban effects will need to consider multi-scale effects. These can be included either explicitly (model domain corresponding to region of interest), through nesting, or by employing stretched grids. With models that have been previously evaluated for the intended application range and the metric to be used (Section 6.3), short-term assessments as well as those related to climate or urban development are possible (Section 6.4).

6.1 MODEL TYPES

6.1.1 Statistical models

Statistical relations for the CL-UHI dependence on both meteorological conditions and morphological characteristics are widely used. The statistical models construct spatial and temporal characteristics of the CL-UHI from environmental parameters and require only small computational costs. Models may be applied using few observations, however model development benefits from large, high-quality, long-term data sets within both the urban and rural areas (Hu et al., 2016). Observations can include multi-scale atmospheric processes that are not only surface driven. Meteorological data, such as for wind speed and cloudiness, are needed to derive reliable statistical models for CL-UHI assessment.

The predictor variables may be determined through a variety of artificial intelligence/machine learning/statistical techniques, including regression analysis (Wilby, 2003) and neural networks. The temporal variability of the CL-UHI may be calculated using local meteorological variables such as near-surface wind speed, cloud cover, near-surface humidity or synoptic-scale weather patterns, yielding an explained variance of 50% and above. To refine the spatial pattern of the CL-UHI beyond the observations, morphological parameters (for example building height or building density, land use, land cover, surface roughness), material characteristics (for example albedo, thermal capacity), and geographical factors (for example terrain height and form, distance to water bodies) are employed.

Combining statistical CL-UHI models with NWP (Subsection 6.1.3) can extend the use of the statistical model, for instance by helping identify situations that increase or weaken the intensity of the CL-UHI using local weather types and using this for a forecast.

Limitations of statistical models include the following (summarized in Section 6.2):

- There is a need for long-term, high-quality training data for developing the statistical relation.

- As the CL-UHI is relatively independent of CL-T, but depends on meteorological conditions and location, these other data such as wind speed and radiation (Section 2.5) are needed at the site of the air temperature observations or a station nearby.

- The applications to scenarios are limited to situations either covered by previous data or consistent with data used for training.

6.1.2 Obstacle-resolving models

Obstacle-resolving models (ORMs)[1] aim to explicitly resolve processes in the UCL with buildings and trees being realistically included at a spatial resolution of ~1 m. Typical model domain sizes are 1–100 km^2. Using Orlanski (1975) scaling, ORMs are also named microscale models.

The 3D time-dependent temperature, airflow and humidity fields are calculated fulfilling the conservation laws of mass, momentum and energy. The ORMs employ uniform, stretched or non-uniform computational grids in the 3D domain. ORMs parameterize sub-grid-scale turbulent processes typically using either a RANS or LES approach. LES resolves the time dependency of the larger but still small vortices (size about 5–8 times the grid width) within the UCL, while RANS provides time-averaged values (averaging time ~1–10 min) with the same spatial resolution as LES, if using the same grid. One realization with an LES model represents an ensemble member; these instantaneous values are not comparable with measured data. Thus, statistical analysis of LES results such as averaging in time or averaging of multiple realizations is needed. Direct numerical simulation (DNS) resolves nearly all turbulent processes but needs even higher resolutions and thus requires larger computational resources; currently it is not used for operational applications in urban meteorology.

For UHI purposes, ORMs can simulate UCL flow and should calculate temperature fields, including radiation and surface heating processes. However, if dynamic radiative exchanges are absent, and heat fluxes are only prescribed at the urban surfaces, the surface heating is crudely parameterized. Also the lack of other important physical details, for example clouds, convection or precipitation, limits the applicability of the ORM. Simulating diurnal cycles of the CL-T and thus the CL-UHI is only possible with inclusion of the dynamic radiative and energy balance exchanges. Active, ongoing research is improving many aspects of the ORMs.

With the high resolution of the ORM, its time step is very small, as it is limited by the Courant–Friedrichs–Lewy (CFL) criterion for ensuring the stability of numerical methods. The number of grid points additionally determines computer resources needed for integration. These are therefore large, and ORM runs are often limited to hours or days. Thus, the horizontal extent of the model domain often only includes a neighbourhood (1–2 km) and not the region of interest with the urban and rural areas. Furthermore, the vertical extent of the ORM may be limited to the ISL (that is, a few building heights), but frequently at least the PBL is included. Some ORMs extend to/above the UBL/PBL to include cloud effects. As is common in atmospheric models, most ORMs use a decreasing vertical resolution at higher model levels, typically coarsening the grid well above building height.

Scenario simulations are possible with ORMs by replacing urban features with natural surfaces to determine microscale to local-scale UCL effects. With urban/non-urban scenarios, neighbourhood-scale modifications of the CL-T and its influence on the CL-UHI can be evaluated from differences in model results. However, the whole intensity of the CL-UHI relative to the non-urban situation depends on the prescribed non-urban surface characteristics. In addition, advective transport from other neighbourhoods might be missing. This and/or differences with respect to rural areas can only be calculated if the spatial extent of the simulation domain includes surrounding rural areas. Ideally, two-way coupled or nested models are used, or stretched grids are employed in the ORM. For deriving the resulting CL-UHI intensity, atmospheric boundary conditions and boundary values are critical.

Limitations of ORMs include the following (summarized in Section 6.2):

– The horizontal extent often only includes a neighbourhood (1–2 km) and not both the urban and rural areas in one model domain.

[1] ORMs used in CL-UHI investigations are either extended computational fluid dynamics (CFD) models that include thermodynamic processes or meteorology models that resolve building, tree and other obstacle effects including their thermodynamics.

– Care is needed when using an ORM and its results: for instance, are non-neutral atmospheric stability conditions simulated, are all appropriate energy exchange processes simulated, are anthropogenic heat fluxes parameterized?

– The ORMs need to have sufficient resolution to resolve buildings and trees. Parameterizations for partly-resolved buildings currently do not exist.

– LES models need to use a sufficient resolution to also resolve small vortices with stable stratification at night, otherwise the turbulent mixing may be underestimated.

– High-resolution data on morphology and thermal and radiative properties are required, but these might not be available for all areas.

– Providing model boundary values is particularly difficult for realistic simulations with LES models.

6.1.3 Numerical weather prediction and climate models

Regional atmospheric and NWP models with the capability to account for urban energy and momentum fluxes at the ground may be able to simulate mesoscale variations of CL-UHI intensity. They cover domains on the order of 10^2–10^3 km and more in the horizontal direction at a grid resolution on the order of 1 km. At these spatial scales, these models can resolve mesoscale atmospheric phenomena. To avoid any confusion with the scales used for classifying urban form (Table 2.1), these models are referred to as regional models (RMs), regional climate models (RCMs) or, if they cover the globe, global models (GMs) and global climate models (GCMs) in the present guidance.

Operational weather forecasting with urban characteristics accounted for is still uncommon in most NMHSs, but such models are already operational in 13 countries in Europe as well as in Brazil, Canada and northern China, with typical resolutions of 1–4 km, and they are used by research institutions. Like ORMs, RMs and GMs numerically calculate the time-dependent 3D temperature, airflow and humidity fields, as well as cloud, rain and – for some models – air pollutant concentration fields fulfilling the conservation laws of mass, momentum and energy. As with ORMs, the computational cost is controlled by spatial extent, resolution and related time step (CFL criterion). All models employ land surface schemes to simulate the heat, moisture and momentum exchanges for each surface environment. This scheme needs to ensure that a consistent approach is taken for both the urban and the rural surroundings to allow the CL-UHI to be determined from the simulation results as the difference between urban and rural areas. However, with coarser resolutions than ORMs, individual buildings and other urban structures (for example, trees) are not resolved, though their effects may be considered in the urban canopy parameterization (UCP). Some model resolutions may be too coarse, or the models may not have any UCP (such as the North American Mesoscale Forecast System (NAM), with 12-km horizontal grid spacing; or the High-Resolution Rapid Refresh (HRRR) model), thus making them inappropriate for direct CL-UHI calculations. To calculate a CL-UHI metric (Table 2.2) using NWP results derived without an UCP requires post-processing (for example a statistical model (Subsection 6.1.1)).

In urban areas, the influences of built form and surface cover including vegetation and bodies of water should be simulated or their effects parameterized. There have been numerous approaches to try to capture critical features. The UCP approaches include the following:

– Bulk: This may not distinguish building facets, but combines the built land cover in one tile.

– Single-layer: This separates the built facets such as walls and roofs and may use a tile approach.

– Multi-layer: This can have multiple auxiliary model levels within the RSL and UCL. The heat, moisture and momentum exchanges are calculated by a turbulence scheme. The schemes also require the radiation and anthropogenic heat fluxes to be vertically resolved. To directly obtain the CL-UHI, a high vertical resolution and the lowest model levels below 5 m AGL are needed, making the models more computationally expensive.

A key difference amongst the various UCPs is the number of facets and other surfaces that are considered within a grid cell. The UCPs also differ in how the surface characteristics are aggregated (tile approach) or in the number of auxiliary height levels used (Martilli et al., 2002).

The UCP may provide integrated fluxes for all the surfaces within a grid cell. However, quite commonly a tile approach is used, where the impacts of vegetated (and other) surfaces are treated separately from those of built surfaces and combined at first model level. This level may be the displacement height or higher or some other height above the roughness length, assuming the displacement height is accounted for (for example, assumed to be included in the ground level height).

Some models additionally include parameterizations of the urban water budget. The approach used impacts the turbulent flux (sensible/latent heat) partitioning model skill.

Like ORMs, RMs require initial and boundary values to be provided from a larger-scale (often global) model to correctly represent the larger scale meteorology and soil moisture. The model performance may be optimized by data assimilation in the RM, but care has to be taken to consider the representativeness of the data used; they might have only microscale or at best local-scale representativeness (Subsection 5.4.3). Data assimilation at local scale and microscale is still a research activity, although forward operators have been developed that help the evaluation of UCPs (Warren et al., 2018).

The NWP and RMs simulate the mesoscale and regional-scale motions and boundary layer turbulent exchanges and take into account the meteorological effects at different scales such as influences of cities on sea breezes and fronts. The large domain size allows whole cities and their surrounding rural areas to be simulated, with the smallest resolved phenomenon about 5–8 times the grid width. The CL-UHI can be simulated for any situation, including day or night, complex terrain, large water bodies and different seasons, within the limitations of the model. The models allow assessments of the CL-UHI for changes in climate and for urban development scenarios, if the urban features are properly considered in the simulations. CL-UHI intensity can be calculated as the difference between urban grid cells and surrounding rural grid cells. This requires consideration of many of the same issues as when the CL-UHI is obtained from observations (Chapter 5). Alternatively, the surface cover can be prescribed as non-urban in a scenario simulation so that the temperatures can be simulated without urban influences and the temperature differences can be calculated and interpreted as the CL-UHI. As previously noted, non-urban surface characteristics are also important.

For calculating the CL-UHI, values at ~1.5 m AGL should be used (Section 2.3). The lowest model levels of RMs and GMs are ~10 m AGL, but higher levels (~45 m AGL) are still in use. As the CL-T is needed below this lowest atmospheric model level, it can be taken from auxiliary grid level values (multi-layer UCP) or needs to be diagnosed. The latter often assumes the use of Monin–Obukhov similarity theory (MOST) or MOST-derived approaches, despite MOST being only applicable in the ISL (Roth, 2000) and not in the UCL (Section 2.2). Hence, care is needed in using the derived CL-T and resulting CL-UHI intensities. Other ways to diagnose CL-T are to use an equation linking the heat fluxes between the various surfaces and the atmosphere, or an offline vertical turbulence scheme with several layers, or to use a multi-layer UCP with the lowest auxiliary level at ~1.5 m.

Limitations of NWP and climate models include the following (summarized in Table 6.1):

– Large cities that cover several model grid cells can impact the modelled atmospheric environment if properly resolved. Note that 5–8 grid lengths is the scale of the atmospheric process that is captured by a model, thus 1 km grids do not cover the urban effects at neighbourhood scale. As the next generation of RMs, now being tested, has grid lengths on the order of 100 m, they will be able to represent surface flux heterogeneities within the neighbourhood scale.

Table 6.1. Advantages and limitations of different model types and urban canopy parameterizations

Model type/UCP	*Advantages*	*Limitations*
Statistical model/ none	Traditional approach with many references Low computational costs Relatively easy to set up	Completely dependent on urban/rural observations available and sites chosen High-quality data needed Need variables (e.g. wind speed, radiation) in addition to rural and urban temperatures Microscale to local-scale representativeness Robustness of CL-UHI values depends on number of sites, length of time series Statistical analogue needed to use these models for scenario assessments Daily mean by synoptic condition: observations for different synoptic conditions needed Spatial pattern: observations at several sites and morphology data needed Seasonal or annual mean: at least one year of data needed
Numerical model/ bulk approach	Traditional model approach (NWP, RM, GM) with many references Fast to integrate on a computer Nesting available Non-urbanized simulation for comparison possible Model area includes at least region of interest (Section 2.3) Temperature differences can be calculated in space and time	Does not directly deliver results at ~1.5 m AGL; CL-UHI metric needs vertical interpolation/extrapolation (Subsection 6.1.3) and/or statistical model for post-processing Vertical extent of buildings treated by logarithmic law or not considered Vertical interpolation has to consider the sub-grid surface data Heat storage of urban fabric not always considered Daily mean by synoptic condition: simulation for different synoptic conditions needed Seasonal or annual mean: at least one year of model results or statistical-dynamical downscaling needed

Model type/UCP	*Advantages*	*Limitations*
Numerical model/ single layer UCP	Fast to integrate on a computer Nesting available Sub-grid-scale surfaces considered to calculate heat storage and emission Vertical heat/humidity/ momentum exchange within urban area calculated in ISL Anthropogenic heat may be added Non-urbanized simulation for comparison possible	Same as bulk approach Requires more computing and data characterization resources than above approaches
Numerical model/ multi-layer UCP	Compared to ORM, fast to integrate on a computer Nesting available Vertical profiles of heat, moisture, momentum fluxes calculated within the UCL Vertical variability in heat storage, radiation and anthropogenic heat emission can be considered Non-urbanized simulation for comparison possible Temperature differences can be calculated	High vertical resolution with the lowest model or auxiliary level below 5 m is needed for direct CL-UHI intensity calculation (otherwise interpolation method is needed, see bulk approach) Requires computing resources larger than for single-layer approaches due to time step limitations and more complex calculations
Numerical model (ORM)/UCL resolving	Each building and tree can be realistically included Local flow, humidity, heat and radiation patterns simulated in time-dependent 3D Non-urbanized simulation for comparison is possible Microscale and local-scale influences can be determined Lowest level below 3 m, model temperature values can be directly used Influences of neighbourhood changes in urban fabric on microscale to local-scale CL-UHI changes can be assessed	Without rural areas in the model domain or nesting, only microscale to local-scale urban effects can be simulated; however, pre-urban scenarios to determine changes in CL-UHI intensities are possible Without temperature calculation and consideration of atmospheric stabilities, not usable for CL-UHI assessment Substantial computing resources needed (time and space) High-resolution input data required Boundary values are difficult to provide for LES-type models Daily mean by synoptic condition: simulations for different synoptic conditions needed Seasonal or annual mean: at least one year of simulation or statistical-dynamical downscaling needed

- The current UCPs need further testing to ensure they properly account for the effects of urban form in model simulations with grid widths below 1 km, where large buildings may partially or completely cover a grid cell (for example train stations, exhibition halls, industrial plants).

- The CL-UHI needs near-surface temperatures at ~1.5 m AGL. With a fine auxiliary grid (multi-layer UCP) these might be directly available from model results; alternatively, they need to be diagnosed, which often assumes the use of MOST or other vertical interpolation schemes.

- The lowest (auxiliary) model level needs to be much higher than the local roughness length to determine heat and momentum fluxes in the energy balance at the surfaces using wall functions.

6.2 CALCULATION OF A CL-UHI METRIC FROM MODELS

An ideal way for determining the CL-UHI would be to have data on the pre-urban setting. This may be possible in land-use scenario studies with models. The pre-urban land use might be the same as the current rural land use in the surrounding areas, so that the results show the CL-UHI based on the current urban area versus the current rural area. However, other pre-urban land uses are possible (for instance completely forested, grass, swamp). The selected pre-urban land use will influence model results and thus the near-surface temperature difference for the scenarios. An alternative, applicable for many applications, is to take model results for an upwind and preferably undisturbed area in the rural surroundings of the urban area as a rural (non-urban) reference, as is done for observations.

The different model types introduced in Section 6.1 may all be used for performing simulations including pre-urban land-use scenarios. However, not all are currently applicable to calculate the CL-UHI based on urban and rural CL-T values. Table 6.1 summarizes model approaches and their advantages and limitations. In general, all model types can be used for each metric (minimum, maximum, daily mean, daily mean by synoptic condition, spatial pattern, seasonal or annual mean). Depending on the model type, the resolution can be very high (some metres). For statistical models, the limitation is dictated by the training data, which have to have at least the spatial and time resolution needed for the metric considered. For NWP (RMs and GMs) and corresponding climate models hourly data are possible, while ORMs can provide time-dependent data on a basis of some minutes or even shorter (LES-type models). In addition, besides large-scale meteorology, the quality of the model type-specific data on the urban area (Table 4.1) is important for achieving a reliable model result. Please note: the quality of the model results depends on model skill (Section 6.3) and how well the user is trained in the use of the model.

6.3 EVALUATION OF MODEL SKILL

Model performance should be assessed with observations and should include more than CL-T data (Warren et al., 2018) for both the urban area and the surrounding rural areas. In both environments the skill to model vegetation and soil moisture is critical. Evaluations should not only compare CL-T values or CL-UHI intensities but should also focus on the performance for the relevant CL-UHI metric (Table 2.2) for the use case. Thus, the evaluation needs to assess if the model is applicable for the intended use.

The needed skill cannot be generally prescribed but depends on (i) the purpose of the modelling, (ii) the resolution of the model used, and (iii) the uncertainty inherent to the class of the observational site. For example, the estimated uncertainty including the measurement uncertainty of 0.2 K is 1.2 K for an urban Class 3 site, while for a typical Class 1 rural site it is 0.2 K (see *Guide to Instruments and Methods of Observation* (WMO-No. 8), Volume I: Measurement of Meteorological Variables, Annexes 1.A, 1.D). Thus, for a single pair of measurements, the simulated maximum CL-UHI may differ by about 1.4 K for a model that does not resolve the microscale effects but uses UCP (Subsection 6.1.3). Note, within this deviation the model is assumed perfect, while modelling assumptions or constraints such as the vertical resolution impact simulated CL-UHI intensities. Knowing the degree of uncertainty in the simulated CL-UHI and its spatial distribution is important to determine the model's applicability for a specific use case (Table 2.2).

Ensuring consistency between the observations (Section 5.2) and the model output (for example location, surface cover, thermal source area, spatial representativeness) for a range of different neighbourhoods and within those neighbourhoods is important for assessing the model performance and for simulating the CL-UHI spatially and temporally. If observations are used for data assimilation, care needs to be taken to account for the instrument siting (Chapter 5). Data assimilated in a model simulation cannot be re-used for evaluation; instead, independent data are needed.

When simulating the current CL-UHI (analyses, nowcasting, NWP) or past CL-UHI (reanalyses, past sub-seasonal to annual), sufficient observational data may exist (Section 7.4) for thorough model evaluation. However, for future climate (decadal or longer) CL-UHI, models can only be evaluated for the current or past climates and with current or past urban characteristics such as fabric and morphology. Sufficient model performance is a prerequisite to applying a model for assessing the CL-UHI dependent on future climate and/or on urban development. However, modelling provides the only opportunity to assess the future changes of the CL-UHI depending on, for instance, city growth or climate change. Therefore, different evaluation approaches (operational, diagnostic, dynamic, probabilistic) (Dennis et al., 2010) may be applied to assess the reliability of a model for scenarios of urban development as well as future climate. For example, dynamic model evaluation focuses on the ability to predict changes in the response of the model to changes in meteorological conditions and, more generally, to changes in forcing. This includes changes in the urban characteristics and thus model application to different types of urban areas. Diagnostic evaluation might focus on single processes in a model, for example how well wind speed or heat fluxes are simulated using corresponding measurements. Given the challenges of assessing future climate CL-UHI prediction, a variety of evaluation methods need to be considered.

6.4 APPLICATION OF MODELS TO DETERMINE THE CL-UHI

6.4.1 Analyses of current and past CL-UHI

The current CL-UHI can be analysed with all model types within their type-specific advantages and limitations (Table 6.1). For this purpose, observations might be assimilated in the model, however, care has to be taken to correctly include the representativeness of the data and what their thermal source area is. For example, an urban observation of microscale representativeness (very small thermal source area; Class 3–5 as per *Guide to Instruments and Methods of Observation* (WMO-No. 8), Volume I: Measurement of Meteorological Variables, Annex 1.D) might be inconsistent with a model with a 1 km grid, but suitable for use in ORMs with 1–10 m grids or NWP model with grids well below 100 m.

To assist interpretation of observational data (Chapter 5), models that take into account dynamic surface energy balance and vegetation phenology may be used to determine the impact of microscale and local-scale morphology on the CL-T and CL-UHI (Subsections 6.1.2, 6.1.3).

For reanalyses of past or even historic CL-UHI it is important to know the urban form for the period that the reanalysis is focusing on. For historic CL-UHI values it is often difficult to obtain this needed information about the urban area. However, as long as the urban area is little changed, the current information on the urban form might be a good first guess.

6.4.2 **CL-UHI forecasts (several days and shorter)**

A very dense urban observation network may allow nowcasts of higher spatial resolution of the CL-UHI than the grid width of the forecast model (NWP, RM, GM). This may be critical to some applications (Chapter 3). Weather forecasts can provide variables (temperature, cloud cover, rain, soil moisture, wind) relevant to CL-UHI intensity and spatial variability. Depending on forecast model complexity and the UCPs employed, the forecast itself or in combination with a statistical model can provide CL-UHI information. However, mesoscale atmospheric phenomena and urban processes need to be resolved in the CL-UHI forecast to be appropriate (Section 6.1). As noted, this is limited by model resolution and domain size as well as the UCP employed. With the CL-UHI considered, the short- and medium-range weather forecasts (1 to 10 days) and nowcasts (up to 6 hours) allow heat stress and extreme weather warnings for urban areas (*Multi-hazard Early Warning Systems: A Checklist*; *Guidance on Integrated Urban Hydrometeorological, Climate and Environmental Services* (WMO-No. 1234), Volume I: Concept and Methodology; *Heatwaves and Health: Guidance on Warning-System Development* (WMO-No. 1142)).

In general, where features of low predictability are important, forecasts should be run as an ensemble and the results presented probabilistically to consider uncertainty in the synoptic evolution on the timescale of several days. It is important to avoid presenting information to users which is not justified by the predictability of the solution. However, as the CL-UHI is strongly influenced by both the local-scale urban form and the meteorological conditions in the rural surroundings, it is likely to be predictable for longer periods than other shorter-lived phenomena such as urban area-influenced or -initiated thunderstorms.

6.4.3 **Climate predictions (sub-seasonal and longer) and projections**

As atmospheric conditions (Section 2.5) influence CL-UHI intensity, the intensity is modified by global and regional climate, and the CL-UHI in turn influences the climate of the urban surroundings. GCMs and RCMs that employ UCPs (Jacobson and Ten Hoeve, 2012; Katzfey et al., 2020; Hertwig et al., 2021b) can, in principle, consider both future climate and urbanization scenarios. The changes in the CL-UHI may be due to regional changes in cloud and wind conditions. The challenge lies in obtaining results at the appropriate spatial scales for urban and rural sites to assess the CL-UHI. To quantify uncertainties in climate projections, full model ensembles are needed. Methods to determine the CL-UHI are given in Section 6.2.

As most **GCMs** have coarse grid resolutions (~200 to ~50 km) (Haarsma et al., 2016), the urban extent is insufficient to cover enough grid cells to be meaningful within the urban area. Furthermore, in many models there is only a simple urban representation (bulk approach, Table 6.1), or the urban parameters used in the model are poor at the global scale (Hertwig et al., 2021b). Therefore, model and input data improvements are needed to enhance the model skill for determining the CL-UHI. High-resolution model runs (~10 km) that are now available will start to overcome some of the current limitations for megacities. The tile approach combines the UCP with the non-urban part within the same grid cell allowing the CL-UHI to be derived from the CL-T with appropriate tile weightings to characterize different states of urbanization (Section 6.1) in the same grid cell (Katzfey et al., 2020). However, this has several constraints. The appropriate urban/rural CL-T needs to be combined using appropriate land cover data. Thus, the resulting CL-UHI values should be treated as a rough estimate for a region. If a multi-layer UCP is employed, the vertical resolution should account for the urban form. Evaluation of GCM performance under current conditions is essential to understand the nature of the CL-UHI values derived (Haarsma et al., 2016). Current GCMs using UCPs show small increases, decreases or minor changes in the CL-UHI for different times of year and regions compared to today's climate without changing the urban form (Oleson et al., 2011; Katzfey et al., 2020).

RCMs generally have a better grid resolution (~50 to ~1 km) than GCMs. The km-scale RCMs (Takane et al., 2020) permit predictions of CL-UHI for larger cities.

Currently, GCM or RCM projections frequently use bias corrections typically based on results for current climate (*Guide to Climatological Practices* (WMO-No. 100); *WMO Guidelines on the Calculation of Climate Normals* (WMO-No. 1203)). Several grid points should be used to enhance the reliability of the climate model results, and thus one would have to include urban and rural areas with several grid cells each. If the model grid cell includes both urban and rural areas, the bias corrections need to be weighted by area fraction. Bias-corrected CL-UHI will have little reliability if the whole urban and rural areas are within the same grid cell. The CL-UHI can be determined from downscaled, bias-corrected future climate data or using simulated atmospheric data driven by the land surface parameterizations (Section 6.1) for the urban and non-urban tiles within a grid cell.

High-resolution climate projections are computationally expensive. Downscaling methods to estimate the CL-UHI include using statistical models (Subsection 6.1.1) combined with GCM or RCM projections (Wilby, 2003). The lower computational demand enables the use of ensemble techniques. As the statistical models are sensitive to biases in the predictors, a bias correction to the GCM/RCM input data is necessary. However, statistical models do not generally consider changes in the urban characteristics (Subsection 6.1.1), and their reliability is highest where training data are used. Given that changes in urban characteristics are very likely in climate timescales, both should be considered. However, the prediction of urban development includes uncertainties and thus scenarios are used (Subsection 6.4.4).

Statistical-dynamical downscaling uses high-resolution numerical model results of simulations performed for selected weather types. These are identified from GCM or RCM results to describe the temporal CL-UHI variability or meteorological extremes (cuboid method) (Früh et al., 2011). The GCM or RCM weather type frequency is used to weight the high-resolution model results to compute the projected climatological mean CL-UHI. Statistical uncertainty is reduced by increasing the number of simulations conducted for each weather type. For example, instead of 2 simulations per weather type (Hoffmann et al., 2018), 3–6 simulations were used by Schoetter et al. (2020).

Another statistical-dynamical downscaling approach uses short periods of high-resolution RCM simulations with and without urban surface characteristics. For each day the time-dependent spatial pattern of the CL-UHI is determined, and the determined CL-UHI signal is added to results of RCM-based meteorologically similar days employing an analogue approach.

Temperatures simulated by GCMs (Subsection 6.1.3) are often used to estimate the heat-related health impacts without including the intensity of the CL-UHI. This leads to an underestimation of the CL-UHI effects on health. With refinement GCMs might be usable to consider the CL-UHI and estimate health impacts (see Takane et al., 2020 for mortality and exposure). This is also done using regional numerical models and epidemiological analysis. The results show that the CL-UHI increases the health risks in warm seasons. However, the CL-UHI may moderate winter-related cold and thereby have positive health effects in that season (Macintyre et al., 2021).

6.4.4 Urban development and the CL-UHI

All model types introduced in Section 6.1 can be applied to assess the impact of urban development, if they have sufficient skill (Section 6.3). Simulations may be performed for the current climate with and without an urban development scenario to study the effect of urban development in isolation or in combination with climate change (Subsection 6.4.3). These simulations may help to identify the appropriate choice of urban development scenario. Essential for scenario studies is the ability to include the urban fabric of the current situation and of the scenario in the model. The challenge is to provide information on the future urban area such as urban sprawl versus compact urban development, urban facets including the materials (for instance wood versus concrete), or anthropogenic heat emissions (for example fewer commuters due to more work from home in a digitalized world). To set up and assess the probability of these scenarios, close collaboration with city planners and scientists is essential (Chapter 8). It should be noted that statistical models may only be used for urban development scenarios if a statistical analogue exists (Table 6.1).

6.5 METADATA FOR MODELLING RESULTS

Model metadata are an essential part of providing model results. Krayenhoff et al. (2021) define a useful set of criteria that may be considered by modellers or result users to assess the reliability and contextualization of model studies. They suggest the following for documenting model studies on urban heat reduction strategies:

- Provision of site metadata
- Characterization of forcing meteorology
- Provision of heat mitigation implementation metadata
- Provision of air temperature in space and time

They suggest that the model skill for the application be assessed using the following three criteria:

- Accurate representation of relevant physical processes
- Successful model evaluation for the targeted model application (impact of heat mitigation measures)
- Model application is sound

For scientific and public information considerations, modellers are encouraged to publish model results (data sets) for assessing CL-UHI as open data fulfilling the FAIR principles (findable, accessible, inter-operable, reusable). For example, the Coupled Model Intercomparison Project Phase 6 (CMIP6) (https://pcmdi.llnl.gov/CMIP6/) provides guidance for modellers, data managers and users including model output specifications for global and regional climate simulations. Downscaled results for several regions are available (Haarsma et al., 2016; CMIP6: https://pcmdi.llnl.gov/CMIP6/; World Climate Research Programme (WCRP) Coordinated Regional Climate Downscaling Experiment (CORDEX): https://cordex.org/). They use standardized variable names following the Climate and Forecast (CF) metadata conventions (Andrioni et al., 2022). Standardization and publication of ORM results are also advisable to make these computationally demanding model results more easily and widely usable, for instance by using the new Earth System Data Branding (EASYDAB) (http://www.easydab.de; Ganske et al., 2021). Many countries now have open data requirements which facilitate data use and a more complete communication of methods.

6.6 MODELLING CHALLENGES IN BRIEF

Given the constraints to modelling the CL-UHI (Table 6.1), the primary challenge results from the gap between typical mesoscale model resolution (O(1 km)) and the microscale that needs to be resolved to explicitly represent the CL effects (~O(1 m)). While advances have been made in representing the complexities within the UCL, much work is aimed at improving the fluxes from the UCL to the atmosphere above for urban NWP and climate assessments. Besides the correct consideration of the horizontal heterogeneity of the urban area, the effects of individual tall buildings or small groups of tall buildings have not yet been properly parameterized (Hertwig et al., 2021a). The simulation of the urban vegetation, and its interaction with the other surfaces, is also important and still a challenge.

To simulate the CL-UHI microscale variability, further advances in ORM modelling are needed. A major challenge is to ensure the microscale models are appropriately coupled to a regional model, for instance by using stretched grids to ensure that the lateral boundaries include the necessary rural environment, or by nesting within coarser atmospheric models.

A wide range of observations are needed to evaluate the characteristics of the modelled urban atmosphere in 3D. In addition, detailed and complete information on the 3D city morphology and building materials, as well as human activities, is needed as input (Chapter 4); this information is needed regardless of the model scale or type, but in varying degrees of detail.

CHAPTER 7. MONITORING THE CL-UHI

Monitoring the CL-UHI allows provision of urban services (Chapter 3) as well as ongoing assessments of the impact of both urban development and climate change on the CL-UHI. Furthermore, CL-UHI monitoring is helpful for assessing the effects of potential adaptation measures.

7.1 DEFINITION OF MONITORING

The goal of CL-UHI monitoring is to provide long-term information. For this purpose, observations and corresponding data analysis are used, as well as modelling, or a combination of both methods (Table 7.1). Monitoring requires observing all the relevant meteorological variables (Subsection 2.5.4; Chapter 5), obtaining the urban–rural characterization parameters (Chapter 4) and metadata (Sections 5.6, 6.5), combined with using the appropriate model(s) (Chapter 6). The metadata are needed to interpret, homogenize and compare intensities of the CL-UHI at different times. The CL-UHI metrics of relevance include the diurnal and annual values, extremes (minimum, maximum), trends with reference periods, and intra- and inter-urban values. Databases from CL-UHI networks for different cities could be useful in regional and/or global upscaling for global climate solutions (Creutzig et al., 2019). The approaches used to monitor the CL-UHI are diverse with complementary attributes (Table 7.1).

7.2 PURPOSE OF MONITORING

Prior to designing a monitoring programme with one or several of the approaches summarized in Table 7.1, the use cases and corresponding CL-UHI metric have to be determined (Table 2.2) with the purpose of identifying the monitoring system needed. The following steps have to be taken:

– The **intended use of the data** from a CL-UHI monitoring network has to be defined.

– Based on the intended use of the data, the **necessary scale** (spatial coverage and resolution) of the monitoring network can be decided and for what purpose models are to be employed (for instance spatial refinement of observational data).

– Given the intended use of the data, the **necessary temporal resolution** has to be defined.

– Data accessibility, formats and any post-processing needed for specific uses should be assessed.

An existing measurement network may be insufficient for the intended use. However, the spatial/temporal resolution needed for the intended use might be only achievable using additional model simulations.

7.3 PARTNERING IN THE INSTALLATION OF MONITORING SYSTEMS

As urban observations and services involve multiple stakeholder groups, they present opportunities for collaboration between NMHSs, agencies and research institutions (*Guidance on Integrated Urban Hydrometeorological, Climate and Environmental Services* (WMO-No. 1234), Volume I: Concept and Methodology and *Guidance on Integrated Urban Hydrometeorological, Climate and Environment Services* (WMO-No. 1234), Volume II: Demonstration Cities). A coordinated approach between operators of systems ensures that more comprehensive observational and modelling data sets are available for the community, and that siting and

Table 7.1. Advantages and disadvantages of CL-UHI monitoring approaches

Approach	*Advantages*	*Disadvantages*
Observations at fixed sites (Chapter 5)	Extensive temporal coverage	Limited spatial coverage At some sites poor spatial representativeness Metadata must be regularly updated to monitor changes in surroundings Potentially expensive if a large number of sites are used
Observations on mobile platforms (Chapter 5)	Good spatial coverage along the track used Detection of hot spots and spatial variability	Extensive post-collection data processing and quality control needed Each observation's surroundings differ Metadata must be regularly updated to monitor changes in the surroundings Collecting field data is labour intensive Measurements not all simultaneous in different parts of the urban area Speed of platform determines spatial resolution
Observations by citizens (opportunistic approach)	Good spatial coverage Detection of hot spots and spatial variability	Extensive post-collection data processing and quality control needed Observation surroundings often unknown (metadata missing) Unknown maintenance of instruments Metadata may not be reliable or not be updated
Modelling (Chapter 6)	Extensive temporal coverage Good spatial coverage within model domain Detection of errors and inhomogeneities in observations	Spatial resolution might be insufficient Data assimilation advisable for the assessment of the current state Model parameters to characterize neighbourhoods need to be regularly updated Reliability of results depends on model physics considered and successful evaluation for the intended purpose Metadata (e.g. model physics, resolution, input data, urban form data) must be regularly updated to monitor changes in the model Regular model evaluation needed

maintenance of the monitoring system are done in coordination with relevant agencies. Collaboration should start very early in the planning process so the observing systems and model set-ups can be designed to support multiple application areas from the outset. Numerous agencies, institutions and companies may deploy sensors for temperature, wind, air quality or hydrological parameters for different purposes (for example hydrology, health, air quality) and with different goals (for example regulatory, safety, planning) and time frames such as day-to-day management, extreme event preparedness or long-term planning with a wide range of scenarios. As NMHSs have a broad overview of requirements, gaps and standards, they can play a central role in facilitating the evolution of observing systems and modelling possibilities within cities. The collaborative approach promotes overall cost efficiencies by standardizing observation and modelling methods and avoiding duplication between agencies and institutions.

Traditional NMHS meteorological networks are installed to observe synoptic or large mesoscale features for the country, typically intentionally avoiding heterogeneous urban areas. Some countries that are small (for instance Singapore) or have NMHSs with an urban focus have already set up urban networks (*Guidance on Integrated Urban Hydrometeorological, Climate and Environment Services* (WMO-No. 1234), Volume II: Demonstration Cities). NMHSs are generally well positioned to implement the networks for CL-UHI monitoring, as they deploy and maintain systems over the long term. Those installing sensors must take into account the siting considerations in Chapter 5. Given the heterogeneity of urban areas and the increasing need for high-resolution data in urban areas, it is likely that sensors in specific areas of interest will be required and/or may be operated by non-NMHS entities such as city agencies and companies.

City agencies may implement CL-UHI monitoring, having monitored air quality already regularly and for longer periods. Setting up combined networks may save resources, if both purposes can be addressed, for instance determining exceedances of limit values for particles and maximum CL-UHI intensities. City-funded CL-UHI monitoring networks are likely to be permanent and maintained as a public service (IUS: *Guidance on Integrated Urban Hydrometeorological, Climate and Environment Services* (WMO-No. 1234), Volume II: Demonstration Cities and *Multi-hazard Early Warning Systems: A Checklist*). As with air quality monitoring, expertise in meteorological observation is important. If expertise is lacking, collaboration with the private sector and others may be challenging. However, university researchers who have established CL-UHI networks from project funding with limited time horizons (Subsection 5.3.3) might become experienced partners.

Ideally, a jointly installed and maintained measurement network should follow the WMO Observing Systems Capability Analysis and Review (OSCAR) tool (*OSCAR: Observing Systems Capability Analysis and Review Tool*, *OSCAR/Surface User Manual*). OSCAR targets users interested in both status and planning of global observing systems and the specifications of instruments for data users:

- OSCAR/Surface and OSCAR/Space: surface- and space-based observing system capabilities
- OSCAR/Requirements: user requirements
- OSCAR/Analysis: compares requirements with the observing system capabilities (Rolling Review of Requirements (RRR))

This information pool allows both experts and observing system operators to identify for example spatial gaps in their observing network and thereby supports their planning efforts.

As for observing networks, the use of models for monitoring will require collaboration with NMHSs and other groups experienced in model application. These include consultants (air quality, urban climate assessment) and university researchers with expertise in modelling urban climate.

7.4 MONITORING THE CL-UHI USING OBSERVATION NETWORKS

In general, monitoring combines observations, analysis and modelling (Section 7.1), and it is the combination of all three that is needed. Combining these methods makes it possible to detect unexpected changes in CL-UHI that would not have been identified by one method alone. This section summarizes the aspects of observation networks described in Chapter 5, focusing on monitoring.

7.4.1 General considerations

Before planning an observational network for monitoring, the user needs must be identified (Section 7.2). With these identified, the sensor, network design, communication technologies and power options can be selected (Chapter 5). A choice must be made between a larger network of lower-cost sensors, a few high-quality meteorological stations, the use of existing measurement sites or a blend of these three, and this choice depends on the use case (Table 2.2). High-quality instruments do not compensate for poor or inadequate exposure and network layout. Any operator, whether of a single station or a massive urban meteorological network, must provide metadata for the sites, instrumentation, station surroundings and exposure (Section 5.6). The (spatial) representativeness, time-dependent thermal source area (Subsection 5.4.3) and network layouts (Section 5.3) need to be considered. Examples are given in Appendix 2.

7.4.2 Monitoring with reference stations in standard instrument shelters

Reference WMO meteorological stations in cities provide high-quality measurements of air temperature with the same instrumentation as rural WMO stations (see *Guide to Instruments and Methods of Observation* (WMO-No. 8), Volume I: Measurement of Meteorological Variables, Chapter 1). However, few reference WMO meteorological stations exist in cities. They are sited at airports or in larger green spaces, and there is rarely more than one in any city. Reference meteorological stations in cities to monitor the CL-UHI intensity must be complemented with reference meteorological stations in the rural surroundings (see Section 5.2 and *Guide to Instruments and Methods of Observation* (WMO-No. 8), Volume I: Measurement of Meteorological Variables, Chapters 1 and 2). With this approach, any city can be monitored but with extremely limited areal coverage; the intra-urban variability of the CL-UHI is not addressed (Section 5.3). If the urban site is not in a built area (or an urban LCZ, Figure 4.1) the CL-UHI will be biased.

A standard meteorological station approach, that is an urban and a rural site pair, should guarantee, if operated following WMO guidelines (*Guide to Instruments and Methods of Observation* (WMO-No. 8), Volume I: Measurement of Meteorological Variables, Chapter 1), that a long-term record can be used to identify how weather and climate in an urban area and the rural surroundings are different. In selecting a representative rural reference station to complement the urban site, it is important to ensure that both sites experience the same mesoscale climate and have the same topographic setting, while ensuring the rural site is free of urban influences currently and for the next decades (Section 5.4).

7.4.3 Monitoring with small automatic weather stations in small instrument shelters

Installing small autonomous thermometers or multi-variable weather sensors on street poles or other street furniture is a logistically feasible, cost-effective option to monitor the intra-urban variability of CL-T with many sites (Subsection 5.4.5). Such networks can provide a detailed distribution of CL-T in different LCZs across a city and can be used to map the CL-UHI across neighbourhoods. Influence from a variety of features such as green space, cold-air drainage and hot spots within cities may be identified. The networks need multiple rural sites (LCZs A–G, Figure 4.1) with the same instrumentation/site configurations, located in different wind directions (upwind) and distances from the city to avoid downwind effects of the urban plume (Lowry, 1977) (Subsection 5.4.1).

Using a larger number of sites requires a much larger effort for communication, maintenance and quality control. Geostatistical or machine learning techniques can help identify poor data and guide the placement of new sensors within existing networks or identify redundant sites. Partnerships with municipal agencies such as transportation and public works departments can facilitate siting and maintenance of sensors.

7.4.4 Mobile monitoring approaches

For long-term monitoring, mobile measurements are challenging, with a few promising exceptions. Sensors (including GPS) mounted on above-ground public transport can provide continuous data from transects through cities, covering large areas across urban–rural transects, though they need to be interpreted with care (Subsection 5.3.2). However, sources of contamination of measured CL-T, such as vehicle engine exhaust, need to be considered (Subsection 5.5.3.2).

7.4.5 Opportunistic sensing – crowdsourcing

As opportunistic sensing (crowdsourcing) is relatively new, the climate record is short and the technologies are still evolving, with implications for long-term monitoring campaigns. Opportunistic sensing (Subsection 5.3.4) can provide data where no permanent measurements exist. Networks of opportunistic sensors could potentially complement well-maintained urban meteorological networks. The largest barriers are associated with being able to undertake rigorous quality control/data assurance (Chapman et al., 2017) linked to lack of metadata (Fenner et al., 2021) and sensor drift from unregulated sensor maintenance and calibration regimes. Rigorous quality control can enhance the data quality. However, deploying well-documented sensors and gathering the required metadata after careful site selection remains the best practice.

7.5 MONITORING THE CL-UHI AS PART OF AN IUS

CL-UHI monitoring and information provision is part of an IUS. The CL-UHI maps produced from measurements or model results, or their combination, can be used for warnings, in the planning process or in other use cases for calculating different CL-UHI metrics (Table 2.2). However, the CL-UHI monitoring information needs to be transformed into other measures, for instance risk maps, to provide services. These services require additional information, for instance on transportation flows or socioeconomic characteristics (Table 4.3), to support the IUS concept (*Guidance on Integrated Urban Hydrometeorological, Climate and Environmental Services* (WMO-No. 1234), Volume I: Concept and Methodology and *Guidance on Integrated Urban Hydrometeorological, Climate and Environment Services* (WMO-No. 1234), Volume II: Demonstration Cities).

7.5.1 Monitoring CL-UHI from the past to today

Examples of observational networks are provided in Appendix 2, and examples of monitoring approaches are provided in Appendix 3. Observed values combined with urban fraction and altitude data (Appendix 3, Example 1), or CL-UHI intensities based on observations combined with plant diversity data (Appendix 3, Example 2), may both provide an enhanced spatial pattern of CL-UHI.

Instruments/models are continuously being further developed, and the network/model settings can change; all this should be documented in the corresponding metadata (Sections 5.6, 6.5). A changed model needs to be evaluated again for the CL-UHI metric used (Section 6.3). For monitoring the CL-UHI with the use of observations or/and models, past changes in the observational data availability as well as the thermal source area of the observations and changes in urban form need to be considered. This is also true for changes in models if the past CL-UHI information is stored in a database and used to derive time series or changes in the CL-UHI. Care has to be taken in deriving temporal developments from data that might have different representativeness (observations) or are now influenced by "new" processes for instance via new model versions. Reanalysing the past CL-UHI with a frozen model version may solve this problem, provided that the data on the urban form are available for the past. Nevertheless, the configuration of models for monitoring requires a compromise between data requirements for characterization of the urban area (Table 6.1), the intended data use (Table 2.2), computational cost and model performance (Chapter 6). The model used should be evaluated for the CL-UHI metric that will be used for monitoring (Section 6.3).

7.5.2 Monitoring CL-UHI into the future

Future changes may include the urban area itself – for instance, linked to infrastructure, technology, people's behaviour and vegetation – as well as climate change. Information about future CL-UHI intensities is likely to be needed for many applications (Chapter 3, Chapter 8). The combined influences will be observed by sensors in these future times. However, by using modelling likely future CL-UHI intensities can be assessed, with the modelling allowing the different origins of effects to be separated. This may help to identify if changes in CL-UHI found for the future are to be attributed to changes in the urban features (Table 4.1) or are a result of climate change.

If bias corrections are used for the model output, these corrections need to be updated whenever the model or the thermal source area for observations assimilated in the modelling change. Therefore, the thermal source area of an observation needs to be assessed from time to time to determine if the thermal source has changed.

7.5.3 Data transfer, archiving and licensing

For combining measurements and modelling for monitoring purposes, automated downloads are critical. Specialized meteoalarm (for example, https://www.meteoalarm.org/en/), early warning and emergency management systems require automated transfer protocols.

The principles of collaboration (Section 7.3) and standardization of provided data are central to long-term monitoring. The distribution of CL-UHI monitoring data, from observations and modelling, requires data sharing and corresponding licensing options to be established. These range between open-data and proprietary (private/commercial) approaches. For scientific and public information considerations, network operators and modellers are encouraged to publish CL-UHI data as open data fulfilling the FAIR principles (findable, accessible, inter-operable, reusable; Section 6.5). Metadata are essential for successful use and interpretation of both observations (Section 5.6) and model results (Section 6.5).

Standardization between operators is challenging but essential as data originates from sources with different reliability and accuracy. Common databases, platforms and protocols, if implemented, enable full utilization of all the monitoring data. Data sharing portals may be operated by NMHSs, agencies or institutions, or by leveraging the WMO Information System (WIS) (*Guide to the WMO Information System* (WMO-No. 1061); *Manual on the WMO Information System* (WMO-No. 1060). The data are to be stored in a long-term, actively maintained data archive.

7.6 MONITORING CHALLENGES IN BRIEF

Monitoring of CL-UHI intensities based on long-term measurements, modelling and analyses is not without challenges:

– All of the challenges outlined for measurements (Section 5.8) and modelling (Section 6.6) apply.

– Methods to integrate and homogenize CL-UHI monitoring (measurements, modelling) data and, in turn, to integrate these between NMHS meteorological services and multi-agency IUSs are important.

- Long-term availability of measurement sites is still rather limited.
- Determination of site characteristics and metadata for historic CL-UHI measurement data is demanding.
- Computing resources and expertise are required for microscale and local-scale model simulations that assess past (reanalyse), current (analyse) and future (forecast, scenarios) CL-UHI.

CHAPTER 8. UNDERSTANDING THE IMPACTS OF CL-UHI MITIGATION AND ADAPTATION EFFORTS

A range of adaptation and mitigation strategies applied at the microscale to the mesoscale could be used to influence CL-UHI. Examples are modification of urban materials (Section 8.1) or providing shading and vegetation and water infrastructure (Section 8.2). Through targeted urban design and planning, the characteristics of the CL-UHI can be modified. The built form, land cover and materials (Table 4.1, 4.2) influence the energy exchange processes at many scales and hence the CL-UHI. For mitigating the CL-UHI several approaches are used, including the examples in the following sections.

8.1 CHANGE OF MATERIALS

At the microscale, materials can be changed through retrofitting or new construction. Careful selection can mitigate the CL-UHI. Possible materials include the following:

- Cool materials with high reflectivity values that can reduce absorption of shortwave radiation and/or the near-infrared band;
- Thermochromic materials with reflective properties that increase at higher temperatures;
- Insulation and glazing materials reducing anthropogenic heat emissions;
- Permeable paving materials modifying water drainage and increasing soil moisture and thus enhancing water availability for evapotranspiration, which in turn reduces CL-UHI intensity.

To determine probable quantitative impacts of choices on CL-UHI intensity, modelling studies are needed, as the near-surface air temperatures also depend on the meteorological conditions (Section 2.5). At the microscale, detailed studies are possible with ORMs (Subsection 6.1.2). For assessing influences of the whole urban area being changed, scenario studies of coarser resolution may be advisable (Subsection 6.4.4).

8.2 NATURE-BASED SOLUTIONS – INCLUDING GREEN AND BLUE INFRASTRUCTURES

With widespread implementation, the microscale changes to mitigate the CL-UHI (Section 8.1) may combine to influence the local scale. Nature-based solutions (including more vegetation and water features in urban areas (Miles et al., 2021)) are another way to mitigate the CL-UHI, with more than a thousand examples around the world (https://una.city/). Green roofs, urban gardens and water bodies (for instance urban aquaculture) can be effective ways to lower urban temperatures in some climates. Measures include the following:

- **Intensive green roofs** can reduce roof temperature (increased evapotranspiration, and possibly higher albedo than roof shingles), slightly reduce the near-ground temperatures and thereby mitigate the CL-UHI. Green roofs have to have sufficient water supply (see Table 2 in Norton et al., 2015).
- **Urban parks** reduce temperature during daytime and thereby daytime CL-UHI, with a tendency for larger parks to cool more. How far into the built-up area the cooling effect spreads depends on wind speed, building density and the vegetation in the park.

- **Water bodies** such as lakes and ponds reduce daytime temperature, especially downwind of the water body, but due to the high heat capacity of water, the night-time temperatures and thus night-time CL-UHIs are often higher than in the built-up urban areas (Schlünzen et al., 2010).

The influences of the nature-based solutions on the CL-UHI have to be carefully assessed as increases in humidity can cause negative influences on heat stress (Section 3.1).

8.3 ADJUSTING URBAN FORM

At the microscale to the local scale, designers and planners can change and regulate urban structures (Sections 8.1, 8.2). These measures may modify the sky view factor (microscale) and ventilation pathways (local scale). Given that heat stress is associated with multiple indices (Subsection 3.1.1), its mitigation may involve modifying other variables beyond air temperature, such as increasing wind speed and/or decreasing humidity.

Modelling studies can help to determine the consequences of cumulative proposed microscale and local-scale changes (for example, whether there are critical thresholds). Examination of proposed measures (for example increased ventilation in town centres) can identify problems, investigate the consequences of such measures for the CL-UHI from timescales of weather cycles to future climates, and explore potential solutions.

8.4 LIMIT ENERGY USE

At the local scale to the mesoscale, energy use, design and people's behaviours (Capel-Timms et al., 2020) influence the heat emissions into the UCL. A sizeable proportion of building energy used is linked to HVAC systems. For example, in the European Union, space heating/cooling amounts to 68%/6% of the total final energy use in households (data for 2012; https://energy.ec.europa.eu/document/download/59766187-f07a-40e1-8097-d5dd09f5341d_en). For some Mediterranean countries, the space heating contribution is considerably lower (for example <40% for Malta and Portugal), while for some north European countries it is higher (for example >90% for Denmark). The energy demand for heating and cooling is closely linked to the current and future climate of the region and, in urban areas, the additional influence of the CL-UHI. It is also linked to the building materials used (Section 8.1), wind speed/cloud cover (Section 2.5), the indoor temperature desired by residents and anthropogenic heat emission (Section 3.3). Reducing anthropogenic heat emissions helps to reduce CL-UHI values. If the summer CL-UHI values are reduced and the winter values kept similar, the annual energy demand may also be reduced. This may be achieved by simple microscale measures such as the following:

- Intensified microscale urban greening (Norton et al., 2015) with vertical greening systems. These increase shading and evapotranspiration if sufficiently supplied with water and slightly reduce the CL-UHI if they are installed on the sunny façade and begin near the ground.

- Window shading with a fixed angle (shade in summer, sunshine in winter) or outdoor blinds/shutters.

- Placing exhaust units on rooftops to avoid anthropogenic heat emission into the urban canyon.

- Deciduous vegetation that shades façades in summer but not in winter.

For these, and other examples, the quantitative impact depends on the actual situation and how widely they are employed. They are best assessed in advance by dedicated modelling studies to increase the likelihood of avoiding unexpected negative impacts.

8.5 DESIGN AND PLANNING CONSIDERATIONS

Urban planning is a joint effort of all groups involved in urban services and demands expertise in meteorological influences if the CL-UHI is to be kept as it is or even mitigated. The following may be considered:

- The impacts of the CL-UHI are not always negative; for instance, the CL-UHI may result in reduced heating demands in winter and more comfortable outdoor temperatures in cold climates. Therefore, the heat-induced health effects may need to be assessed for a full year.

- For mitigating the CL-UHI, intended urban design and changes in the microscale to regional-scale climate have to be considered in the planning phase. To achieve this, there is a critical need for urban planners, architects, meteorologists, hydrologists and city administrators (see Recommendations section in *Guidance on Integrated Urban Hydrometeorological, Climate and Environmental Services* (WMO-No. 1234), Volume I: Concept and Methodology) to work together on scenarios.

- The intra-urban variability in urban form may induce strong spatial variability in the CL-UHI across an urban area. Awareness of these intra-urban differences is important. In rapidly developing cities, with new neighbourhoods being built and existing neighbourhoods being rebuilt, it is important to "consider the climate at the early stages of urban development" (Oke et al., 2017). Consequently, a single CL-UHI value is not sufficient for developing urban heat mitigation strategies.

8.6 CHALLENGES FOR FINDING THE RIGHT MEASURES TO MITIGATE CL-UHI

It should be noted that there is no best design that has positive impacts on all urban services (Chapter 3). Typically, trade-offs are needed. The CL-UHI mitigation strategies may have secondary negative impacts that have to be assessed in the context of all urban services. Examples include:

- A reduction of CL-UHI intensity can have both positive and negative impacts on concentrations of primary and secondary pollutants. A reduction of the daytime temperatures reduces the potential for ozone formation. In addition, urban greening can reduce ozone formation potential through shade, reducing radiation. However, a reduced night-time CL-UHI might lower the UBL height, increasing pollutant concentrations (Section 3.2).

- CL-UHI reduction measures are likely to have different effects on air quality in cities of different sizes and urban forms, in different locations and with different emission and climate conditions. Therefore, it is recommended that urban design considerations should not only include impacts on CL-UHI using the corresponding metrics for extremes (Table 2.2, part (a)) or seasonal and annual values (Table 2.2, part (b)) but also other impacts, including those associated with air quality and energy use. Taking an IUS view allows for unintended consequences to be explored at different scales and from a multi-agency perspective (Grimmond et al., 2020; *Guidance on Integrated Urban Hydrometeorological, Climate and Environmental Services* (WMO-No. 1234), Volume I: Concept and Methodology and *Guidance on Integrated Urban Hydrometeorological, Climate and Environment Services* (WMO-No. 1234), Volume II: Demonstration Cities).

- Increasing pavement and wall albedo may decrease CL-T and thus CL-UHI, but it increases mean radiant temperature as well as the amount of energy reflected to the buildings with potential net adverse effects for outdoor thermal comfort and building energy consumption. In addition, high albedo "smart" surfaces such as cool streets, roofs and walls can reduce energy demand for cooling but might increase ozone formation (Section 3.2). Improved insulation can reduce demand for both cooling and heating and also reduces anthropogenic heat emissions, which also reduces CL-UHI.

- Roof albedo changes that are beneficial in summer may be detrimental in winter if they increase heating demand. If the goal of an intervention is to save energy, the net annual balance should be considered. The intervention should be compared to other practices such as efficient roof insulation or other measures which may have a smaller impact on CL-UHI but result in greater savings relative to investment.

- Increasing evaporation may reduce CL-UHI but has little impact on thermal comfort and building energy loads, as both depend on the enthalpy of the air (which includes humidity effects) and not just temperature.

- The beneficial impacts of vegetation on CL-UHI by evapotranspiration depend on water availability. In many climates, increasingly severe water shortages may limit water for urban irrigation. Thus, even if vegetation may be the most effective temperature reduction measure, it may not be possible to implement it because of water scarcity.

- Street trees reduce CL-UHI and daytime mean radiant temperature by providing shade, but may reduce ventilation in small urban canyons (decreasing comfort) and in consequence reduce dispersion (increasing pollutant concentrations and exposure). Additionally, trees emit a range of volatile organic compounds, many of which are precursors for ozone formation. Increased ozone concentrations impact the health of people (respiratory and cardiovascular diseases). However, vegetation takes up CO_2, and other pollutants are deposited onto the vegetation, which reduces concentrations of primary pollutants. Trade-offs need to be found.

- Reducing the S-UHI does not automatically lead to a reduction in CL-UHI, or a reduction in heat stress and energy consumption (Stewart et al., 2021).

- There are co-benefits associated with measures lowering the urban area-induced heat risk: increased access to green and blue spaces can benefit mental health and well-being, reduce heat and air pollution and help reduce atmospheric CO_2 concentrations. However, more shading and trees might reduce the ventilation in the canopy layer and the stagnant air might lead to increased air pollution and reduced thermal comfort. In some areas, the additional green and blue spaces may increase relative humidity to levels that might further reduce well-being as assessed by thermal indices (Subsection 3.1.2). In addition, more vegetation increases the pollen load in urban areas which is an additional threat for allergy sufferers (combined with a longer pollen season in urban areas; Section 3.4).

- Increasing the streets' ventilation potential by a better street channelling can reduce both heat stress and air pollution in the UCL. However, a reduced CL-UHI intensity might reduce turbulent mixing, thus decreasing the UBL, resulting in higher near-surface concentrations of primary pollutants (CO, NO_x). Thus, both effects need to be carefully assessed.

- The measure taken, such as a new green area, must be clearly defined before implementing it, to assess its impacts on and interactions with the CL-UHI and other features, for instance air quality. Many of the feedbacks within the urban area are dynamic and therefore need to be described within the models used for assessment (Chapter 6). Their influences may be largest when natural radiative fluxes are smallest. For example, wintertime CL-UHI may be influenced by anthropogenic heat emission from both traffic and building energy management, which in turn impacts atmospheric composition (Section 3.2) and health (Section 3.1). Once the measure has been implemented it is necessary to ensure that the changes that are occurring in the urban fabric are incorporated into the databases that describe the city (Chapter 4).

The presence of a city, with its buildings, streets, parks and other urban structures, modifies the local climate making it different from the surrounding rural climate. While daytime CL-UHI intensities are low, the values at night-time are higher. Through effective management of the urban form, it is possible to create microclimates that are more comfortable than those of the rural surroundings, especially during daytime, as the presence of daytime urban cool islands indicates (Kuttler et al., 2015; Martilli et al., 2020). Night-time reductions remain difficult for two principal reasons: (a) with heat storage in dense urban areas being larger than in the rural surroundings, the heat stored during the daytime is released during the night; and (b) wind speed is reduced by the flow resistance of the 3D urban structures, with the result that the surface energy budget has reduced heat fluxes due to lower wind speeds. Despite these difficulties, well-designed urban development can keep CL-UHI within tolerable limits.

APPENDIX 1. A CASE STUDY OF INFLUENCES ON CL-UHI AND OTHER TEMPERATURES

The CL-UHI is the canopy layer air temperature difference between urban and surrounding rural areas (Chapter 2). It is important to understand the types of UHI (Section 2.6) and atmospheric temperature-related features when talking to stakeholders and end users with different application needs (Chapter 3). This Appendix can help to ensure that the same feature is being discussed. For illustration purposes, model simulation results are used.

Set-up of sensitivity simulations

To illustrate influences contributing to the CL-UHI, a set of idealized simulations with the mesoscale Weather Research and Forecasting (WRF) model coupled to the multi-layer urban canopy parametrization Building Effect Parameterization – Building Energy Model (BEP–BEM) (Martilli et al., 2002) are presented (Table A1.1). In all cases, the urban area has the same characteristics (compact low rise, LCZ 3; Figure 4.1), size (10 × 10 km^2), and surroundings (flat terrain) with case-specific homogeneous rural land use. The simulations are performed for 21 June (no particular year, northern hemisphere summer solstice) with a geostrophic wind of 6 m s^{-1} from the West. The initial specific humidity is the same in all simulations (0.005 kg kg^{-1}), but the soil moisture, land use in the rural area and latitude differ. Soil moisture is the same in both urban and rural areas but varies from 0.1 m^3 m^{-3} (dry case) to 0.4 m^3 m^{-3} (wet case). The urban fraction (building and paved) is assumed to be 90% in the urban area. Simulations start for 18:00 local solar time (LST). The assessments provided here are for a full day, from 00:00 to 24:00 LST. The CL-UHI is computed as the difference between the value at the centre of the city and the value 15 km upwind of the city's upwind edge, which is considered to be far enough from the city to reduce the upwind influence of the city.

The simulation results are discussed in the sections that follow. Note that these results are selected to illustrate the influence factors (first two sections below) and illustrate differences between CL-UHI intensity and other temperature-related phenomena that cannot be described by the CL-UHI (remaining sections).

Soil humidity matters

The differences in soil moisture cause differences in the latent heat fluxes between the dry and wet cases (Table A1.1). In the dry cases, the atmospheric humidity stays almost constant at 0.005 kg kg^{-1}, while for the wet case humidity increased to 0.012–0.014 kg kg^{-1} in the atmosphere and the soil moisture decreased due to evapotranspiration by the end of the simulation (not shown). In the *dry_mid_lat* case the urban area has a higher maximum CL-T than in the *wet_mid_lat* case (Figure A1.1a), but lower daytime CL-UHI values (Figure A1.1b).

Table A1.1. Characteristics of idealized mesoscale model case study simulations with WRF/BEP–BEM

Case	*Land use in rural area*	*Latitude*	*Climate*	*2 m air temperature (°C)*	*Soil moisture (m^3 m^{-3})*
dry_mid_lat	closed-canopy shrubland (LCZ C)	45° N	Dry	27	0.1
wet_mid_lat	deciduous broadleaf forest (LCZ A)	45° N	Wet	27	0.4
dry_low_lat	closed-canopy shrubland (LCZ C)	25° N	Dry	32	0.1
dry_high_lat	closed-canopy shrubland (LCZ C)	55° N	Dry	22	0.1

Note: Temperature and soil moisture values are initial values for the whole domain.

Source: Table provided by Alberto Martilli.

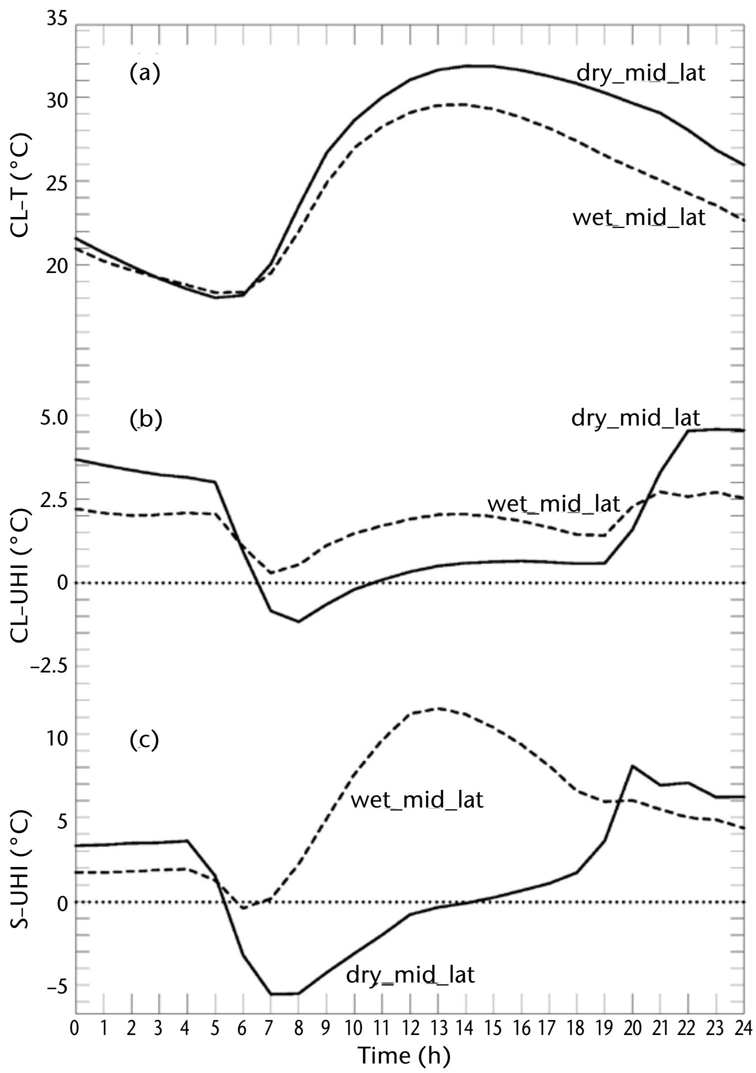


Figure A1.1. Results of idealized simulations with WRF/BEP–BEM with values for: (a) urban near-surface air temperature (CL-T) at the urban centre, (b) the CL-UHI as the difference of temperatures upwind of the urban area and at the urban centre, and (c) S-UHI for the same places as (b).

Source: Figure provided by Alberto Martilli.

In the *dry_mid_lat* case, CL-UHI may be negative during the day, indicating an urban cool island (Figure A1.1b). For this case CL-UHI intensity is at its maximum at night (for reasons see Subsection 2.5.2) and is higher than for the *wet_mid_lat* case, which has similar values at day and night (Figure A1.1b).

Latitude matters

The latitude (altitude is not investigated here) determines the amount of solar radiation received and angles of incidence of direct sunlight, and thus the available energy for the surface energy budget. For latitudes 25 °N (*dry_low_lat* case), 45 °N (*dry_mid_lat* case) and 55 °N (*dry_high_lat* case), latitude-representative air temperatures were chosen to initialize the simulations (Table A1.1).

In the simulations, CL-T for *dry_high_lat* (55° N) is in a range between 14 °C and 27 °C, for *dry_mid_lat* (45° N) it is in the range between 18 °C and 32 °C, while for the *dry_low_lat* (25° N) case CL-T reaches almost 40 °C (Figure A1.2a). However, the CL-UHI values are very

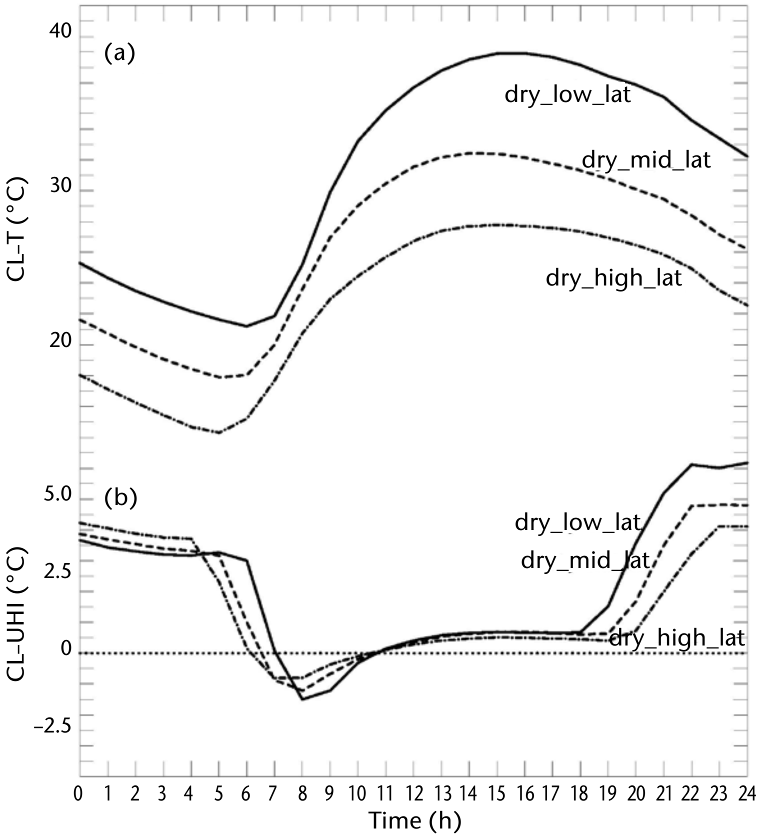


Figure A1.2. Modelled (a) CL-T and (b) CL-UHI for three cases: dry_low_lat (25° N), dry_mid_lat (45° N) and dry_high_lat (55° N) (Table A1.1).

Source: Figure provided by Alberto Martilli.

similar for all three cases (Figure A1.2b), especially during the day. Therefore, while cities may have similarly large CL-UHI intensities, only those at lower latitudes, which already experience a warmer climate, might have large urban heat problems.

S-UHIs versus CL-UHIs

Depending on humidity, S-UHIs and CL-UHIs peak at different times (Figure A1.1b, c). The two quantities have different magnitudes and different controls (Section 2.6). Note that the modelled urban surface temperature used to calculate the S-UHI (Figure A1.1c) is derived from the upward longwave radiation from roof and roads only, not from the total upwelling longwave radiation, and therefore is most comparable to a satellite nadir (which would see the plan area of vegetation) view (a non-nadir view sees walls, vegetation, roof shading). The differences in the results for the CL-UHI and S-UHI show that it is not possible to design or evaluate an urban heat mitigation strategy (Chapter 8) aiming to improve (decrease or increase) the CL-UHI based on the S-UHI alone (Martilli et al., 2020).

Large CL-UHI is not necessarily related to high urban temperatures

A large CL-UHI intensity (see dry cases in Figure A1.1b, A1.2b) does not necessarily indicate high temperatures in the urban area in the absolute sense, and therefore it cannot be used to assess the existence of urban overheating (for instance CL-T >30 °C). The CL-UHI is part of the temperature signal measured within the urban area and depends on several factors, including the regional climate of the urban area and its surroundings (Chapter 2). Furthermore, the timing of maximum values for the CL-UHI and CL-T differs: in general, daily CL-UHI intensity is at its maximum at night (Chapter 2, Figure A1.1b, A1.2b), whereas the maximum of CL-T is during the day (Figure A1.1a, A1.2a). This is relevant because the time of maximum CL-T has implications for heat exposure in urban areas (Section 3.1) which cannot be addressed exclusively by reducing the maximum CL-UHI (for metrics see Table 2.2; for mitigation see Chapter 8).

The CL-UHI does not create heatwaves

A heatwave is driven by regional synoptic conditions that influence both urban and rural areas, and is therefore not caused by the presence of an urban area. The heatwave and CL-UHI will, however, interact, modifying local weather. The spatial scale of the heat wave is larger than the urban area itself. A heat wave lasts several days, while the CL-UHI has a diurnal pattern in addition to annual changes. Because synoptic conditions associated with heatwaves such as high pressure, stagnation and low wind speeds are often favourable for CL-UHI formation (Subsection 2.5.3), large CL-UHI values can often be observed during heat waves. Thus, consecutive "hot nights" are more likely to occur in urban than rural areas.

The CL-UHI is not global warming

Due to the CL-UHI, urban areas are warmer than rural ones, especially at night, and thus climate change will lead to higher values in urban areas than in rural areas. However, the CL-UHI should not be mistaken for an indication of global warming or climate change. Greenhouse-gas induced global warming occurs at different spatial and temporal scales and has different causes than the CL-UHI. The CL-UHI contributes only slightly to global warming; however, when using measurements to assess global warming it needs to be considered that the data taken in an urban area might be influenced by the urban area (Subsection 5.4.3).

There can be feedbacks between global warming and the CL-UHI. For example, a warmer climate might lead to more heatwaves, increasing CL-UHI (see previous subsection). Also, excessive energy release, for instance from space cooling, increases anthropogenic heat flux that in turn increases CL-UHI intensities (de Munck et al., 2013) (surface influences explained in Subsection 2.5.1). There are indications that CL-UHI intensities may change with climate change: no changes to slight increases or decreases are found for cities around the globe in model studies (Oleson et al., 2011; Katzfey et al., 2020). To assess this effect for a specific urban area, changes in the synoptic situation, as well as changes in the urban characteristics (Chapter 4) must be considered for the scenario assessment. Modifications to urban design (Chapter 8) might change the CL-UHI but might not influence greenhouse gas emissions which contribute to global warming.

CL-UHI intensity is not simply an assessment of heat added by the urban area

As explained in Section 2.3, the CL-UHI is an atmospheric warming effect associated with cities. However, there are many influences and factors. Furthermore, CL-UHI intensities are based on temperature differences and thus need a non-urban reference, and difficulties can arise in finding the proper reference values. The ideal way for determining the CL-UHI would be to have data from the pre-urban setting. This might be possible in model studies, but despite the possibility of performing scenarios with a pre-urban land cover the question that needs to be answered is what the pre-urban land cover might have been (Section 6.2). More pragmatically, measurements or model results in the rural surroundings of the urban area are taken as non-urban reference. However, the temperature measured in a rural area close to an urban area might be influenced by it (advection, see Section 5.2), but taking the rural values upstream of the urban area (as done in the example case study in this Appendix) avoids these problems. Nonetheless, finding the rural reference can be challenging in the Anthropocene when cities are becoming larger and more numerous, their boundaries are less clear, and the closest rural locations to the urban area are frequently agricultural, and therefore also modified by humans (Lowry, 1977; Martilli et al., 2020). Especially in spring and autumn, when the agricultural areas quickly change their vegetation cover, a difference in CL-UHI intensities might be more a result of land cover changes at the rural reference site than at the urban site.

CL-UHI intensities cannot be reduced to zero

The presence of an urban area with its different urban structures modifies the local climate (Section 2.7), making it different from the surrounding rural climate, which may also be modified by human activities. While daytime CL-UHI intensities are low, the values at night-time are higher. Effective management of the urban form might create microclimates more comfortable than in the surrounding rural areas, especially during daytime, while night-time reductions remain challenging (Section 8.6). The heat storage in dense urban areas might still be larger than in the rural surroundings, with the result that daytime stored heat is released to the air during the night. Moreover, wind speeds reduced by the drag from buildings impact the near-surface heat fluxes.

APPENDIX 2. EXAMPLES OF OBSERVATION NETWORKS

Four network approaches with examples are shown here. Germany's Deutscher Wetterdienst (DWD) uses urban–rural pairs (Figure A2a) in seven cities to monitor long-term urban effects on weather and climate. Each urban station is sited in one dominant LCZ and is paired with a more rural site (often the city's airport).

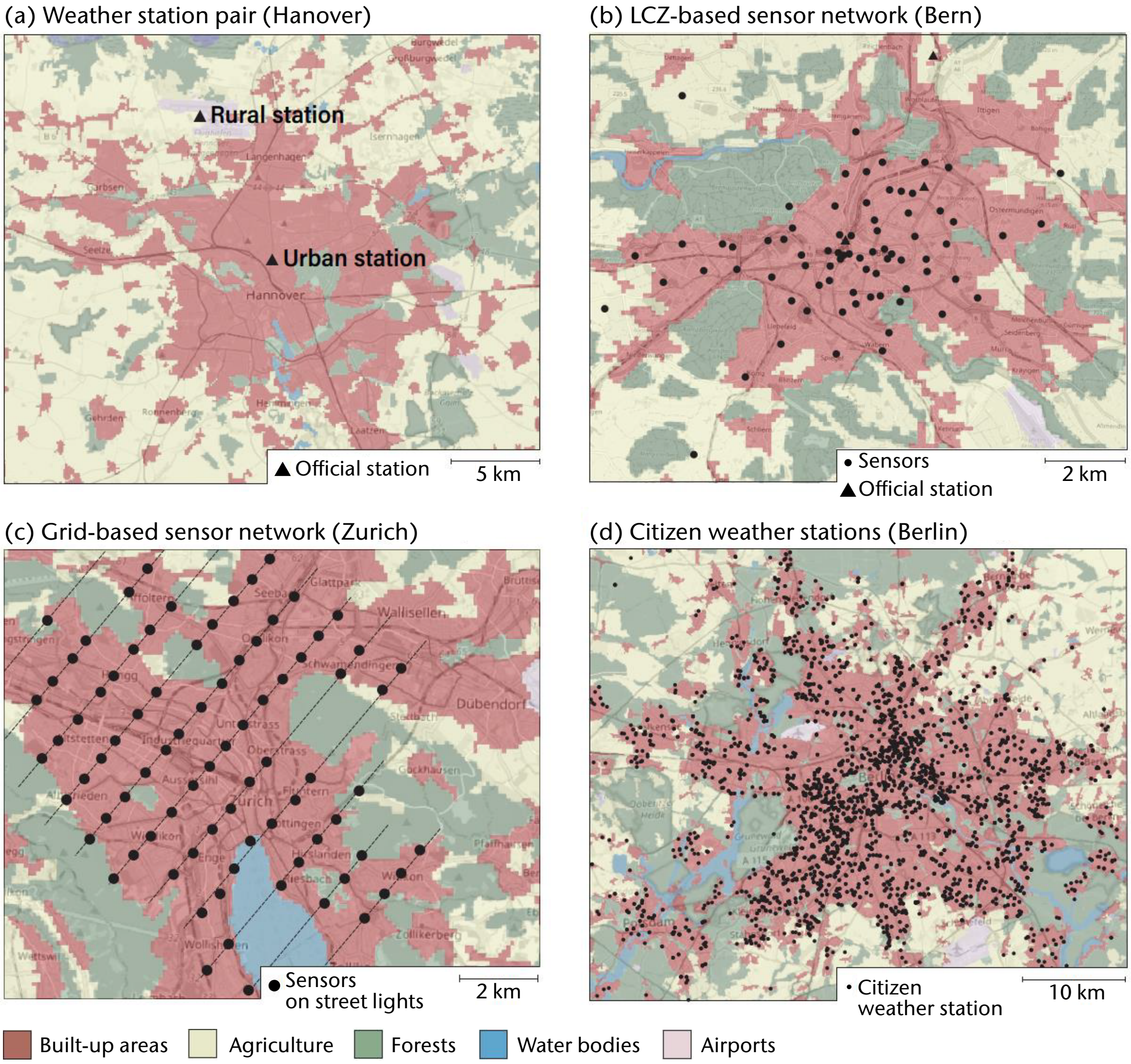


Figure A2. Examples of different observation networks to monitor UCL temperatures used to determine CL-UHI: (a) standard WMO site pair in Hannover, Germany (operated by DWD); (b) sensor network designed based on LCZ classification in Bern, Switzerland (Gubler et al., 2021); (c) grid-based network layout of small automatic weather stations in Zurich, Switzerland (meteoblue AG); and (d) more than 3 000 citizen weather stations (Netatmo) in Berlin, Germany (Fenner et al., 2019).

Source: Background map: © OpenStreetMap contributors; land cover: © European Union, Copernicus Land Monitoring Service 2018 European Environment Agency (EEA). Figure provided by Andreas Christen.

Strategies to plan urban meteorological networks include: mapping the urban area, such as using LCZs (Section 4.3), and manually selecting representative sites (e.g. Bern, Switzerland in Figure A2b) to ensure site-specific thermal source areas are similar independent of wind direction (Subsection 5.4.3). Using a regular grid to distribute sensors (e.g. Zurich, Switzerland, Figure A2c) provides an equal density of sensors across an urban environment that matches numerical model grids. An irregular but dense network is created by citizen weather stations (e.g. Berlin, Germany, Figure A2d).

APPENDIX 3. MONITORING EXAMPLES

Example 1. Meteorological measurements

Météo-France and the city of Toulouse (France) have constructed an IUS based on a network of approximately 70 stations (Figure A3.1c, d) across the urban to rural area. The network is owned by the city. The IUS provides real-time data and maps of the CL-UHI (Figure A3.1c, d).

The 'rural reference' uses observations in areas of low vegetation (individual area size >0.1 km^2), including fields and crops around the urban area. The average temperatures for these areas are normalized to have a zero mean CL-UHI intensity. For the S-UHI (70 m resolution, Figure A3.1a, b) the same rural areas are used to define the base-level S-UHI.

The CL-UHI and S-UHI intensities can be compared for one day (Figure A3.1a, c) and another night (Figure A3.1b, d):

- The midday S-UHI reaches 15 °C west of central Toulouse at the Airbus factory (extensive sealed surfaces) and at light industrial and commercial areas in the south. At this time the river Garonne appears cold (Figure A3.1a).

- The CL-UHI is more homogeneous, with a lower intensity (Figure A3.1c).

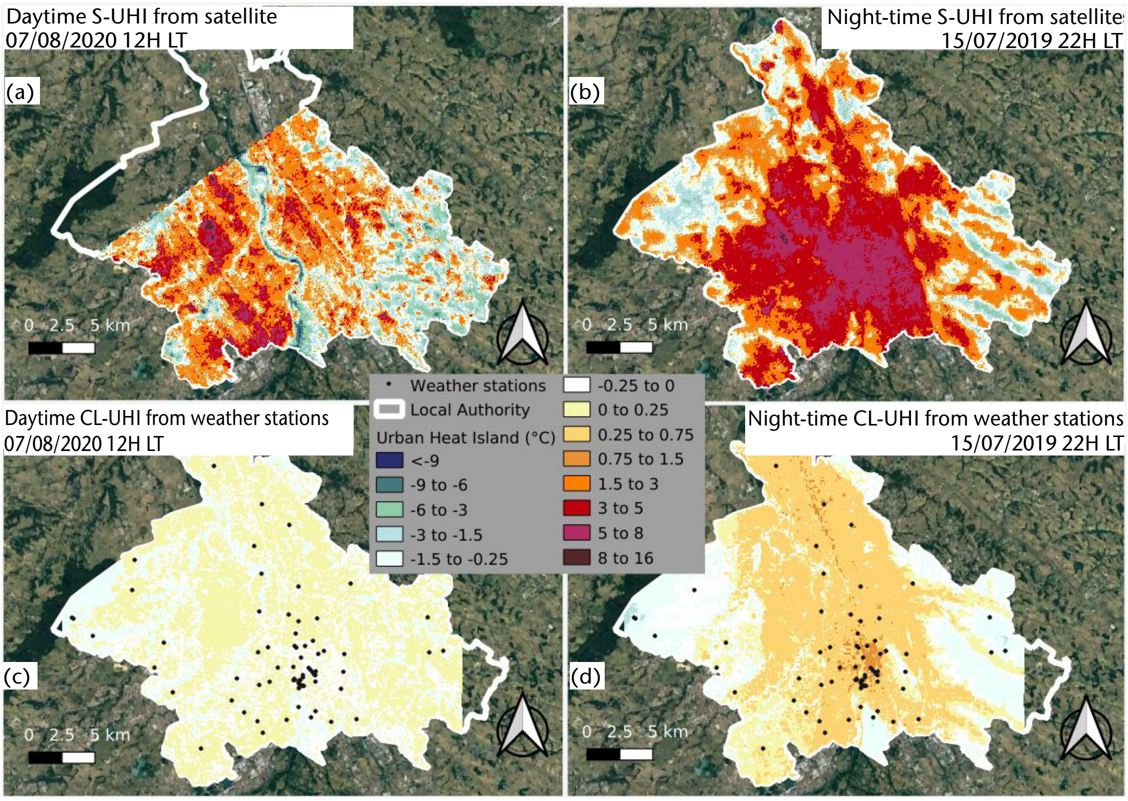


Figure A3.1. Toulouse, France (a, b) S-UHI (ECOSTRESS satellite, 70 m resolution) and (c, d) CL-UHI spatially interpolated network (dots) to 250 m using additional information on urban fraction and altitude (Touati et al., 2020). (a, c) 12:00 local time, 7 August 2020, (b, d) 22:00 local time 15 July 2019.

Source: Guillaume Dumas, National Centre for Meteorological Research (CNRM) laboratory & Toulouse Métropole local authority; with contributions from Aurélie Michel, National Office for Aerospace Studies and Research (ONERA) laboratory.

– At night the CL-UHI is well pronounced, but the S-UHI is more intense than the CL-UHI (Figure A3.1b, d). The river, visible by higher temperatures, influences both signals.

As satellite data cannot provide the CL-UHI information, a network of meteorological stations (Figure A3.1c, d) was installed. The monitoring network data will be used to develop more IUSs, including supporting future urban planning.

Example 2. Floristic mapping for deriving climate maps of the annual average CL-UHI

Bechtel and Schmidt (2011) used floristic mapping of species composition in combination with in situ measurements (15 years of data) (Schlünzen et al., 2010) to determine the spatial pattern of the climatological average CL-UHI. The presence and absence of 1 643 vascular wild plant species was observed at 1 km^2 resolution (by volunteers) in areas of no or very little maintenance. The species composition data were used to determine Ellenberg indicator values for temperature (EIT) to derive overall temperature preference of the plant species (at 1 km^{2}) (Bechtel and Schmidt, 2011). EIT values are correlated with CL-UHI intensities based on five measurement sites (Figure A3.2).

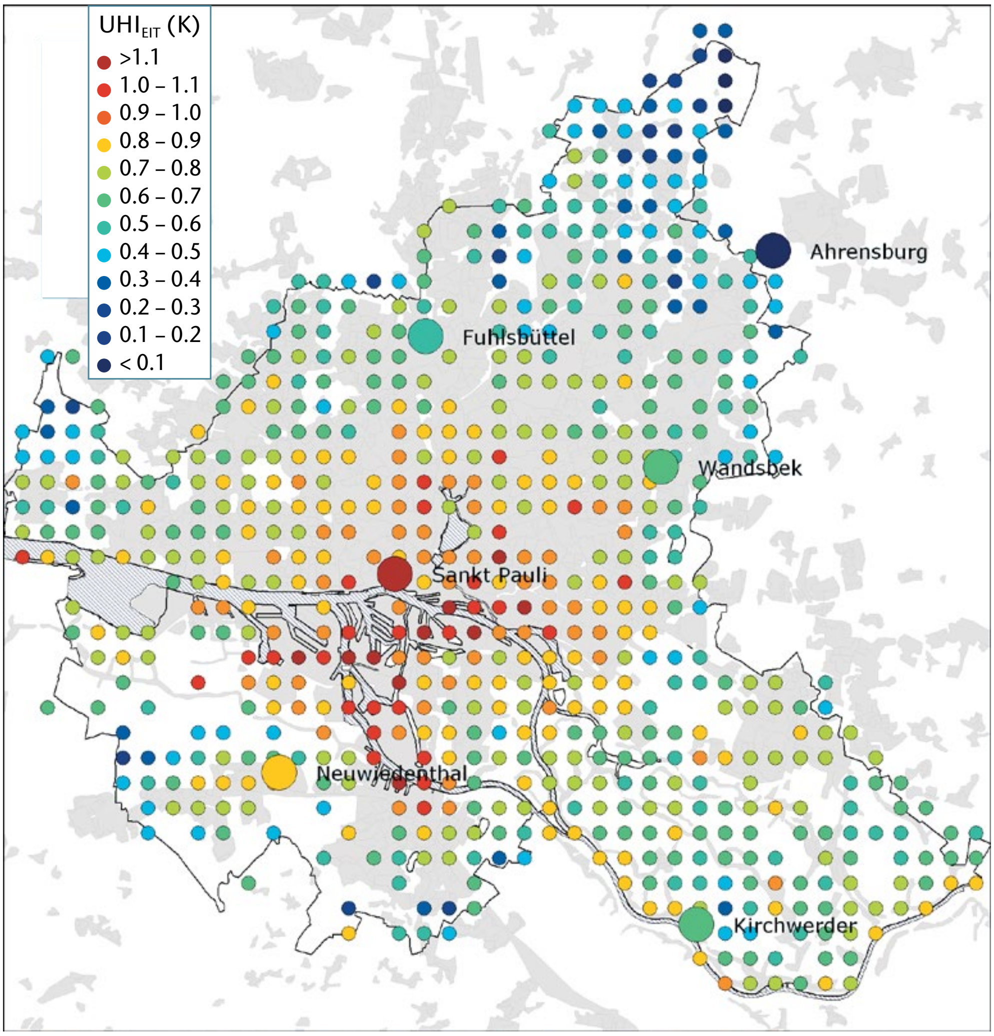


Figure A3.2. Climate average (15 years) heat island intensity for Hamburg, Germany, derived from mean Ellenberg indicator values for temperature (small circles, 1 km^2 grid) compared with decadal average CL-UHI values derived from measurements.

Source: Bechtel and Schmidt (2011).

Using the EIT pattern, a CL-UHI with climate-averaged intensities (Table 4.3 metric: annual average CL-UHI (15 years)) was derived (Figure A3.2). Influences from urban morphology (city centre at St. Pauli) and water bodies (river Elbe, lake and harbour in the centre and south; indicated with dashed lines in Figure A3.2) are evident, with larger values in the city centre and near water bodies. The CL-UHI pattern derived from floristic mapping is much more detailed than using the five measurement sites, allowing average simulated CL-UHI pattern to be verified (Hoffmann et al., 2018).

This approach uses information on plant community diversity for long-term integrated monitoring, and requires knowledgeable plant enthusiasts (for example, community associations, ecology/biogeography students). In addition, the city must allow wild plants to grow (this is becoming common again for many ecological reasons). The community involvement has other benefits beyond providing continuous monitoring of the CL-UHI distribution and intensity.

ABBREVIATIONS

2D	two-dimensional
3D	three-dimensional
AC	atmospheric chemistry
AGL	above ground level
AWS	automatic weather station
BEP–BEM	Building Effect Parameterization – Building Energy Model
CFL	Courant–Friedrichs–Lewy
CL	canopy layer
CL-T	canopy layer temperature (near-surface air temperature)
CL-UHI	canopy layer urban heat island
CORINE	Coordination of Information on the Environment (European Union programme)
DNS	direct numerical simulation
EASYDAB	Earth System Data Branding
GAW	Global Atmosphere Watch
GCM	global climate model
GIS	geographical information system
GM	global model
GURME	GAW Urban Research Meteorology Environment (WMO project)
HVAC	heating, ventilation, and air conditioning
ISL	inertial sublayer or constant flux layer
IUS	integrated urban services (a term comprising integrated urban hydrometeorological, climate and environmental services)
LCZ	Local Climate Zone (classification scheme for land cover and surface form)
LES	large eddy simulation
LST	local solar time
MOST	Monin–Obukhov similarity theory
NMHS	National Meteorological and Hydrological Service
NOAA	National Oceanic and Atmospheric Administration
NWP	numerical weather prediction

ORM	obstacle-resolving model
OSCAR	Observing Systems Capability Analysis and Review
PBL	planetary boundary layer
RANS	Reynolds-averaged Navier–Stokes
RCM	regional climate model
RM	regional model
RRR	Rolling Review of Requirements
RSL	roughness sublayer
SL	surface layer (UCL + RSL + ISL)
S-UHI	surface urban heat island
SS-UHI	subsurface urban heat island
UBL	urban boundary layer
UBL-UHI	urban boundary layer urban heat island
UCL	urban canopy layer
UHI	urban heat island
UCP	urban canopy parameterization
USGS	United States Geological Survey
WIGOS	WMO Integrated Global Observing System
WIS	WMO Information System
WRF	Weather Research and Forecasting model
WUDAPT	World Urban Database and Access Portal Tool

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Appendix 1. Example case study for influences on CL-UHI and other temperatures

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For more information, please contact:

World Meteorological Organization

7 bis, avenue de la Paix – P.O. Box 2300 – CH 1211 Geneva 2 – Switzerland

Strategic Communications Office

Tel.: +41 (0) 22 730 83 14 – Fax: +41 (0) 22 730 80 27

Email: cpa@wmo.int

public.wmo.int

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