Urban Shift for green innovations

URBAN HEAT ISLANDS (UHI)

May 2023

Multicriteria

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Contents

Foreword

Urban Shift (UShift) is an experimental, impact-based, and transdisciplinary education programme that focuses on creating lasting change by bringing together students from Higher Education Institutions (HEI), a Vocational Education Institution (VET), urban experts, and business partners. This is to be achieved by combining intersectional environmental education, knowledge exchange, transdisciplinary collaboration, and sustainable innovation.

By providing the learners with the necessary GREEN LABOUR MARKET SKILLS (digital, green, business and transdisciplinary/resilient skills), UShift is creating a LIVING ECOSYSTEM for 80 learners from diverse backgrounds (urban design, environmental engineering, media and business) that fosters the development of solutions to pressing urban challenges. The learners, divided into two batches, will create 10 startup teams working on urban challenges linked to urban heat islands (UHI)/cooling, and food waste/circularity, or climate/extreme weather predictability and mobility/circularity. Thus, the project allows students to successfully transform into change makers and EU GREEN DEAL AMBASSADORS by equipping them with the knowledge and experience needed to become green entrepreneurs and/or future employees of green jobs on the global market.

The culmination of this education programme are two sets of LIVING EXHIBITIONS (8 separate exhibitions) spread across Barcelona, Genoa, Copenhagen, Stuttgart, and Vienna. Their purpose is to showcase the solutions and success stories that flourished from the UShift project lifetime in order to raise public awareness for humanity's biggest challenges (i.e., pressure on planetary boundaries, resource scarcity, persistent poverty, social injustice, exponential population growth, urbanization boom, global pandemics, etc.) and interest in the UShift LIVING LABS curricula, the European Green Deal, and the United Nations (UN) Sustainable Development Goals (SDGs). This will be done through an interactive exhibition programme made up of panel and roundtable discussions, media discourse, artistic events, workshops and knowledge exchange via the exhibition of the developed courses and start-up prototypes. The goal is to inspire individual stakeholders such as NGOs, consumers, green start-ups, policy makers, and incubators to take part in the global Urban Shift as active change makers.

Even after the project's lifetime, UShift will continue to have a positive impact via the establishment of an easily adaptable LIVING CURRICULUM template and OPEN ONLINE TRAINING sessions that will be made available on YouTube to inspire future transdisciplinary collaboration. Furthermore, the establishment of an ALUMNI NETWORK serves as a tool to foster sustainable project outputs and the continuation of the start-up teams, as well as serves as a channel for peer-to-peer learning, support, knowledge and expertise exchange, collaboration, co-creation, and mentorship between the learners, start-up teams, business partners and urban expert during and after the project.

Urban Shift is a project developed by Wirtschaftsuniversitat Wien - WU (Austria), Institute for Advanced Architecture of Catalonia - IAAC (Spain), Hochschule Der Medien - HdM, (Germany), Wirtschaftskammer Österreich - WIFI (Austria), Multicriteria- MCRIT (Spain), Terra Institute - TERRA (Italy), Pretty Ugly Duckling - PUD (Denmark), Green Innovation Group A/S - GIG, (Denmark), and co-funded by the Erasmus+ Key Action 2 Partnerships For Innovation Alliances For Innovation 2021 Programme of the European Union.

What is an Urban Heat Island (UHI)?

Definition of the Challenge

In our world today, urban populations are increasing rapidly in size as more and more people continue to leave rural areas to migrate to cities. Because of this rapid urbanization, cities require large amounts of energy in order to function properly. Although cities occupy only about 2% of the earth's surface, city dwellers consume over 75% of the total energy resources available to carry out everyday activities in the urban environment (Madlener & Sunak, 2011).

As an urban area develops, changes occur in the natural landscape. **Buildings and roads begin to replace open space and vegetation**, causing surfaces that were once pervious and moist to become impervious and dry. These changes lead to the development of a phenomenon known as an urban heat island (UHI).

UHIs occur when a ***densely populated urban area experiences significantly higher temperatures than the surrounding rural or less populated area***. When naturally vegetated surfaces such as grass and trees are replaced with **non-reflective, impervious surfaces**, those surfaces absorb a high percentage of incoming solar radiation, causing a warming effect (Taha, 1997).

The heat 'island' is the result of an unintended climate alteration due to a modification of land surfaces, caused mainly by an increase in **urbanization and anthropogenic activities**.

Urban heat islands are an important issue because **they can pose both health and environmental risks due to increased heat exposure and enhanced levels of air pollutants**, specifically ozone. It is imperative that city planners take the heat island effect into account when planning for a city to ensure the best actions are being taken to create a healthy environment for all inhabitants.

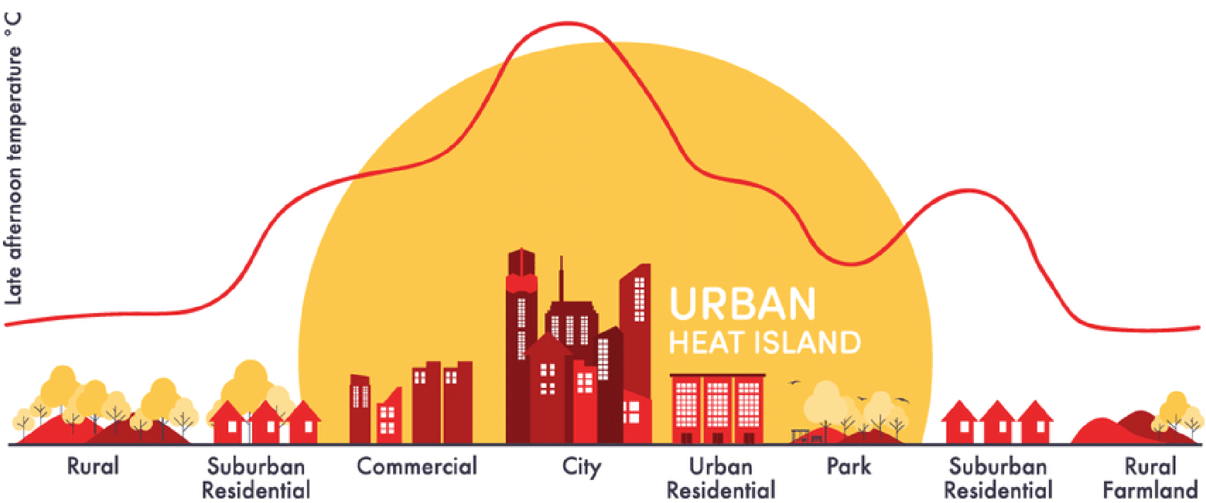


Fig. 1. Urban Heat Island effects upon different territorial environments. Source: Fuladlu et al., 2018.

KEY IDEAS

- Cities occupy only about 2% of the earth's surface but city dwellers consume over 75% of the total energy resources.
- UHIs occur when a densely populated urban area experiences significantly higher temperatures than the surrounding rural or less populated area.
- The heat island effect is related to the building materials of the city, and its ability to absorb and retain heat during the day, and emit it at night.
- Urban heat islands are an important issue because they can pose both health and environmental risks due to increased heat exposure and enhanced levels of air pollutants.

Background

History

Luke Howard, a British chemist and amateur meteorologist, was **the first to recognize the effect that urban areas have on local climate**. Between 1800-1830, Howard studied weather and climate in London and analysed temperature records through which he was able to detect and describe the urban heat island phenomenon many decades before any other researchers. His studies showed that temperatures in London, compared to those simultaneously measured in the surrounding countryside, were 3.7°F warmer at night, and cooler during the day (Mills, 2008). He attributed the concentration of smog (which he called 'city fog') to this phenomenon.

Since Howards first contributions towards studying urban heat islands, many researchers have been following his path. The makeup of urban areas differs across the world, causing the heat island effect to be magnified in certain locations rather than others due to geographic characteristics and variances. Researchers suggest the **annual mean air temperature of a city with one million or more people can be 1 to 3°C** (1.8 to 5.4°F) **warmer than its surroundings, and on a clear, calm night, this temperature difference can be as much as 12°C** (22°F) (U.S. EPA, 2008).

Sustained study of the urban climate effect did not begin until the late 1940's when researchers began to explore local variations in atmospheric properties, most notably air temperature. The table below presents a history of the field broken down by decade, with those contributions that represent critical developments in the field (Howard et al., 2009).

Period	Approach
1940-	Observation and description of urban effects using conventional meteor-ological equipment (e.g. thermometers).
1960-	Employment of statistical methods to test hypotheses; Move toward energy budget approach and explanation.
1970-	Application of computer modeling techniques; Observations of energy fluxes; More rigorous definition of urban 'surface', urban scales and observing urban effects.
1980-	Adoption of common urban forms for modeling and measurement; Use of scaled-physical models; Measurement of fluxes in different cities.
1990-	Establishing relationships between urban forms and their climate effect; Urban field projects examined by research teams.
2000-	Improved models of urban geometry; Increased links between modeling and measurement programs.

Fig. 2. Evolution of the UHI study in the 20th century. Source: Howard, 2007.

The work of Luke Howard has a special place in the history of the field because he is the first to recognize the UHI and because his analysis proves so prescient. The International Association for Urban Climate (IAUC) presents the Luke Howard Award to individuals that have made outstanding contributions to the field (Howard, 2007).

How are Urban Heat Islands and Climate Change related?

As it has already been explained, urban heat islands refer to the elevated temperatures in developed areas compared to more rural surroundings. The warming effect that results from urban heat islands is an example of **local climate change**. Local climate changes differ from global climate changes in that their effects are confined to the local scale and decrease with distance from their source. Global climate changes, such as those caused by excess greenhouse gas emissions, are not locally or regionally confined, though **the impacts from urban heat islands and global climate change are often similar**. For example, both urban heat islands and global climate change can increase energy demand, mainly through heating and cooling, and both can cause an increase in air pollution and greenhouse gas emissions.

Urban areas cover less than 3% of the global land area, and the area of extra heat is local and too small to have a direct impact on global climates. However, the UHI has relevance for the study of global climate change because **it makes it difficult to detect the influence of human activity on the global mean temperature**.

Many of the earliest established observation stations used to construct the globally averaged surface temperature record have initially been located near urban areas and their readings may have become contaminated by the UHI as settlements have grown over time. Some of the research on historical data indicates that global temperature trends are not significantly affected by the UHI and the effect on the global temperature trend is no more than 0.05°C through 1990 and not considered significant (e.g., Parker, 2006).

Others contend that attempts to adequately remove the urban effect, e.g., by using empirical relations between city size and UHI magnitude from urban-rural pairs together with population data or satellite measurements of night light used to classify urban and rural stations, may be inadequate and underestimate the urban effect (e.g., Kalnay and Cai, 2003).

Cities, however, **have an indirect responsibility for the observed global warming as the major contributor of green-house gases**. More than half of the world's population currently lives in cities, and, thanks to their intensive metabolism, they release more than 70% of the total emissions of carbon dioxide (CO_2) of anthropogenic origin and a substantial proportion of other known greenhouse gases. In urbanized areas, these emissions have three main causes, which are **transport, energy use in households and public buildings, and manufacturing and industry**, with each sector contributing about one-third of the total. Energy use is sensitive to temperature, and there is a **strong interdependence between the UHI and electricity demand** where fossil fuels are used to generate the electricity that is driving air conditioning. Electricity demand for cooling increases 3%–5% for every 1°C increase in air temperature above approximately 23°C ± 1°C (Sailor, 2002). This implies that a 5°C UHI can increase the rate of urban electric power consumption for cooling by 15%–25% above that used in surrounding rural areas during hot summer months and for cities located in (sub)tropical regions.

UHIs have impacts that range from local to global scales, which emphasize the importance of urbanization to environmental and climate change. Magnitude and rate of urban warming are comparable to that considered possible at the global scale, and any global warming will raise the base temperature on top of which the UHI effect is imposed. At the same time that cities, their inhabitants and infrastructure are exposed to the effects of climate change, **they are also important agents in mitigating global climate change**. Many of the proposed mitigation and adaptation methods to increase the environmental sustainability of cities and make them more resilient to climate change are related to the urban thermal environment.

KEY IDEAS

- Sustained study of the urban climate effect did not begin until the late 1940's.
- Local climate changes differ from global climate changes in that their effects are confined to the local scale and decrease with distance from their source. UHI is an example of local climate change.
- UHI has relevance for the study of global climate change because it makes it difficult to detect the influence of human activity on the global mean temperature.
- Also, there is a strong interdependence between the UHI and energy demand. Cities have an indirect responsibility for the observed global warming as they are the major contributor of green-house gases.

The need for an urban focus on UHI and climate change adaptation in Europe

Climate change is upon us. With global temperature records being broken year after year and increasingly dire prospects for the magnitude of future climate change and its effects, in the 2020s the world and Europe have entered a new era. Unprecedented extreme weather and climate events —

deadly heat waves, devastating droughts, sudden floods sweeping through city streets — are no longer tales from distant lands or far futures but a reality in the European context.

In November 2019, the European Parliament declared a global 'climate and environmental emergency' as it urged all EU Member States to commit to net zero greenhouse gas emissions by 2050 (EP, 2019). At the local level, the climate emergency was recognised by the mayors of 94 major global cities in September 2019 (C40 Cities, 2020). Despite the increasing awareness, the United Nations Environment Programme (UNEP) Emissions gap report 2019 found that, even if all countries' unconditional nationally determined contributions (NDCs) under the Paris Agreement are implemented, we are still on course for a 3.2 °C global temperature rise (UNEP, 2019). Therefore, as recognised by the proposed European climate law, which aims for climate neutrality by 2050 and enhanced climate resilience, **climate change is already creating and will continue to create significant stress in Europe, despite mitigation efforts**. Thus, increasing efforts to enhance adaptive capacity, strengthen resilience and reduce vulnerability are crucial (EC, 2020). The vulnerability of our society and the urgent need to increase its resilience to shocks have been brought home in 2020 by the coronavirus disease 2019 (COVID-19) crisis.

The sense of urgency in addressing climate change is felt by European citizens, too: 2019 will be remembered as the first year when school children initiated climate strikes out of concern for their future. The number of Europeans who consider climate change to be a very serious problem — currently 8 out of 10 — has grown over the past few years, and over two thirds of Europeans believe that adapting to the adverse impacts of climate change can have positive outcomes for EU citizens (EC, 2019).

Cities, towns and other human settlements are particularly important locations for urgent implementation of adaptive measures. As we have already seen, urbanisation is one of the main causes of increased local temperatures, and changes in temperature lead to an increase in energy demand, which, at the same time, raises anthropogenic emissions. What constitutes a challenge is that the proportion of Europeans living in urban areas is expected to increase from nearly 75 % in the present moment to over 80 % by 2050 (Eurostat, 2016). This evidence makes Urban Heat Islands a growing phenomenon.

Adaptation of cities is also necessary from an economic perspective. Urban areas host industry and services and are focal points of economic activity, generally characterised by high values of gross domestic product (GDP) per capita (Lavalle et al., 2017). Failure of climate change mitigation and adaptation was in 2019 seen as the number one risk to the economy in terms of its impact, and the second biggest risk in terms of likelihood of occurrence within the next 10 years, according to the World Economic Forum (WEF) multistakeholder survey. Since 2017, extreme weather has been assessed in the Global risks report as having the highest likelihood among the threats to the economy (WEF, 2020).

KEY IDEAS

- Climate change is happening, projected to continue and posing serious challenges for cities.
- Urban areas are the places in Europe where most people are, and will be, vulnerable to the effects of climate change. UHI will be a growing phenomenon as urbanization is

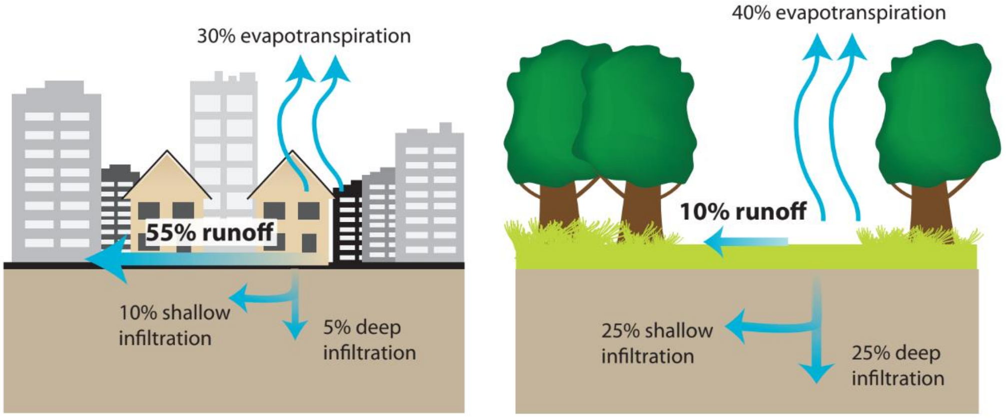
- expected to increase.
- Europe's future depends on strong and resilient cities - towards a joint, multi-level approach to cope with climate change.

Causes: How do Urban Heat Islands form?

Reduced vegetation in urban areas

The UHI effect results from the interaction of different physical processes. One of the main causes of UHI is the reduced vegetation in urban areas.

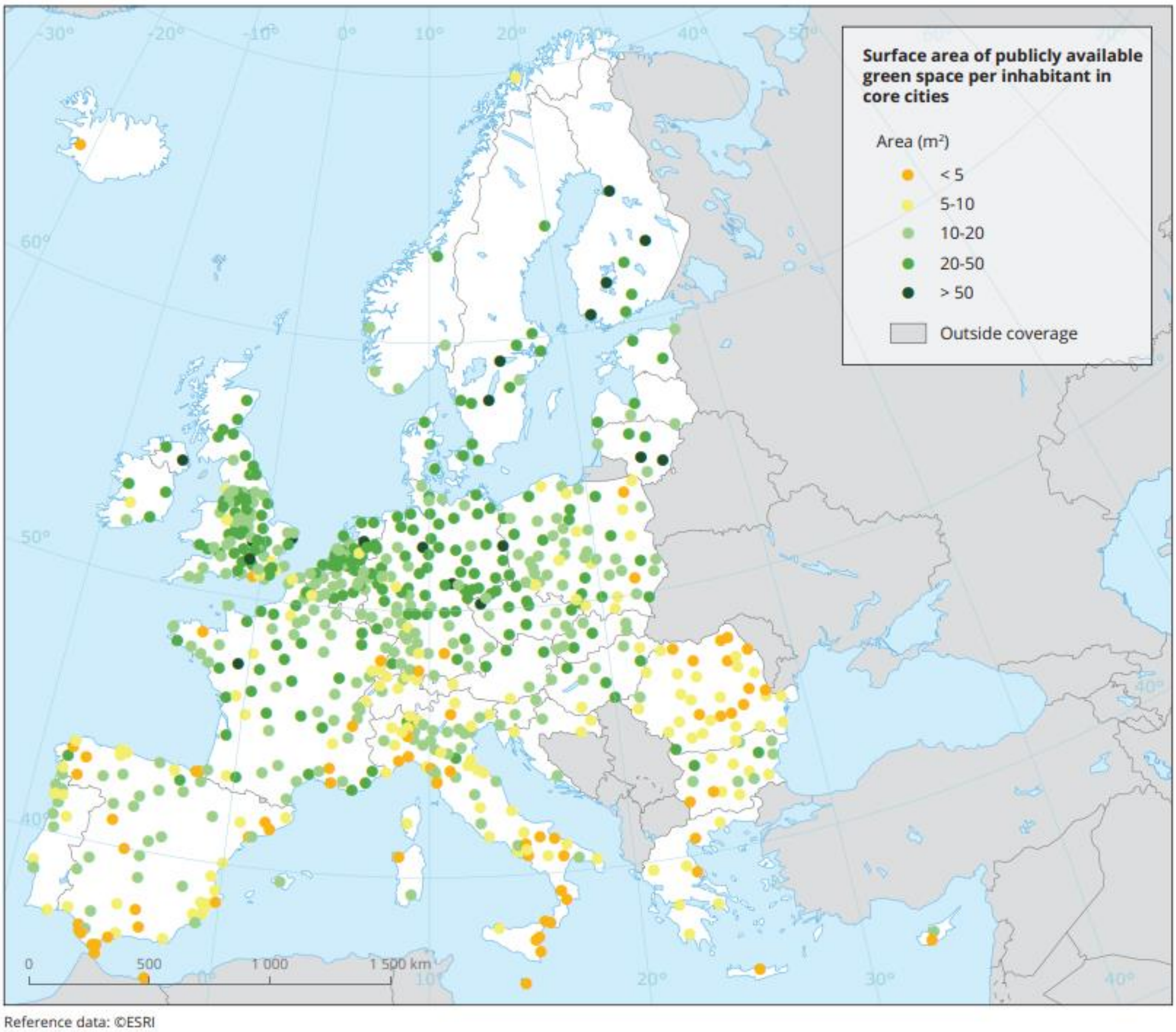
In rural areas, vegetation and open land typically dominate the landscape. Trees and vegetation provide shade, which helps lower surface temperatures. They also help reduce air temperatures through a process called evapotranspiration, in which plants release water to the surrounding air, dissipating ambient heat. In contrast, **urban areas are characterized by dry, impervious surfaces, such as conventional roofs, sidewalks, roads, and parking lots**. As cities develop, more vegetation is lost, and more surfaces are paved or covered with buildings. The change in ground cover results in less shade and moisture to keep urban areas cool. Built up areas evaporate less water (see Figure 3), which contributes to elevated surface and air temperatures.



Highly developed urban areas (right), which are characterized by 75%-100% impervious surfaces, have less surface moisture available for evapotranspiration than natural ground cover, which has less than 10% impervious cover (left). This characteristic contributes to higher surface and air temperatures in urban areas.

Fig. 3. Urban Heat Island effect upon different territorial spaces. Source: Filho et al., 2018.

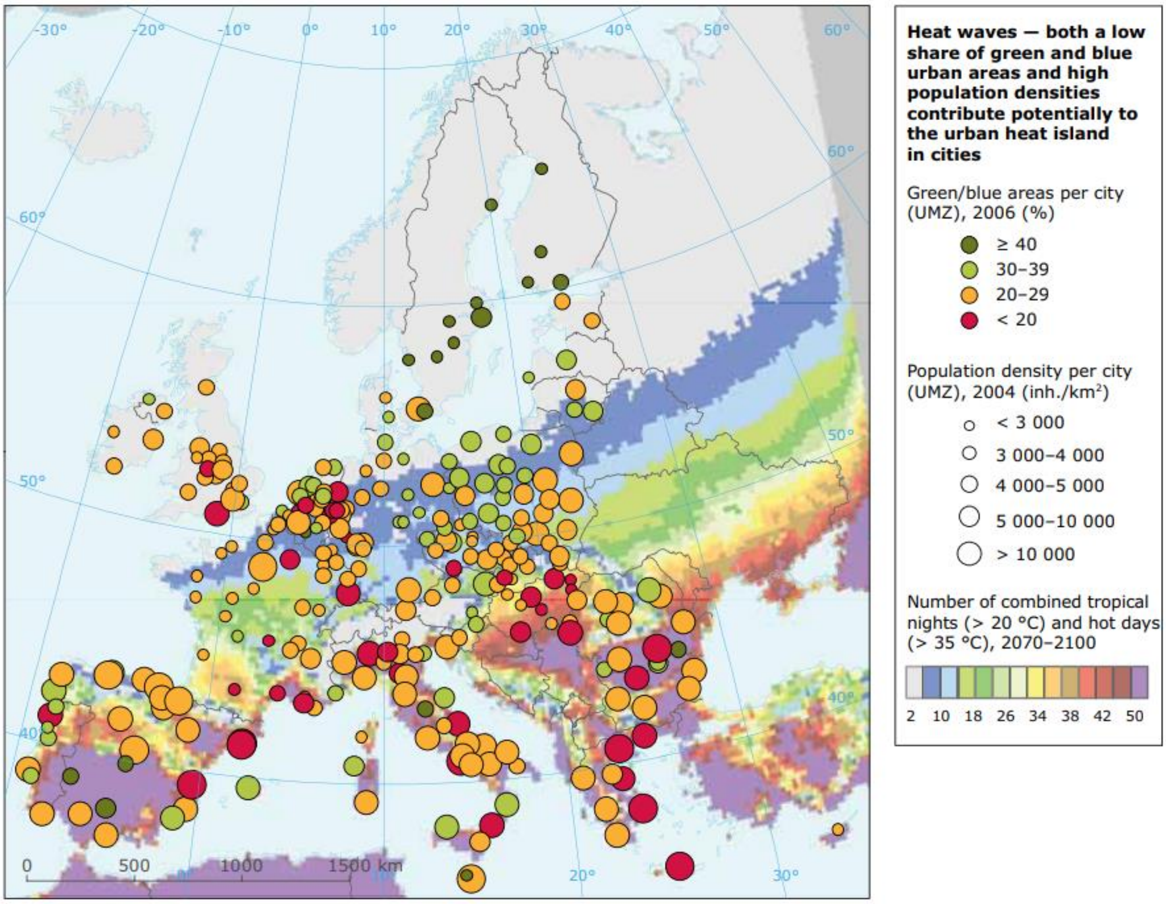
At present, around 40 % of the surface area of European cities consists of green space, with an average of 18.2 m2 of publicly accessible green space per inhabitant. Only 44 % of Europe's urban population currently lives within a walkable distance (300 m) of a public park (Maes et al., 2019).



Map 1. Surface area of publicly available green space per inhabitant in core cities. Source: EEA, 2020, adapted from Maes et al., 2019.

Notwithstanding, the presence and accessibility of green areas (both public and private) varies greatly between countries and between individual cities. According to the 2016 European Quality of Life Survey, **the highest numbers of people with difficult access to recreational or green areas were in Albania, Turkey, Romania, and the lowest numbers were in Denmark, Sweden and Finland** (Eurofound, 2016). The access to publicly available green space shows a North-South disparity in Europe (see Map 1). Therefore, in some of the cities where the highest increase in frequency of heatwaves is projected (Map 1), poor access to green space may deprive the urban population of an effective cooling mechanism.

Map 2.5 Heatwaves — both a low share of green and blue urban areas and high population densities can contribute to the urban heat island effect in cities



Map 2. Green areas and blue areas (with water bodies) per city. Source: EEA, 2006.

Materials

Properties of urban materials, in **particular solar reflectance, thermal emissivity, and heat capacity**, also influence urban heat island development, as they determine how the sun's energy is reflected, emitted, and absorbed.

The following figure shows the typical solar energy that reaches the Earth's surface on a clear summer day. Solar energy is composed of ultraviolet (UV) rays), visible light, and infrared energy, each reaching the Earth in different percentages:

- 5 percent of solar energy is in the UV spectrum, including the type of rays responsible for sunburn.
- 43 percent of solar energy is visible light, in colours ranging from violet to red.
- 52 percent of solar energy is infrared, felt as heat.

Energy in all these wavelengths contributes to urban heat island formation.

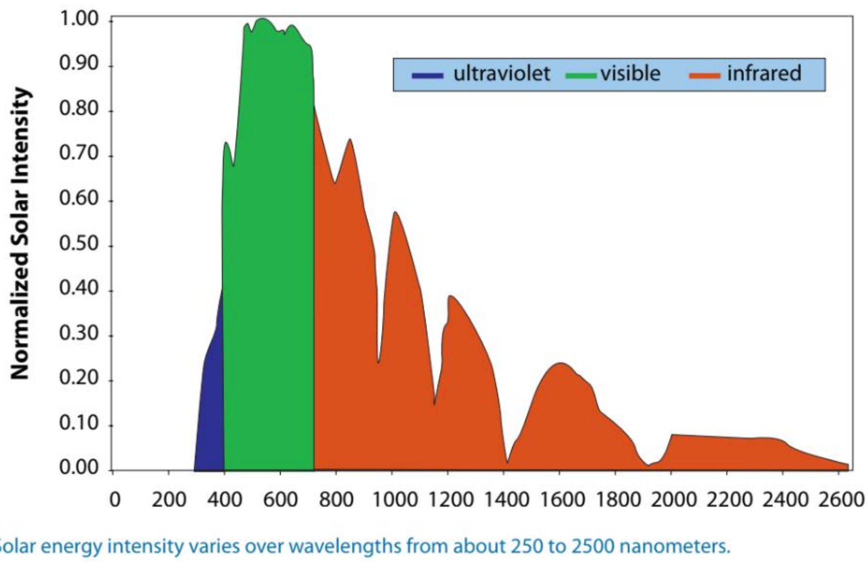


Fig. 4. Solar Energy versus Wavelength Reaching Earth's Surface. Source: EPA, 2017.

Solar reflectance, or albedo, is the percentage of solar energy reflected by a surface. Much of the sun's energy is found in the visible wavelengths; thus, solar reflectance is correlated with a material's colour. **Darker surfaces tend to have lower solar reflectance values than lighter surfaces**. Researchers are studying and developing cool coloured materials, though, that use specially engineered pigments that reflect well in the infrared wavelengths. These products can be dark in colour but have a solar reflectance close to that of a white or light-coloured material.

Urban areas typically have surface materials, such as roofing and paving, which have a lower albedo than those in rural settings. As a result, **built up communities generally reflect less and absorb more of the sun's energy**. This absorbed heat **increases surface temperatures** and contributes to the formation of surface and atmospheric urban heat islands (EPA, 2017).

Although solar reflectance is the main determinant of a material's surface temperature, **thermal emittance**, or emissivity, also plays a role. Thermal emittance is a measure of a surface's ability to shed heat or emit long-wave (infrared) radiation. All things equal, surfaces with high emittance values will stay cooler, because they will release heat more readily. Most construction materials, except for metal, have high thermal emittance values. Thus, this property is mainly of interest to those installing cool roofs, which can be metallic.

Another important property that influences heat island development is a **material's heat capacity**, which refers to its ability to store heat. Many building materials, such as steel and stone, have higher heat capacities than rural materials, such as dry soil and sand.

As a result, cities are typically more effective at storing the sun's energy as heat within their infrastructure. Downtown metropolitan areas can absorb and store twice the amount of heat compared to their rural surroundings during the daytime.

Heating and cooling energy needs

The formation of UHIs is not only due to a city's fabric. **Heat emitted by human activities - such as cooling or heating of buildings, industrial processes, and transportation - also plays a key role**. These anthropogenic heat emissions can increase air temperatures by approximately 1-3ºC (Ma et al., 2017).

Although anthropogenic heat emission is generally larger in winter, **the negative impact is strongest in summer during heat waves**, when already high temperatures are being increased even further.

One of the summer sources of anthropogenic heat emissions is **air conditioning systems**. Although they improve indoor conditions through cooling, air conditioning systems can negatively influence the outdoor urban microclimate due to their emission of waste heat in the urban canyon. Modelling studies have shown that during prolonged heat periods, air conditioning usage can increase urban air temperatures up to 3ºC locally (de Munck et al. 2013).

Air conditioning usage in cities increases	Energy demand increases	Increase of climate change and UHI effect
Due to rising temperatures and prolonged heat wave events, high demand for cooling of indoor spaces has arisen	The growing use of air conditioners in homes and offices around the world is expected to be one of the top drivers of global electricity demand over the next three decades	Air conditioning systems further add to the UHI effect as the waste heat generated by these systems increases local temperatures in built-up areas

Table 1. Anthropogenic heat feedback cycle, based on ZAMG & Hollósi and de Wit, 2020.

Additional factors

Weather and location strongly influence urban heat island formation. While residents have little control over these factors, communities can benefit from understanding the role they play.

Weather	Geographic location
Two primary weather characteristics affect UHI: wind and cloud cover. In general, urban heat islands form during periods of calm winds and clear skies, because these conditions maximize the amount of solar energy reaching urban surfaces and minimize the amount of heat that can be convected away. Conversely, strong winds and cloud cover suppress UHI.	Climate and topography, which are in part determined by a city's geographic location, influence UHI formation. For example, large bodies of water moderate temperatures and can generate winds that convect heat away from cities. Nearby mountain ranges can either block wind from reaching a city, or create wind patterns that pass through a city. Local terrain has a greater significance for heat island formation when larger-scale effects, such as prevailing wind patterns, are relatively weak.

Table 2. Additional factors contributing to UHI.

Urban Heat Islands in Europe

Overview of climate-related risks to European cities

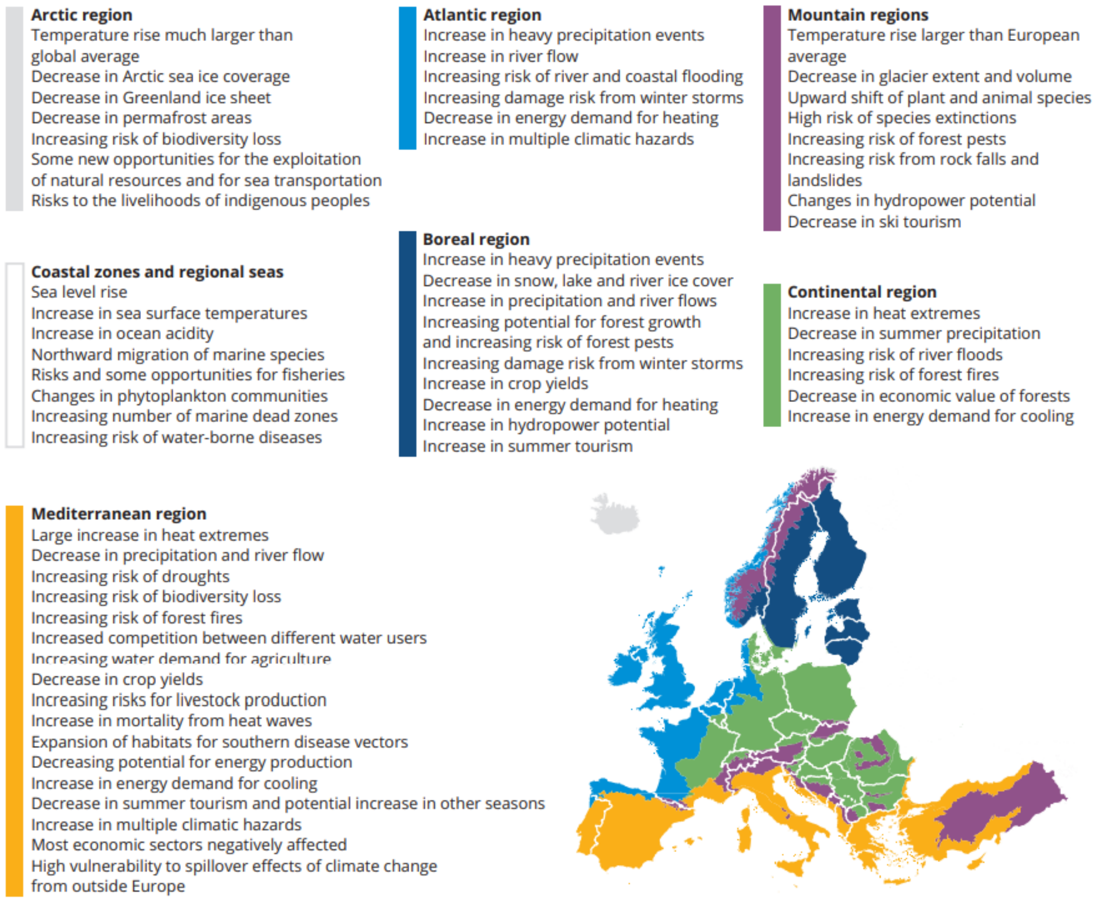
The key climate change hazards and impacts in Europe, both present and projected, vary among regions (EEA, 2017b).

Boreal region	Atlantic region	Mediterranean region	Continental region
Projections suggest a larger than average temperature increase, in particular in winter, an increase in annual precipitation and river	The low-lying coastal areas have been affected by coastal flooding in the past and these risks are expected to increase as a result of sea level rise and potentially	It is facing decreasing precipitation and increasing temperatures, in particular in summer. The competition between different water users over decreasing water	Increasing heat extremes are a key hazard. Together with reduced summer precipitation, they can increase drought risk,

flows, less snow and greater damage from winter storms. More frequent and intense extreme weather events are projected to have an adverse impact on the region.	storm surges. Stronger extreme precipitation events, in particular in winter, are projected to increase the frequency and intensity of winter and spring river flooding, urban floods and associated impacts.	resources is expected to increase. Forest fires and adverse impacts of heat on human health and well-being are expected to increase, alongside propensity for vector-borne diseases.	health risks and energy demand in summer.

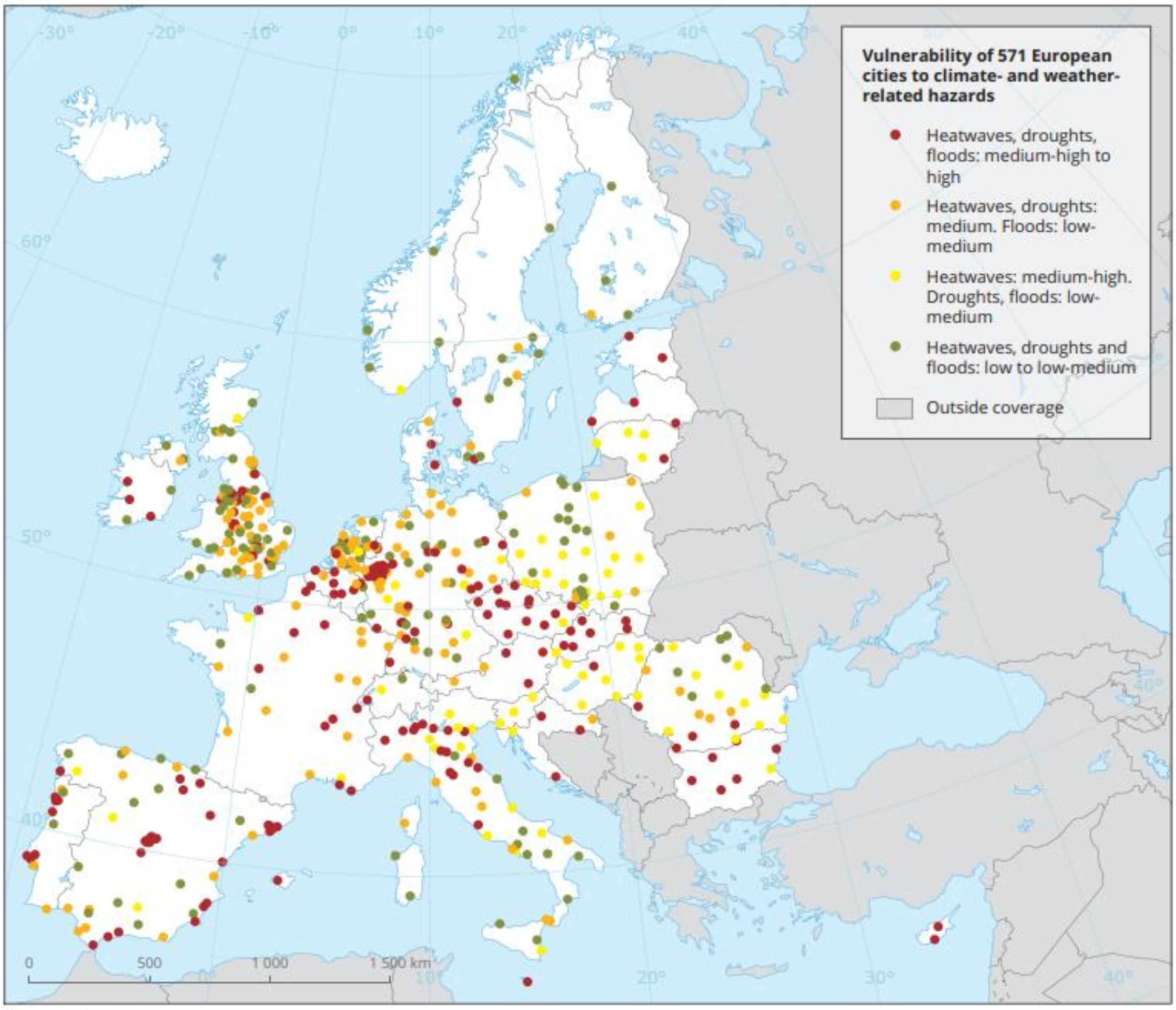
Table 3. Climate change hazards and impacts in Europe among regions, based on EEA 2017.

A more detailed description of the different climate-related risks is provided in the following map:



Map 3. Key observed and projected climate change and impacts for the main biogeographical regions in Europe. Source: EEA, 2020.

Within the framework of the Horizon 2020 research project Reconciling adaptation, mitigation and sustainable development for cities (Ramses), Tapia et al. (2017) assessed the vulnerability of 571 European cities using a range of indicators from thematic domains. The cities were clustered according to their vulnerability to heatwaves, flooding and droughts. According to this analysis, it is difficult to identify clear spatial patterns of vulnerability among European cities. **The cities with high levels of vulnerability to all hazards are more numerous in central Europe, Estonia, parts of Germany, Latvia and Romania but also scattered throughout Europe**.



Map 4. Vulnerability of 571 European cities to climate- and weather-related hazards. Source: EEA, 2020, based on Tapia et al., 2017.

High temperatures

Climate projections for Europe show a temperature increase across the continent, the strongest seasonal warming occurring during summer in southern Europe and during winter in northern Europe (IPCC, 2014). In particular, the projections show a marked increase in temperature extremes, leading to an increase in the number, frequency, and intensity of heatwaves.

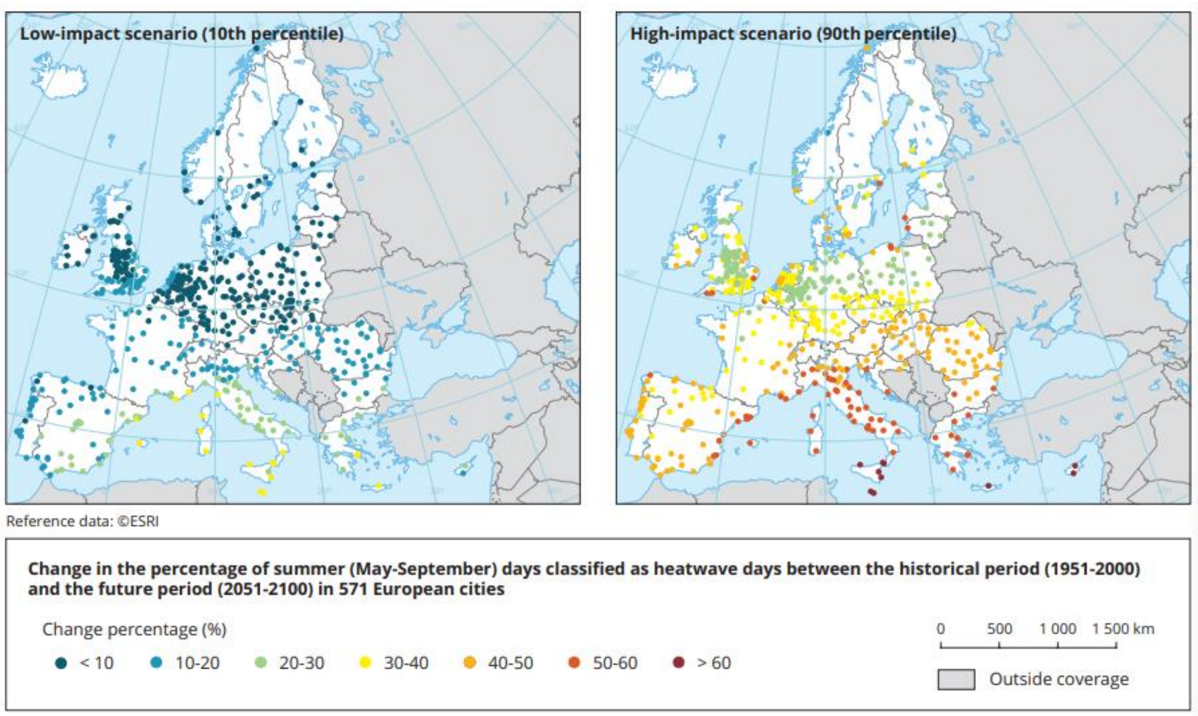
With the need to develop a good study of urban heat islands and how they impact society, it's necessary to clarify exactly what a heat wave is and what defines it. According to the World Health Organization (WHO) and World Meteorological Organization (WMO), there is no consensus on the definition of a heat wave, however, as an operational definition it is understood as an unusually **hot, dry or humid period, day or night, that begins and ends abruptly, lasting for at least two to three days, with discernible impact on humans and natural systems**.

Under a high-emissions scenario, by the end of the century 90 % of the summers in southern, central and north-western Europe will be warmer than any summer from 1920 to 2014, with the most severe health risks for southern Europe and the Mediterranean coasts, where many densely populated urban centres are located (Lehner et al., 2016). In the second half of the 21st century, under the RCP 8.5 scenario, very extreme heatwaves are projected to occur as often as every 2 years (Russo et al., 2014).

For some cities, the projected temperature increases are much higher than the computed global averages. Under the RCP 8.5 scenario, by the end of the century, many cities (e.g. Bucharest, Madrid and Zagreb) are likely to experience average temperatures of up to 7 °C in the hottest months compared with current conditions (Milner et al., 2017); for some cities, the number of heatwave days is expected to increase by a factor of 10 (Lauwaet et al., 2015; Wouters et al., 2017).

Heatwaves

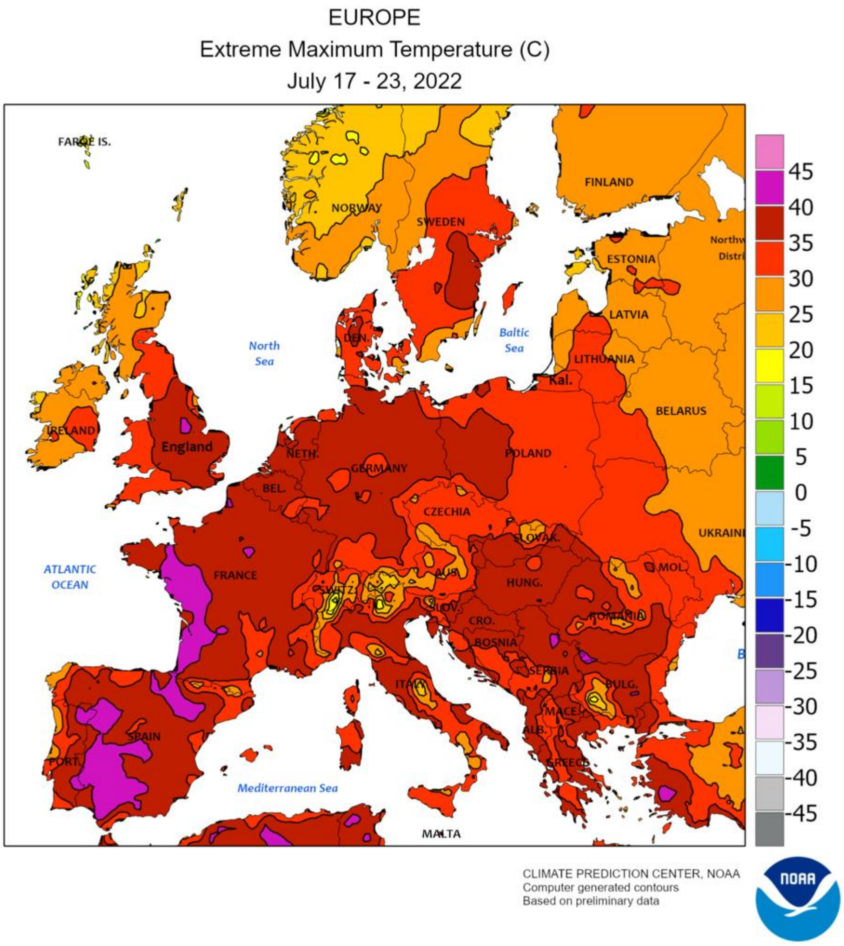
European countries are strongly affected by heat waves; this natural hazard causes more deaths in Europe than any other. However, according to Guerreiro et al. (2018), **cities in southern Europe will see a larger increase in the number of heatwave days** (Map 5). The projected increase in the number of heatwave days ranges from 4 % in Trondheim (Norway) for the low-impact (10th percentile) scenario to 69 % in Lefkosia (Cyprus) for the high-impact (90th percentile) scenario. However, **increases in maximum temperature during heatwaves are expected to be larger in cities located in central Europe** (Guerreiro et al., 2018).



Map 5. Change in the percentage of summer (May-September) days classified as heatwave days between the historical period (1951-2000) and the future period (2051-2100) in 571 European cities. Source: EEA (2020), adapted from Guerreiro et al. (2018).

Recent examples of heat waves include the record-breaking heat wave in Europe in 2003 and the Russia heat wave in 2010, which caused unprecedented heat-related death tolls (Schär & Jendritzky, 2004; Russo et al., 2015). The August 2003 heat wave caused more than 14,800 deaths in France, while Belgium, the Czech Republic, Germany, Italy, the Netherlands, Portugal, Spain, Switzerland, and the United Kingdom all reported high excess mortality rates (Confaloniere et al., 2007). **European countries were also affected by heat waves during the summer of 2015, 2019** (NOAA, 2015; WMO, 2019), **and 2022**, when record maximum temperatures were recorded. Southern and southeastern Europe was greatly affected by the heat wave of 2017 (Kew et al., 2018). The 2022 heat waves affected certain parts of Europe, causing evacuations and heat-related deaths. The highest temperature recorded until now in the continent was 47.0 °C (116.6 °F) in Pinhão, Portugal, on 14 July. In September 2022 it was reported that the European Union saw 53,000 excess deaths in July, although no causal link was attributed. Oficial losses include 26,304 deaths: France 11,000; Germany 8,138; United Kingdom 3,200; Spain 2,894; Portugal 1,063; Ireland 6; Poland 3 (EU, 2022).

Below, the map shows the July 2022 heatwave that heavily affected Europe, and broke all records of previous highest temperatures.



Map 6. Extreme Maximum Temperature of the Heat Wave in July 17 to 23, 2022. Source: Climate Prediction Center, NOAA (2022).

Analysis of the impact of extreme thermal conditions on mortality in Croatia showed that mortality during warm events is more pronounced than during cold events. The prolonged effect of high temperatures can significantly **increase mortality**, which was the highest during the first three to five days of extreme heat (Zaninovic & Matzarakis, 2013). A proportion of the deaths during heat waves can be attributed to very ill people, who might have lived longer without the heat stress situation (Confaloniere et al., 2007).

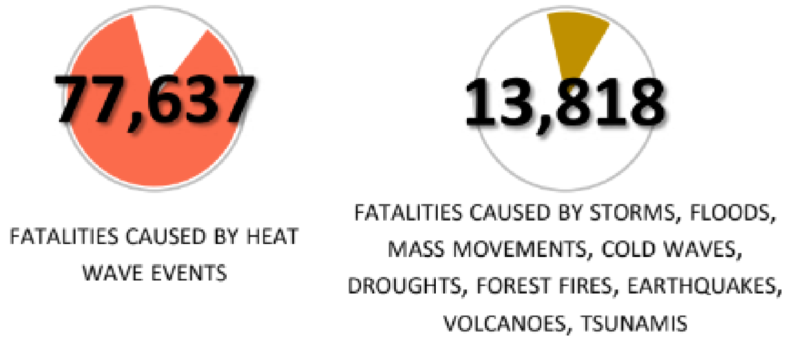


Fig. 4. Of all the natural hazards affecting the EEA member states in the period 1980-2017, heat waves account for some 68 percent of the fatalities and about five percent of total economic losses. Source: EEA, 2019.

A study of three heat wave events affecting the city of Cluj-Napoca in Romania in 2015 also shows **economic losses related to heat waves**. The estimated potential loss reached more than €2.5 million for each heat wave day, totaling more than €38 million for the three cases considered (Herbel et al., 2018).

KEY IDEAS

- Europe is strongly affected by heat waves, and the UHI effect enhances the excessive heat in cities during heat waves.
- Heat waves cause more deaths in Europe than any other natural hazard.
- Economic losses related to heat waves are huge and need to be considered.

The UHI effect

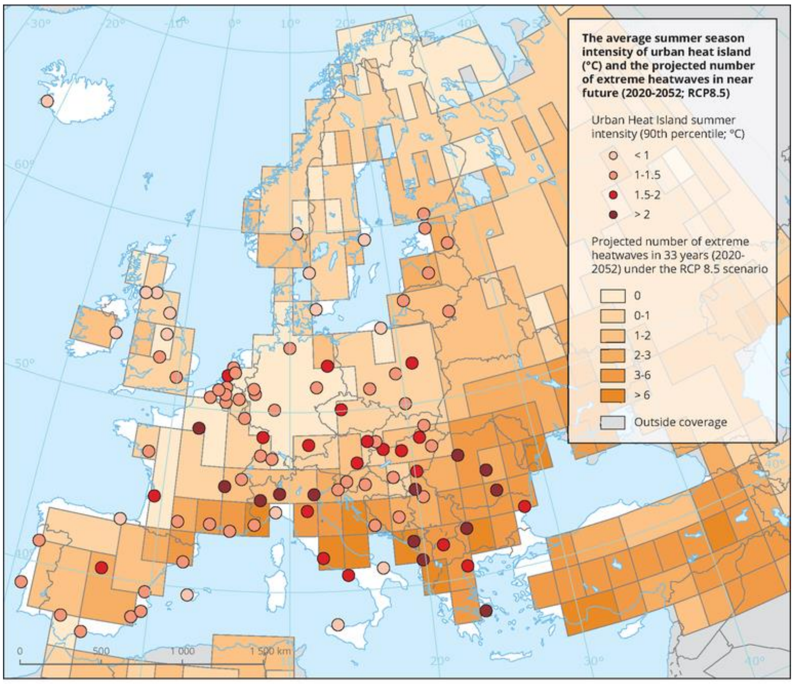
The UHI effect is strongly linked to climate conditions (the average wind speed and the number of sunny days), so a strong north-south gradient is present among the European cities. **The UHI effect is particularly strong in some of the locations that are projected to experience a dramatic increase in the number of extreme heatwaves** (see Map 7). These include cities in **south-eastern Europe**, such as Tirana (Albania), Sofia (Bulgaria) or Podgorica (Montenegro), **central EU and the Baltic republics**. However, predicted future heat waves will hit specially the coast of the Mediterranean.

Studies in Central Europe show that **maximum UHI values can develop during night** (Santamouris, 2007). Maximum UHI intensity varies between 1-12ºC and the highest values correspond to anticyclonic periods of weather, while much larger variations (more than 10-15ºC) are rarely observed due to local wind circulation reinforcement that mixes air and limits the extent of UHI.

The UHI effect is a typical feature associated with urban climate that enhances the excessive heat in cities during heat waves, and has negative impacts on people's health and city functions. The presence of cities more vulnerable to heatwaves mainly in the southern and central EU and the Baltic republics is linked to a combination of elderly populations, high air pollution levels and small average dwelling sizes.

Heat waves and extreme temperatures are an increasing concern for many cities across Europe and globally. Extreme temperatures are among the deadliest hazards in Europe. Between 1980 and 2017, heatwaves accounted for 68 percent of natural hazard-related fatalities among the European Economic Area countries and five percent of economic losses. The increase in the intensity and frequency of heat events is linked to global climate change, which poses a serious challenge for urban areas in Europe.

The following map presents the projected number of extreme heat waves in the near future across Europe and the summer intensity of the urban heat island effect in 100 European cities.



Reference data: ©ESRI

Map 7. The summer season intensity of urban heat islands (ºC) and the projected number of extreme heatwaves in the near future (2020-2052; RCP 8.5). Source: EEA (2019); VITO (2019).

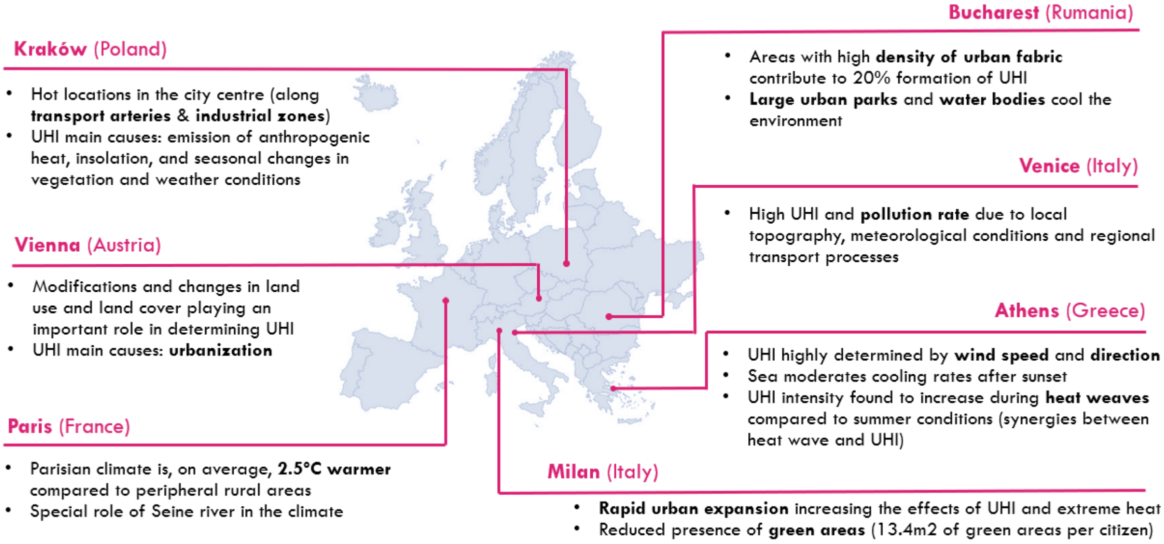
KEY IDEAS

- Heatwaves claim more human lives than any other weather-related disasters, and UHI exacerbates the risks to vulnerable populations.
- While temperatures are projected to rise across Europe, cities in south-eastern Europe face the highest projected increase in the frequency of heatwaves combined with the lowest provision of green space and the most pronounced urban heat island (UHI) effect.
- Climate change is conducive to the incidence of vector-borne diseases in Europe, in particular in the south. Higher urban temperatures improve the climatic suitability for vectors such as the tiger mosquito, contributing to the risk of disease spread.

UHI case-by-case: some European examples

In this section, general descriptions on how UHI is caused and its effects on different European cities is presented, with the main objective of understanding the multiple elements that affect this climate-related phenomenon as well as its consequences.

First, a map with the summarised information is provided:



Map 8. UHI in different European cities. Source: own elaboration.

Kraków

- Hot locations are mainly in the city centre, along the main transport arteries and industrial zones.
- The thermal structure is influenced by emission of anthropogenic heat, insolation of the surfaces, and seasonal changes in vegetation and weather conditions.
- Despite relatively small height differences in the city's buildings (about 100 m), relief is an important factor, as it forces the formation of a cold air lake in the valley floor (outside densely urbanised areas) and air temperature inversion.

Vienna

- Modification and changes in land use and land cover play an important role in determining local climate
- Building construction and increasing soil sealing lead to intensification of the UHI effect.
- City growth induces higher heat load, which in the future is expected to superimpose on regional climate warming, and can lead to long-term consequences.

Venice

- The climate of Venice has a seasonal pattern: temperature rises in summer and contributes to increasing levels of temperature, demands on cooling systems, and health problems related to both mixing and dispersion of pollutants.
- Several studies have shown that the local topography and meteorological conditions, natural and anthropogenic emissions and regional transport processes, make this area one of the most polluted in Europe.

Paris

- The nocturnal UHI is concentrated over the city centre and the densely built-up suburbs but rapidly decreases and becomes insignificant (i.e. less than 0.5 C) beyond 5 km from the city core.

- At night there is a heat release from urban infrastructures that is mostly observed in dense urban areas. Inversely during the day, the city centre is less affected by UHI, because it is partially protected from incident radiation due to shading effects related to the high building density.
- The residential districts undergo cumulative effects of urban warming and soil drying under heat wave conditions.
- At night, the maximum UHI reaches 2.84 C for the city centre compared to the surrounding countryside.
- Great proportion of inhabitants are affected by UHI (PUHI = 42% in this case).

Milan

- Increase of mean air temperature for Milan from 1900 to 2000
- Rapid urban expansion which enhances the effects of extreme heat
- Reduced presence of green areas: on average only 13.4 m2 of green areas for ever citizen, approximately the 9% of the total size of the city terrain

Bucharest

- Highly urbanised areas change the characteristics of the active surface and, in such a way, alter the natural climate of the area, deviating daily, monthly and yearly means of temperature and humidity, changing wind speed and direction.
- Points with high density of urban fabric have certain locations within a city that contribute with a proportion of 20% to the formation of urban heat islands.
- Some elements of spatial context such as large urban parks or water bodies can alter the relationship between density of urban fabric and temperature.

Athens

- UHI amplitude is highly determined from the wind speed and direction but also the daily maximum ambient temperature.
- The daily maximum UHII and the daily maximum ambient temperature are not necessarily synchronized, although they usually occur around afternoon hours.
- The synoptic wind largely determined the development or not of sea breeze at the coastal sites, influencing the amplitude of UHI.
- The higher heat capacity of water at coastal sites establishes more stable conditions, moderating cooling rates after sunset.
- The UHI intensity was found to increase during heatwaves, contributing to synergies between HWs and UHI.

Effects: Why do we care about Urban Heat Islands?

Urban populations are expected to increase by 2–3 billion by 2050, but we have limited understanding of how future global urban expansion will affect urban heat island (UHI) and hence change the geographic distributions of extreme heat risks. This is why shedding light on the multiple effects of this phenomenon is not only interesting but also necessary.

Elevated temperatures from heat islands can affect a community's environment and quality of life in multiple ways.

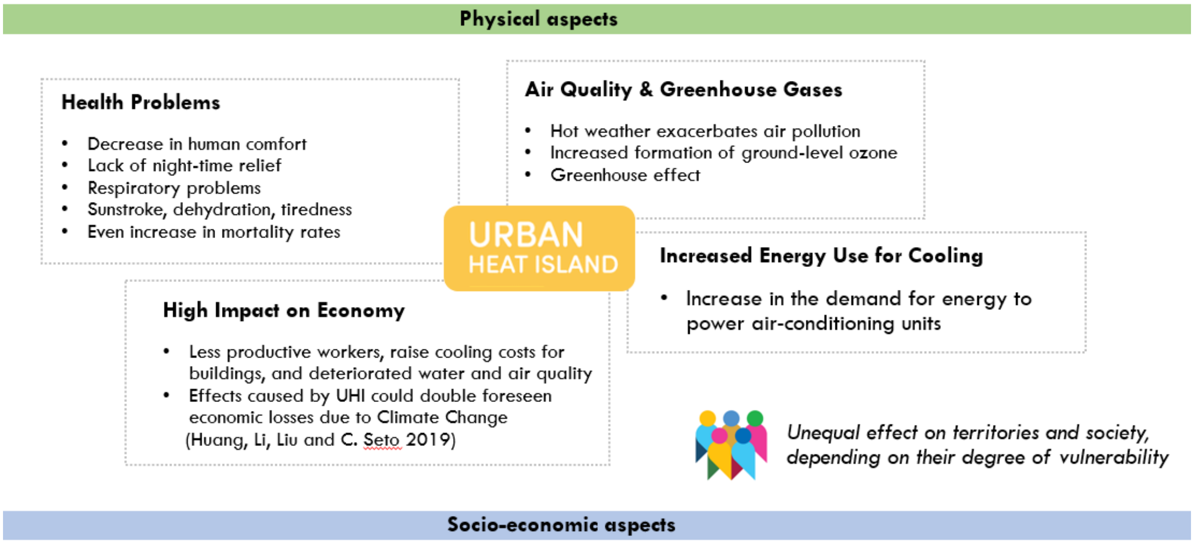


Fig. 5. Effects of UHI, from physical to socio-economic aspects. Source: own elaboration.

Human Health

Urban residents are exposed to high heat-related risks in a changing climate. Besides experiencing the effects of global temperature rise, they experience local temperature increase due to the UHI effect.

Increasing temperatures decrease human comfort in hot climates and raise mortality rates at temperatures outside an optimum range. People living in urban areas exposed to the UHI are at greater risk than those in nonurban regions. In many parts of the world, heat already has a devastating impact on human health, and excessive heat events (heat waves) have led to many deaths in many large, midlatitude cities (e.g., Athens, Chicago, New York, Paris, Philadelphia, Rome, Shanghai, and Seoul), making it the most important weather-related killer. Higher minimum temperatures due to the UHI and subsequent lack of night-time relief exacerbate the heat wave process and likely increase heat stress and mortality. Air conditioning seems to have a positive effect in reducing heat-related deaths, but waste heat emitted by air conditioning is also contributing to the UHI (Cooling Singapore, 2017).

The impacts that these heat situations generate in cities have an impact on both the **physical and mental health of people**. Also, there are indirect impacts, like increase in accidents, loss in labour productivity, increased risk of forest fires, impacts on water resources, transport restrictions, agricultural losses… Regarding the health effect of the maintained heat waves of the UHI, it affects particularly **vulnerable groups**.

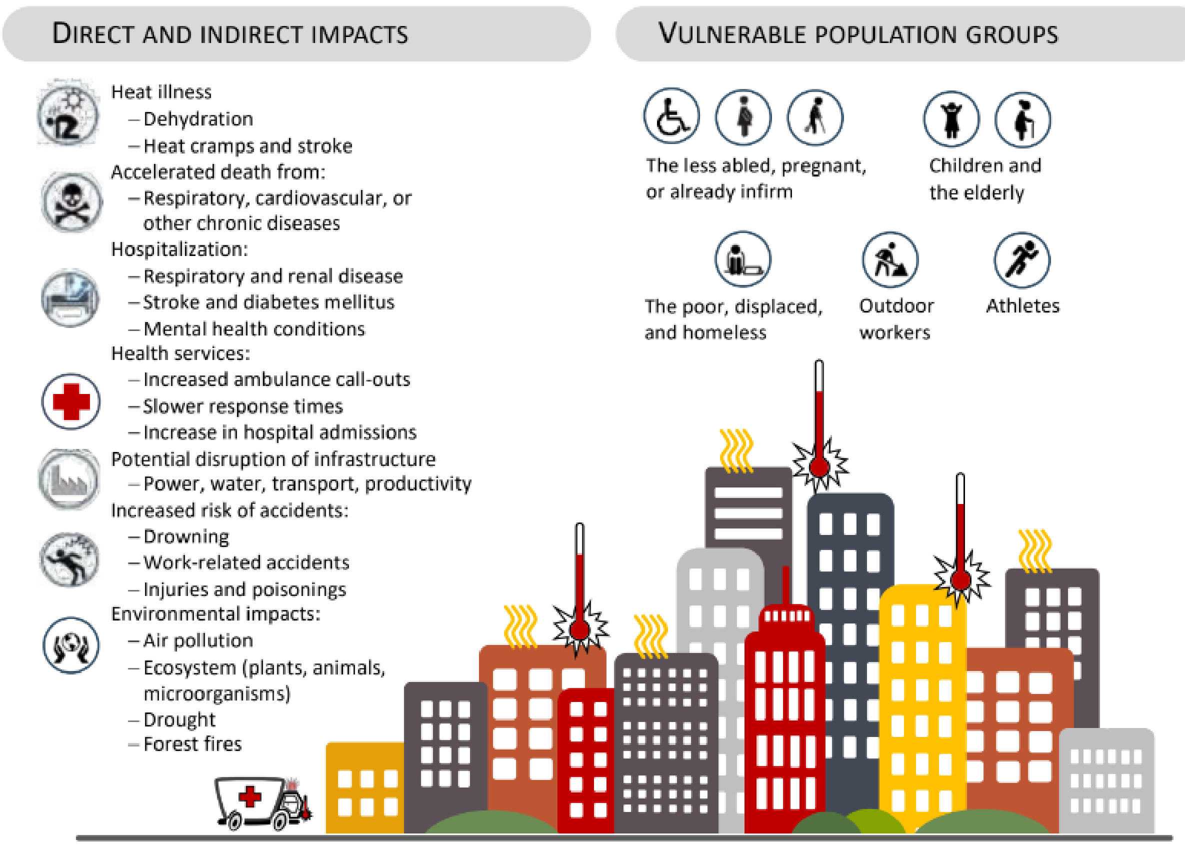
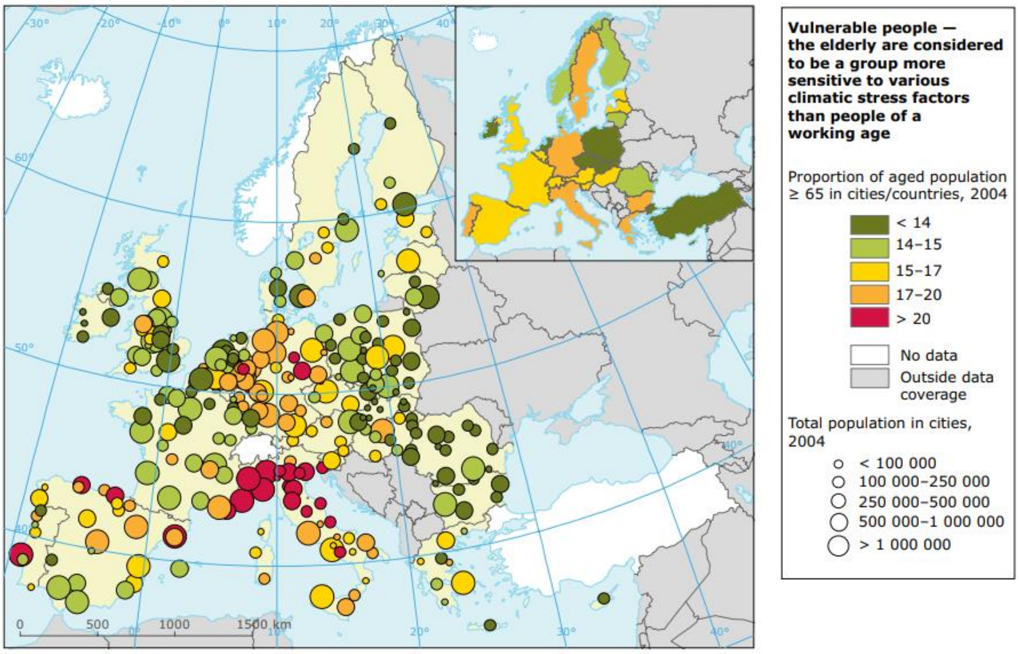


Fig. 6. Direct and Indirect impacts of heat waves and UHI effects on people. Source: Analysis of Heat Waves and Urban Heat Island Effects in Central European Cities and implications of Urban Planning.

Vulnerable groups include the **elderly, due to changes in their thermoregulatory system, as well as infants, whose thermoregulation is still immature and whose dependency level is high**. In addition, **workers** who might be exposed to extreme heat all day, as well as pregnant women, people with chronic diseases, and sick and poor people, are at high risk during heat waves. Housing conditions and social isolation are additional risk factors. Living in a poorly insulated building or on the top floor can aggravate the situation and pose additional risk factors, since the living space cannot be kept cool. Social isolation may lead to a delay when help or medical care is needed.

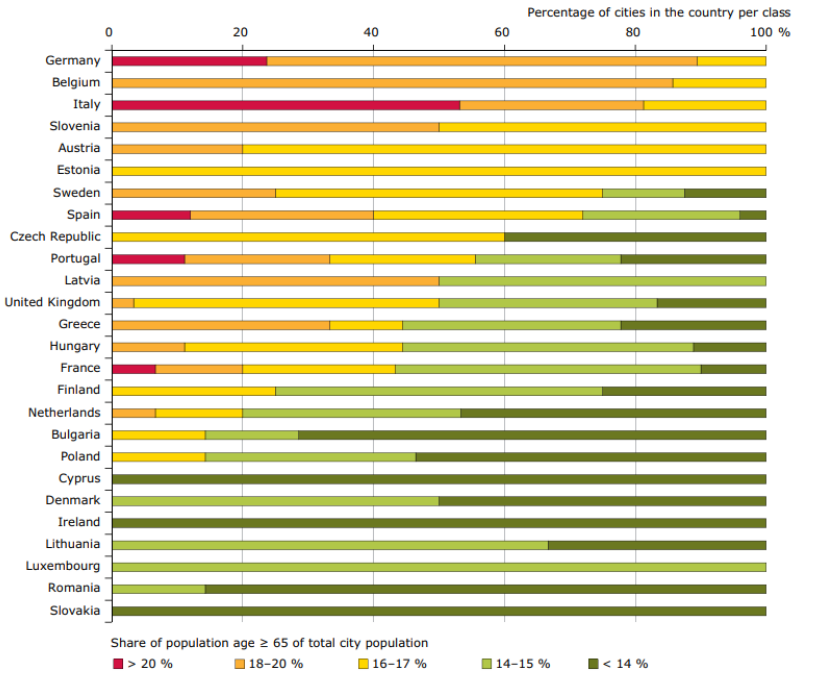


Note: Total population in cities; proportion of population aged ≥ 65.
Data for Bulgaria, Cyprus, Czech Republic, Finland, France, Ireland and Latvia are from 2001.

Source: Eurostat, Urban Audit database, 2004.

Map 9. Proportion of aged population (65 years or more) in cities/countries, 2004. Source: EEA, 2017, extracted from Eurostat, Urban Audit database, 2004.

Figure 2.3 Percentage of population aged ≥ 65 — share of cities per class per country (based on Map 2.7)



Note: Generally, only cities with more than 100 000 inhabitants are considered.

Fig. 7. Proportion of aged population (65 years or more) in cities/countries, 2004. Source: EEA, 2017, extracted from Eurostat, Urban Audit database, 2004.

Air Quality and Greenhouse Gases

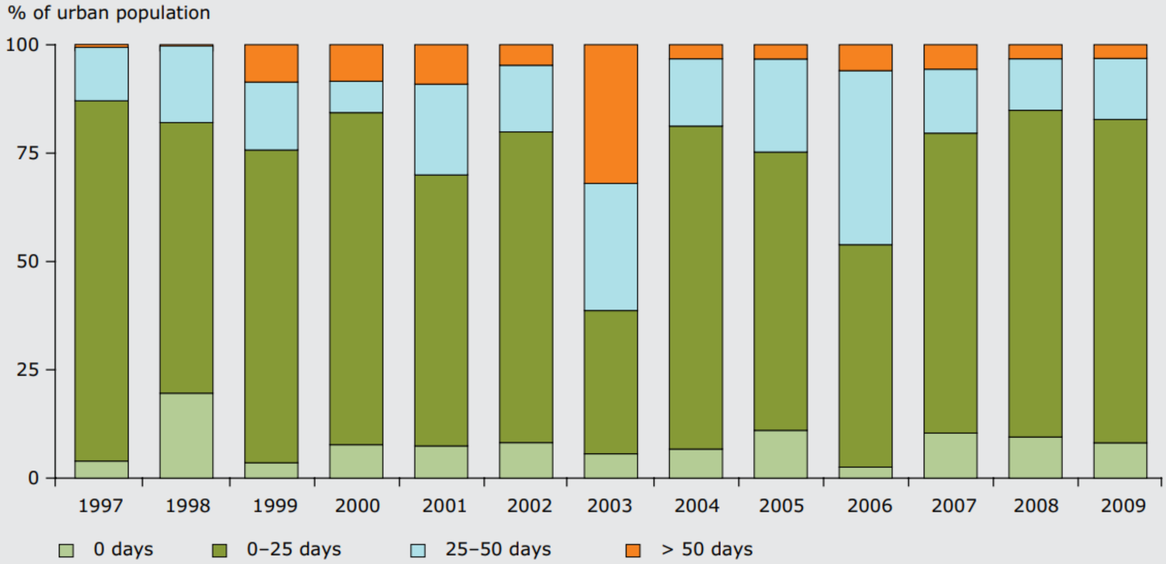
Air pollution in urban areas places additional stress on humans, and some pollutants have synergies with heat (Nawrot et al., 2007). Hot weather exacerbates air pollution through increased formation of ground-level ozone and, because periods with high temperatures usually coincide with dry periods, more particulate matter remains in the air (EEA, 2010). Evidence for a synergistic effect on the mortality rate due to high temperatures and ozone-levels is increasing (Bell et al., 2005; Medina-Ramón et al., 2006; Stedman et al., 1997). Hence, part of the health effects and increased mortality during heatwaves – which are exacerbated by UHI - may therefore be caused by decreased air quality (Filleul et al., 2006).

The EEA 'Air quality in Europe 2021' report updates and expands on an earlier assessment of the status of air quality by comparing pollutant concentrations in ambient air across Europe against the new WHO air quality guidelines published in September 2021. It finds that t**he majority of Europeans are exposed to levels of air pollutants known to damage health**.

- In the 27 Member States of the European Union (EU), 97% of the urban population is exposed to levels of fine particulate matter above the WHO guideline. Levels of particulate matter are driven by emissions from energy use, road transport, industry and agriculture.
- Regarding nitrogen dioxide, 94% of the urban population is exposed to levels above the WHO guideline, due predominantly to emissions from road transport.
- 99% of the urban population is exposed to levels of ozone above the WHO guideline, linked to emissions of nitrogen oxides and volatile organic compounds, including methane, and high temperatures associated with climate change.

Increasing temperatures and heatwaves in the future are expected to exacerbate the existing ozone problem. Forsberg et al., 2011 projects an **increase of ozone-related deaths over the next 60 years in Europe**, with 10 to 14 % increase being marked for Belgium, France, Portugal, and Spain.

Figure 2.4 Percentage of the EU and EEA-32 urban population potentially exposed to ozone concentrations over the target value threshold set for protection of human health, 1997–2009



Source: EEA, 2011c (CSI 004).

Fig. 8. Percentage of the EU and EEA-32 urban population potentially exposed to ozone concentrations over the target value threshold set for protection of human health, 1997-2009. Source: EEA, 2011.

Human activities are the key driver behind the dangerous levels of particulate matter, nitrogen dioxide and ozone in urban air. Overall emissions of all key air pollutants across the EU declined in 2019, maintaining the trend seen since 2005. Nevertheless, delivering clean and safe air for Europe will require ongoing and additional reductions in emissions. Looking ahead, the report says more action is required by all Member States if they are to meet future emission reduction commitments under the **EU's National Emissions reduction Commitments Directive (NEC Directive)**.

The EU has also set standards for key air pollutants in the EU's Ambient Air Quality Directives. Under the European Green Deal's Zero Pollution Action Plan, the European Commission set the 2030 goal of reducing the number of premature deaths caused by PM2.5 by at least 55% compared with 2005 levels.

To this end, the European Commission initiated a revision of the Ambient Air Quality Directives, which includes a revision of EU air quality standards to align them more closely with WHO recommendations. Citizens and stakeholders are invited to express their views through a public consultation run by the European Commission until 16 December 2021.

In 2019, air pollution continued to drive a significant burden of premature death and disease in Europe. In the EU, 307,000 premature deaths were linked to exposure to fine particulate matter in 2019, a decrease of 33% on 2005.

Top 10 European cities with the cleanest air

City name	Country	Fine particulate matter in ug/m3	Population in the city
Umeå	Sweden	3,1	125080
Faro	Portugal	3,6	61015
Funchal	Portugal	3,9	104024
Tampere	Finland	4,1	238140
Narva	Estonia	4,2	53424
Stockholm	Sweden	4,2	1745766
Uppsala	Sweden	4,2	219914
Tallinn	Estonia	4,5	438341
Bergen	Norway	4,7	267950
Reykjavik	Iceland	4,9	132252
Norrkoping	Sweden	4,9	140927

Table 4. Top 10 European cities with the cleanest air. Source: EEA, 2021.

Top 10 European cities with the least clean air

City name	Country	Fine particulate matter in ug/m3	Population in the city
Nowy Sącz	Poland	26,8	83896
Cremona	Italy	25,7	72399
Padova	Italy	25,3	210077
Venezia	Italy	24,6	258685
Vicenza	Italy	24,2	109855
Slavonski Brod	Croatia	23,7	52836
Brescia	Italy	23	196340
Zgierz	Poland	22,5	56529
Lomza	Poland	22,4	63000
Zory	Poland	22,1	62456
Gliwice	Poland	22,1	179806

Table 5. Top 10 European cities with the least clean air. Source: EEA, 2021.

Water Quality

High temperatures of pavement and rooftop surfaces can heat up stormwater runoff, which drains into storm sewers and raises water temperatures as it is released into streams, rivers, ponds, and lakes. Water temperature affects all aspects of aquatic life, especially the metabolism and reproduction of many aquatic species. Rapid temperature changes in aquatic ecosystems resulting from warm stormwater runoff can be particularly stressful, and even fatal, to aquatic life.

One study found that urban streams are hotter on average than streams in forested areas, and that temperatures in urban streams rose over 7°F during small storms due to heated runoff from urban materials (Somers, K. et al, 2020).

Biodiversity

The urban heat island effect has been linked to species distributions and abundances in cities. However, effects of urban heat on biotic communities are nearly impossible to disentangle from effects of land cover in most cases because hotter urban sites also have less vegetation and more impervious surfaces than cooler sites within cities.

Despite the short history of research on the biotic effects of urban heat, researchers have found important patterns across diverse taxa. For example, remnant native plant communities in urban environments may be altered under warming conditions, favouring more xerophilic species.

Energy Use

Heat islands increase demand for air conditioning to cool buildings. In an assessment of case studies spanning locations in several countries, electricity demand for air conditioning increased approximately 1–9% for each 2°F increase in temperature (Santamouris, M., 2020). Countries where most buildings have air conditioning, such as the United States, had the highest increase in electricity demand. This increased demand contributes to higher electricity expenses.

Heat islands increase both overall electricity demand, as well as peak energy demand. Peak demand generally occurs on hot summer weekday afternoons, when offices and homes are running air-conditioning systems, lights, and appliances. During extreme heat events, which are exacerbated by heat islands, the increased demand for air conditioning can overload systems and require a utility to institute controlled, rolling brownouts or blackouts to avoid power outages.

Economy

A recent study published by IOP Publishing indicates that the effects associated with the warming caused by urban heat islands could double foreseen economic losses due to climate change (Huang et al., 2019). As already mentioned, higher temperatures cause workers to be less productive, raise cooling costs for buildings, and deteriorate water and air quality.

On average, the global gross domestic product (GDP) is expected to drop by 5.6 percent by 2100 due to climate change. In contrast, the most-impacted cities are expected to lose 10.9 percent of their GDP (University of Sussex, 2017).

A report published by the University of Sussex in 2017 pointed out that overheated cities face climate change costs at least twice as big as the rest of the world because of the urban heat island effect. The study by an international team of economists of all the world's major cities was the first to quantify the potentially devastating combined impact of global and local climate change on urban economies.

The researchers provided cost-benefit analyses of several cooling measures in the report, including cooling pavements, green roofs and the reintroduction of vegetation in urban areas. For example, transforming 20 percent of a city's pavement and rooftops to cooling surfaces could save a city up to 12 times what the structures cost to maintain and install, providing a bump to the local GDP.

The authors explained that their new research is significant because so much emphasis is placed on tackling global climate change, while they show that local interventions are as, if not more, important.

Thus, city-level adaptation strategies to limit local warming have important economic net benefits for almost all cities around the world. Measures that could limit the high economic and health costs of rising urban temperatures are therefore a major priority for policy makers.

KEY IDEAS

- Urban heat islands can affect a community's environment and quality of life in multiple ways.
- The impacts of elevated temperatures are not equally distributed among the population. Effects on territories and society depend on their degree of vulnerability.
- Increasing temperatures have an impact on both the physical and mental health of people.

Mitigation Measures: Strategies to reduce Urban Heat Islands

Strategic Planning

Modification and changes in land use and land cover play an important role in determining local climate characteristics. City growth—both in terms of densification and urban sprawl—induces higher heat load, which in the future is expected to superimpose on regional climate warming.

Strategic planning is the best way to go. Having considered climate change projections, urbanisation and anthropogenic heat, the data can help cities better analyse UHI effects. Extensive meteorological observational networks and different data sources from remote sensing and citizen weather stations can be used for urban climate analysis. Examples of cities that use various data sources include Cluj-Napoca and Vienna. These tools include monitoring networks, with the establishment of an appropriate operational monitoring system (cost-intensive); alternative networks like citizen weather stations (supplemental information); measurement campaigns (evaluate specific aspects of urban climate); or remote sensing data.

The highest surface temperatures are found in urban areas and are related to local land use characteristics. Satellite data on land use and land cover, can provide complimentary information to guide sustainable urban planning (World Bank, 2020).

There are many steps that cities can take to make them more resilient to extreme heat events and the negative impacts of the UHI effect. Cities need to gain a better understanding of what drives the heat waves and UHI effects they are subject to. Strategic planning for increased resilience to UHI effects should identify specific public investments and actions to promote green, blue, or white adaptation measures (the first ones related to increasing vegetation, the second to water bodies, and the third to cool materials).

Fig. 9: Different climate adaptation measures. Source: World Bank, 2020.

There are analytics and models available to inform urban planning and infrastructure development resilient to future climate change. In parallel to improved urban planning, cities also need to also plan for improved preparedness and response to UHI effects.

Strategies and Processes to reduce UHI

Over the last decades, an increase of UHIs could be observed as a manifestation of micro-climatic changes in urban environments seen in cities worldwide. If cities seek to become more resilient to both long-term impacts of climate change and short-term UHI effects, it is essential to **improve adaptation efforts by sustainably modifying the city structure, the building design, and the urban planning of living space**.

A robust integrated approach involving urban planners, architects, meteorologists, climatologists, geographers, economists and social scientists appears to be useful when developing UHI adaptation strategies. Some of the tools that result from this approach go through the change of how we build and arrange our cities, and include different strategies and processes, from the implantation of green roofs and high albedo roofing materials to the adaptation and change of urban planning.

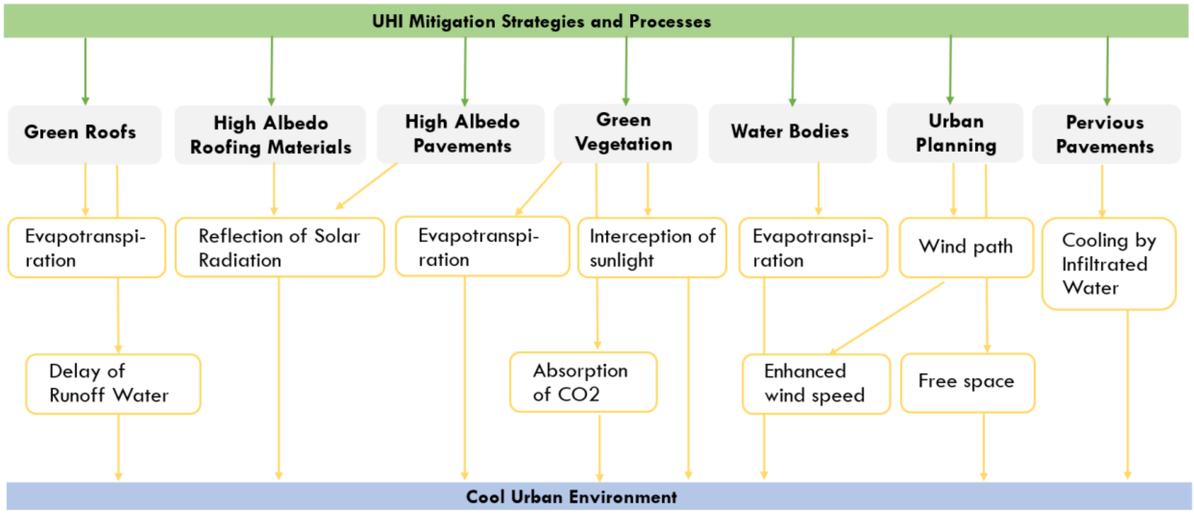


Fig. 10: UHI Mitigation Strategies and Processes. Source: own elaboration, extracted from Nuruzzaman, 2015.

In general, we can differentiate five types of measures when dealing with the mitigation of UHI in urban settings:

- Vegetation
- Urban Geometry
- Materials & surfaces
- Water bodies & features
- Shading

The following sections present a general description of these measures, and a more detailed approach to them is presented in *Annex. Strategies and Processes to reduce UHI: some examples*.

A. Vegetation

Vegetation has been used extensively as a UHI mitigation strategy worldwide and expert studies argue that more actions should be taken to increase the share of green areas in cities for mitigative and adaptive purposes.

Properties of vegetation include high albedo and low heat admittance that have the effect of reducing accumulation of incoming solar energy in the urban area. Additionally, certain types of vegetation such as trees can provide shade and minimise the heat gain from solar radiation, which then improves thermal comfort significantly. Also, the ambient air temperature reduction and building shading by vegetation can lower building energy demand for indoor cooling purposes.

Green infrastructures can perform multiple roles in urban areas, such as providing recreation, biodiversity, cultural identity, environmental quality and biological solutions to technical problems. It is this multifunctionality of green resources that differentiate it from its ‘grey’ counterparts, which tend to be designed to perform one function, such as transport and drainage, without contributing to the broader environmental, social and economic context.

Green resources do not only support adaptation, but also mitigation efforts. Human-related activities (building, power and heat production, transportation) in cities are responsible for about 70% of the CO2 emissions; therefore, climate change mitigation requires rapid modification of a city's metabolism (IEA, 2017). Although the achievements of emission reduction goals are mainly related to a modification of production and consumption patterns and increases in efficiency (IEA, 2017), the cooling effect of urban green resources may indirectly translate into lower CO2 emissions by decreasing the power demand for indoor cooling and heating (Song et al., 2018). At the same time, it can increase carbon storage and sequestration rates. Green approaches may also contribute to reducing transport-related emissions by linking strategies to reduce or avoid private car usage with cycling and pedestrian facilities (i.e., green corridors, parks). This may reduce pollutants as well.

However, perhaps the most crucial contribution of urban green resources from a climate change perspective is that they **foster the resilience building of urban dwellers**. Due to the UHI effect, urban dwellers are particularly vulnerable to thermal stress and their impacts that are being intensified due to climate change (Filho et al., 2018). For urban areas to be sustainably livable both now and in the future, as well as ensuring the filtration of pollution, noise reduction and thermal comfort, there appears to be a solid case for the implementation of urban greening policies and strategies, especially in the developing countries of the global south.

Fig. 11: Integrating nature into cities can provide citizens with urban cooling, cleaner air, regulated water supplies and flood protection. Image credit - Max Pixel, licensed under CCO.

B. Urban geometry

Urban geometry can provide numerous opportunities in promoting liveable environments and can be effective in getting the most out of natural effects/elements to counter UHI. T**he building layout, the location of urban elements, the building height and geometry** are variables that condition the thermal performance of the urban area. The arrangement of these elements affects the spatial coverage of the shadowed areas as well as the wind environment.

The implementation of **effective shading during the day** in combination with **increased night ventilation** proves to be a viable strategy to avoid summertime overheating. Enhancing air movement in between buildings through suitable urban design of street canyons and building geometry can be an efficient measure. Also, passive cooling strategies and design measures, such as orientation of the building, glazing, shading, and thermal mass, as well as nighttime ventilation, should be exploited in order to reduce or ideally avoid air conditioning systems in residential buildings. These passive design measures have the benefit of being both cost-effective, when considered at an early planning stage, as well as highly effective in terms of energy efficiency.

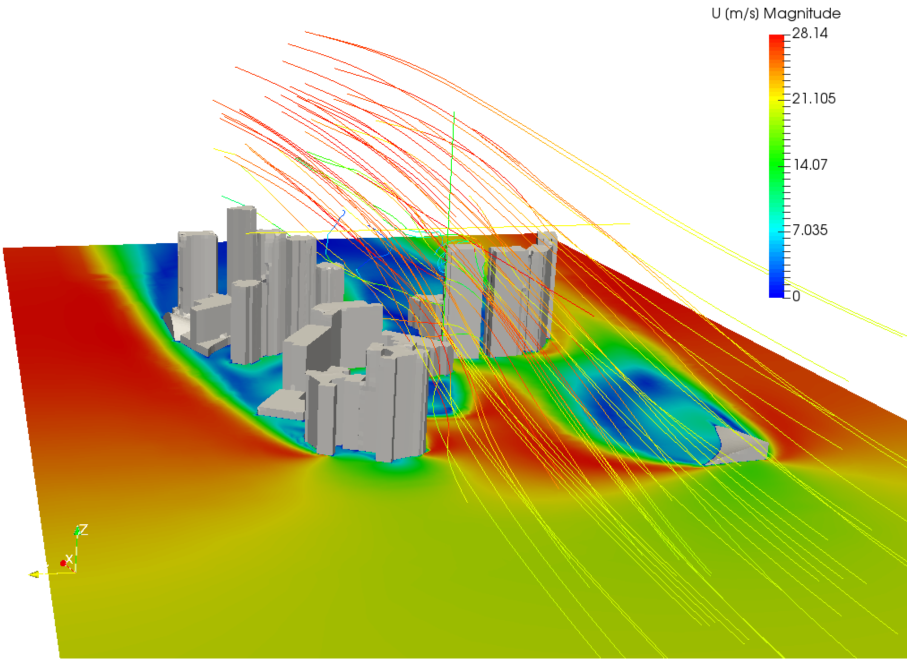


Fig. 12: Urban ventilation and airflow. Image credit - Climate Resilient Cities.

C. Materials & surfaces

Traditional pavements such as concrete and asphalt can reach temperatures of up to 48-67ºC (120-150 ºF) in the summertime (EPA, 2008). As we have already explained, these surfaces contribute to urban heat islands, especially at night time, by trapping and storing heat during the day and releasing it at night. Hot pavements can also heat stormwater as it washes over the pavement and into local waterways, causing the water to warm and impairing water quality.

The use of reflective pavements is one of the most well studied and most cost effective mitigation measures for combating the UHI effect by **reducing the surface temperature of the pavement**. It is easier to vary the albedo of a pavement than its thermal inertia.

Essentially, to make a pavement more reflective, two parameters can be changed: the colour of the pavement, and its surface roughness (Santamouris, 2013). One of the most practical means for mitigation of the UHI effect is to make pavement surfaces whiter, or as light-coloured as possible (Pomerantz et al., 2003). Making a pavement surface a lighter colour decreases the amount of solar radiation that it absorbs, and increases the amount of light and heat radiation that it reflects back into the atmosphere. A reflective pavement with an increased albedo can be developed by applying reflective paint or a sealant of thin bitumen with exposed light coloured aggregates to the surface of the pavement (Mohajerani et al., 2017).

Ideally, cool materials would be used on every road construction site; however, their application is often limited for economic or aesthetic reasons, and, instead, warm or hot pavements are used. The global implementation of reflective roofing, pavements and other structures would **reduce the air and pavement temperature, offset billions of tons of carbon dioxide emissions, reduce smog and aid the ailing environment** (Yang, Wang and Kaloush 2015). Hence, making cool pavements more available, durable and affordable may be an effective area of future study.

Fig. 13: A stretch of Coronado St. in Los Angeles is one of 15 blocks that is piloting a cool pavement. Image credit - Jed Kim/Marketplace.

D. Water bodies & features

Water bodies' ability to regulate the microclimate arguably has the potential to mitigate the UHI effect. Water bodies commonly found in urban areas are usually described as a permanent or temporary collection of water in the form of small stationary water or ponds. These **water bodies contribute to altering the surrounding thermal environment due to its cooling effect**, either by evaporation or transfer of heat between air and the water. In real urban conditions, however, the heterogeneity makes it difficult to assess the cooling benefits and to isolate the effects of individual parameters (such as shape, surface area, wind condition or solar radiation) under the complex physics process involved in urban meteorology (Nedyomukti et al., 2016).

Water bodies and features can act as **countermeasures to improve overheated building environments to some degree**. The effect of water is related to its surface temperature, which does not increase as much as the rest of the urban area. Thus, it can be considered as a cool sink. Also, water evaporates and increases the humidity of the air. Depending on the regional context, this can have a positive impact on the local thermal comfort. Additionally, depending on the size of the water body, specific wind circulation patterns can be developed with its corresponding consequences in the nearby environment.

Huanchun Huang, et. al., in "*Scale and attenuation of water bodies on Urban Heat Islands",* proposed the concept of core water surface ratio and a related method for measuring the scale sensitivity, with a view to investigating the variation patterns of water bodies and heat islands in daytime data. The study showed that the effect of the water body in reducing the temperature of its surroundings gradually decreases with increasing distance. Specifically, temperature rises by 0.78 °C for every 100 m away from the water surface.

During summer daytime, water surfaces reduce UHI, and **the reduction is low in the morning and maximum in the afternoon**. This illustrates that the cooling effect of water bodies has clear temporal variation (Huanchun Huang, et. al., 2017).

Fig. 14: Granary Square Fountain in London. Image credit - Culture Whisper.

E. Shading

Shading is a key measure to mitigate UHI because it leads to **the reduction of air and surface temperature and can therefore result in cooling benefits**. Simultaneously, it affects the thermal sensation and adaptation of pedestrians, mitigating heat stress.

Urban shading can be provided by adequate urban geometry and building/street orientation. Additional physical control to solar access can be achieved through horizontal and vertical shading structures or devices, as well as trees and vegetation.

Urban trees cool the environment mainly through shading and evapotranspiration. Leaves reflect and absorb solar radiation, preventing the radiation from being absorbed and stored in a surface (shading). The energy absorbed by a tree is then used for the plant's processes, including evapotranspiration, thus increasing the latent heat flux that transfers the heat to the atmosphere, resulting in the air cooling (Rahman and Ennos, 2016). While shading mostly affects the local microclimate, evapotranspiration is considered important for regional cooling (Rahman et al., 2018; Rahman and Ennos, 2016).

Fig. 15: The “Metropol Parasol” in Seville, the world’s largest wooden structure. Image credit - Inhabitat.

KEY IDEAS

- There are multiple analytics and models to inform urban planning and infrastructure development resilient to future climate change.
- A robust integrated approach involving urban planners, architects, meteorologists, climatologists, geographers, economists and social scientists is necessary when developing UHI adaptation strategies.
- Measures for UHI mitigation are related to vegetation, urban geometry, materials and surfaces, water bodies and features, and shading.

Legal Barriers to Urban Heat Islands Mitigation Strategies

Legal Barriers

There are several legal barriers to deploying pilots and strategies to mitigate Urban Heat Islands in European cities and rural smart communities. These include:

- **Privacy and data protection laws**: The European Union has strict laws regarding data protection, such as the General Data Protection Regulation (GDPR), which can make it difficult to collect and use data in smart city projects.

- **Regulatory barriers**: Different cities and regions in the EU have different regulations and requirements for deploying new technology. This can make it difficult to roll out pilot projects on a larger scale, as each city or region may have its own unique set of rules and regulations that must be followed. For example, some cities may have specific regulations regarding the use of drones, while others may have more restrictive regulations on the use of cameras in public spaces. These regulatory barriers can make it difficult for companies and organizations to develop and deploy smart city projects that are consistent across different cities and regions.

- **Liability and safety concerns**: When deploying new technology in public spaces, there are potential liability and safety concerns that must be addressed. For example, if a self-driving car were to be involved in an accident, there may be questions about who is responsible for the accident. Additionally, there may be concerns about the safety of the technology, particularly if it is being used in a way that it has not been tested or validated. These concerns can make it difficult to secure funding and insurance for pilot projects, as investors and insurers may be hesitant to invest in or insure a project that carries significant liability or safety risks.

- **Procurement laws**: EU countries have different procurement laws and regulations which can make it difficult for companies to bid for and win contracts for smart city projects.

- **Interoperability**: lack of standardization of infrastructure and software across EU countries can make it difficult to ensure that different smart city systems can work together effectively.

These barriers can be overcome by developing clear regulations and guidelines, securing funding, and building partnerships between public and private sector organizations. To mitigate these concerns, it's important to conduct thorough testing and evaluation of the technology before deployment, to develop clear guidelines and regulations for the use of the technology, and to establish clear liability and safety protocols. Additionally, partnerships between public and private sector organizations can help to mitigate these concerns by sharing the risk and responsibilities.

There may be specific regulations or guidelines that govern the use of certain strategies or pilots regarding urban heat island. For example, there are legal regulations for installing sensors in European cities. The European Union has strict laws and regulations regarding data protection, such as the General Data Protection Regulation (GDPR), which applies to the collection, processing, and storage of personal data. These regulations can have an impact on the deployment of sensors in European cities, as they can limit the types of data that can be collected, how it can be used, and how long it can be stored.

Additionally, there are regulations and laws that govern the installation of sensors in public spaces. For example, there may be regulations that prohibit the installation of cameras in certain areas, or that require certain types of notifications to be provided to the public before sensors are installed.

Furthermore, different cities and regions may have their own regulations regarding the installation of sensors in public spaces, so it's important to check the specific regulations that apply in the location where you plan to install the sensors.

To comply with these regulations, it's important to conduct a thorough **data protection impact assessment (DPIA)** before the deployment of sensors, to ensure that the data collected, processed and stored complies with the GDPR and other regulations, to provide clear information to the public about the sensors, and to establish clear protocols for data management, security and retention.

Institutional Barriers

Barriers in this field include:

- Lack of consumer acceptance: the lack of acceptance by the consumer or the customer creates the need for their education to expand awareness about sustainability, which is still quite limited.
- Lack of regulatory incentives: the challenge of the lack of regulatory incentives is associated with the government, which often fails to stimulate business with public policy, adequate regulation and incentives for sustainability. Stronger legislative pressure and supportive economic incentives are needed to achieve a sustainable economy.
- Institutional fragmentation: it represents another important barrier. Different departments/organisations usually work in line with their own vision, legal frameworks and procedures, and use their own sectorial language.

Organizational culture

Barriers in this field include:

- Difficulty in reconciling resources and the actors involved: lack of partners and low availability of materials, lack of information exchange between supply chain actors, and conflicting interests between supply chain actors.
- Lack of scaling up sustainable startups: the main barrier to deploying and scaling up a climate solution is the need for a mature value chain. A startup needs to consider many different players and stakeholders to successfully launch a product. Furthermore, scaling up climate tech often requires enormously large capital. This is often facilitated by financing mechanisms structured as project- or asset-based investments provided by debt or infrastructure investors or via dedicated large scale climate tech financiers. The barriers to companies' scale up can exist even after a successful pilot, when technical risks have been overcome and unit economics are promising.

KEY IDEAS

- There are several legal and institutional barriers, as well as barriers related to the organizational culture, to deploying pilots and strategies to mitigate UHI.

- These barriers can be overcome by developing clear regulations and guidelines, securing funding, and building partnerships between public and private sector organizations.

Case Studies: What will be needed in the future?

Urban Projects

A. eCitySevilla (Spain)

- Public-private partnership initiative led by the Andalusian Regional Government, the Seville City Council, the Cartuja Science and Technology Park (PCT Cartuja) and Endesa.
- Proposes the development of an open, digital, decarbonised and sustainable ecosystem city model on the island of La Cartuja by 2025.

Fig. 16: eCitySevilla. Source: Sevilla municipality.

B. Vauban Sustainable Urban District (Freiburg, Germany)

- Based on the city government's aim of restoring an old military barracks based on ecological and social cohesion criteria
- Creation of more than 40 cooperative housing groups and creation of participation initiatives

related to climate, consumption and gender

- Bioclimatic architecture criteria: green facades, greening, construction using local wood, building with high energy efficiency, renewable energies, rainwater collecting mechanisms, etc.

Bioclimatic architecture & greening

Fig. 17: Vauban ecodistrict. Source: Vauban municipality.

C. Climate Shelters (Barcelona, Spain)

- The City of Barcelona identified schoolyards as an underutilized resource since they were only used by the school population, during school time. The rest of the time, most schoolyards were not accessible to the surrounding community.

- Through a project funded by the Urban Innovation Actions of the European Commission, the City of Barcelona turned through carefully selected interventions, 11 school yards to "cool islands", termed as Climate Shelters.

- The Climate Shelters were added to the Schoolyards Open to the Neighborhood Program in operation since 2011, namely a municipal service that makes the courtyards of the city's schools, leisure, educational and shared spaces for families, children and adults outside school hours, on weekends and during school holidays.

- This was accomplished by means of blue and green interventions at the selected school buildings and their yards. These measures included:
    - Blue interventions: inclusion of points providing water, such as drinking fountains or unique places for children to play with water.
    - Green interventions: more green space, improvements in vegetation, creation of shade with green walls, more garden space, trees, green pergolas and fencing.

Fig. 18: Blue and green interventions, the first one in the Climate Shelter at School Ramon Casas and the second one in Font d'en Fargas. Source: Urban Innovative Actions.

- As a result, 1,000 square metres of natural space was regained, with vegetation in playgrounds and the creation of 2,213 square meters of new shade using pergolas and awnings. In addition, 74 trees were planted and 26 new water sources were installed.

D. RESILIO - Resilience nEtwork of Smart Innovative cLimate-adaptative rOoftops (Amsterdam, The Netherlands)

- The RESILIO project aims to address critical urban climate challenges related to flooding, heat, water supply, energy consumption and urban livability by repurposing the rooftops of climate-vulnerable neighbourhoods of Amsterdam.
- The project has taken 12,683 m2 of rooftop space and turned it into smart blue-green roofs. With this project, four different building complexes in Amsterdam neighborhoods acquired smart blue-green roofs – as well as the Tropenmuseum. Smart blue-green roofs can retain excess rainwater and provide a place to nature, adding biodiversity and creating a future-proof city at the same time.
- The roofs have a "smart flow control" that anticipates heavy rain or drought, releasing or retaining water accordingly. The roofs are connected in a network, enabling remote regulation of rooftop water levels based on weather forecasts and water management settings.

Fig. 19: Smart blue-green roof in Amsterdam. Source: Resilio.

E. Green Bus Stops (Poland)

- Four cities in Poland have chosen to use the so-called Green Bus Stop as a Nature Based Solution to reuse rainwater as a resource and contribute to the reduction of UHI effect.
- Each bus-stop is covered with a plant-based green roof with a water retention layer – such a roof stops up to 90% of the stormwater falling on its surface. During dry weather, the water is used by the plants and evaporated, making space for the next fallout.
- Part of the water, which is not used on the roof, together with the excess stormwater from the surrounding sidewalk, is retained in a vegetated retention-infiltration box in the back of the shelter.
- Green Bus Stop emits less heat than the traditional counterpart does, at times as much as 10°C less.

Fig. 20: Green Bus Stop in Białystok. Source: Bialystok City Office.

Start-ups and Initiatives

A. ECOTEN Urban Comfort (Czech Republic). Helping urban developers build more resilient cities

- Data-driven approach to help cities adjust by designing greener and cooler cities.
- Conducts urban heat vulnerability assessments (and identifies critical hotspots) and conducts urban microclimate simulations to assess the impacts of potential urban projects.

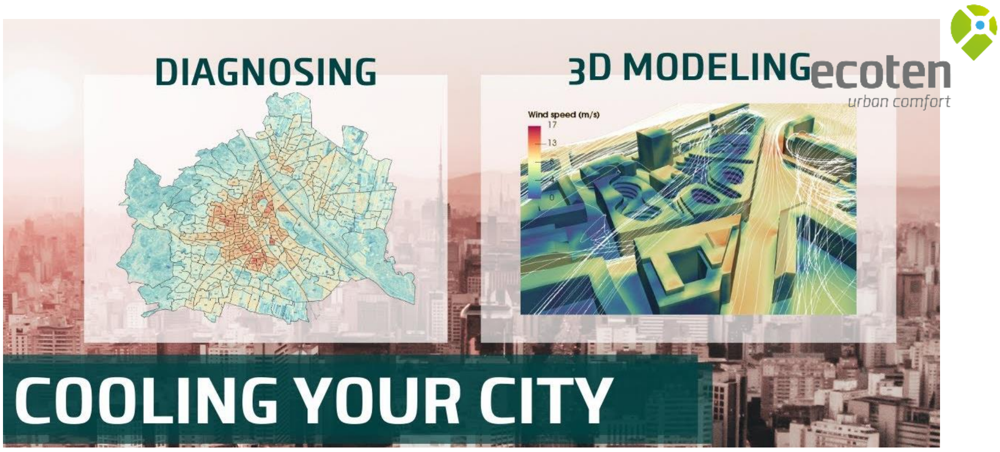


Fig. 21: Ecoten approach. Source: Ecoten.

B. Urban Canopee (France). Greening the Cities

- Deploys plant canopies at key locations in urban areas.
- These canopies combat heat, restore urban biodiversity, fight air pollution, and improve the quality of life for citizens.

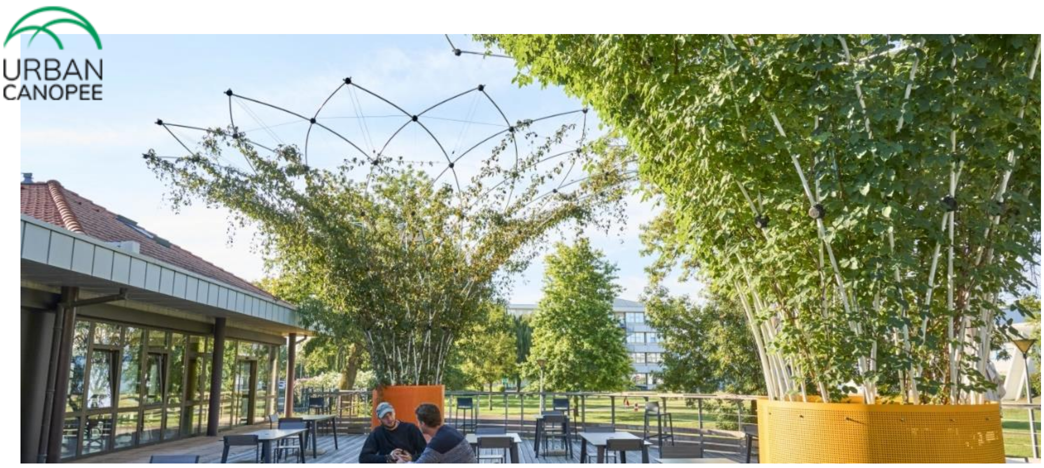


Fig. 22: Urban Canopee Solution. Source: Urban Canopee.

C. Cbalance (India). Recycling plastic into insulation

- Works with communities to pioneer passive design solutions.
- Some of these turn waste into materials that prevent heat absorption. i.e. Discarded plastic packaging can be recycled into sheets and insulation boards.

Fig. 23: Cbalance solution. Source: Cbalance.

D. MetroPolder (The Netherlands). Rainwater as a resource

- Metropolder's innovation tackles both extreme heat and heavy rainfall by capturing water in a special layer on flat roofs, preventing urban flooding and later releasing water to cool buildings during periods of excessive heat.

Fig. 24: A roof garden terrace in Amsterdam. Source: MetroPolder

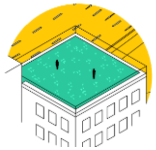
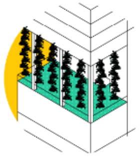
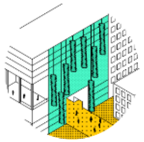
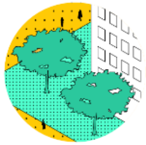
E. SUGi (international). Native, diverse pocket forests

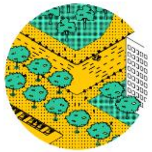
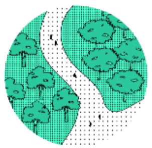
- In May 2019, SUGi launched as a global platform fully dedicated to biodiversity building, ecosystem restoration and reconnecting people to Nature through the creation of ultra-dense, biodiverse forests of native species primarily in urban areas.
- With 142 pocket forests planted in 28 cities we have reconnected 19,500 youth and community members to nature. The social impact of creating forests in cities is considerable, as are the environmental benefits, yet there is much more that can and must be done to grow this effort exponentially.

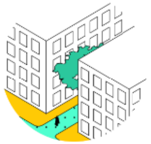
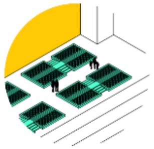
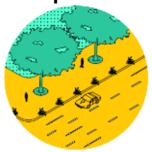
Fig. 25: SUGi Project. Source: SUGi

Annex. Strategies and Processes to reduce UHI: some examples

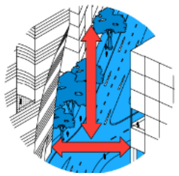
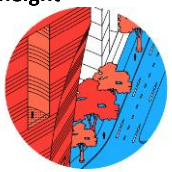
About 1. Vegetation

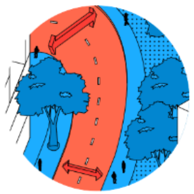
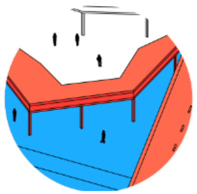
Measure	Description	UHI effect	Urban planning
Green roofs 	Incorporating green roofs involves placing a vegetative layer such as plants, shrubs, grass, and/or trees on building rooftops. They are also called 'rooftop gardens' or 'eco roofs'. Green roofs can be installed as a thin layer (around 5 cm) of groundcover up to a thick layer (around 1m) of intensive vegetation and trees. The thickness depends on the chosen soil type, drainage system, and vegetation species.	This strategy allows for the reduction of the urban heat accumulation due to a lowering of the temperature of roof surfaces. Similarly, nearby air temperature is also influenced by evapotranspiration. It produces benefits in terms of UHI mitigation and the reduction of building energy consumption.	Implementation should be aided by the development of building codes and energy efficiency guidelines. Green roofs can be developed both in public and private buildings.
Vertical greenery 	Vertical greenery is defined as the growing of vegetative elements on the external facade of the building envelope. There are two kinds of systems: a support system that allows plants to climb through them, and a carrier system where plants can settle and develop.	These systems allow for a reduction of the external surface temperature of the building façades, especially in the case where intense sun radiation occurs, such as on the south facing façades. Consequently, the temperature inside the building can remain more stable, and thus there is a reduction in the building energy consumption for cooling. Similarly, there is a reduction of the nearby air temperature providing benefits for pedestrians' thermal comfort.	Implementation should be aided by the development of building codes and energy efficiency guidelines. Adequate greenery systems should be selected in accordance to the building structure, the maintenance required, and safety. They could be developed both at public and private buildings at low costs.
Green walls/facades 	Green facades are vegetative layers such as small plants, grass and/or moss attached to external building façades. They are also called 'living walls' and 'vertical gardens'. Green façades can be considered as an alternative to insulating construction materials and reducing indoor overheating.	The strategy allows for a reduction in the temperature of façades, especially those exposed to intense sun radiation, such as the south facing façades. Consequently, the temperature inside the building can remain more stable and thus there is a reduction in the energy consumption required for cooling indoors. Similarly, there is a reduction of the nearby air temperature providing benefits of thermal comfort for pedestrians.	Implementation should be aided by the development of building codes and energy efficiency guidelines. Green walls/façades can be developed both in public and private buildings.
Vegetation around buildings 	Arranging adequate vegetation elements around buildings can provide shade to pedestrians, building and ground surfaces. The effect can vary depending on the vegetation coverage, size and distribution.	Vegetation can absorb the incoming solar radiation and thus reduce heat accumulation in urban materials. At the same time, it provides shadowing, especially trees. Similar to green façade, the reduction of solar radiation (shade) in buildings will reduce the energy demand for indoor cooling.	In planning, it is required that urban design considers carefully the exposure of buildings to direct solar radiation. On the whole, urban design needs to look for thermal pleasure by developing an urban asymmetrical thermal environment dominated by cool spots in urban spaces (Emmanuel, 2016) and at the same time enabling low-energy cooling within indoors.

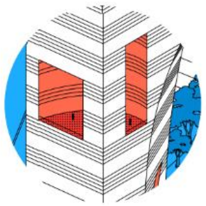
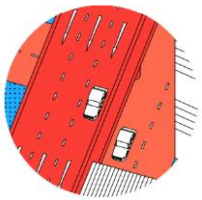
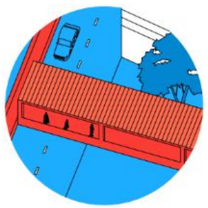
Selective Planting 	Planting vegetation in selective areas can provide beneficial shade but also obstruct the wind flow. This measure concerns choosing the more effective vegetation species as well as the optimal orientation and arrangement.	Vegetation allows for the following: a reduction in urban heat accumulation; shadowing that increases pedestrian thermal comfort; and reduction in building energy consumption. Combination of the different types of vegetation species and the way they are arranged can improve the thermal performance of the surrounding considering their ability to influence the urban energy balance.	Implementation should be aided by the development of building codes and energy efficiency guidelines. New development or retrofit should consider the disposal of vegetation in a way that can provide the highest environmental benefits. In any case, any urban greening programme implemented would need to be appropriately designed to get the most benefit out of reducing temperature (Bowler et al., 2010).
Green pavements 	This measure reduces the amount of artificial material on urban pavements with the replacement of natural soil elements with grass. But it can also be installed by using permeable pavers, previous concrete or porous asphalt in order to increase the permeability of the pavement.	Any urban greening programme implemented would need to be appropriately designed to achieve the full benefit of reducing temperature (Bowler et al., 2010). It allows for the reduction of urban heat accumulation by decreasing pavement temperature, thus influencing pedestrians' thermal comfort and to a large extent the UHI.	Implementation should be focused on areas/pavements with little shadowing (lowrise building development, for example) because the accumulation of heat can rise in pavements under these conditions.
Infrastructure greenery 	This measure covers elements that are not part of natural growing vegetation. Greenery can be added on existing infrastructure such as bridges, tunnels, highways and bus stations.	It allows for the reduction of the urban heat accumulation by decreasing surface temperature, and thus influencing pedestrians' thermal comfort.	Implementation should be focused on areas/pavements with little shadowing because the accumulation of heat can rise in pavements with these conditions. Additionally, the development of small green urban areas that are located strategically or grouped around buildings should be encouraged. These are more easily implemented when retrofitting in comparison with the development of big urban parks inside urban areas (Wong and Chen, 2009).
Macroscale urban greening 	Macro scale urban greening concerns the large-scale increase of the presence of vegetation in urban areas focusing on big urban parks, forests and natural reservoirs. They can be located at the edge or in central areas of the city with different effects in the local climate. They are also called 'cold islands'.	Areas like forests and green belts do not only assure a better thermal perception inside them, but can also provide coolness to nearby urban areas, thus helping to regulate the accumulation of heat in the whole urban area.	Implementation of macroscale urban greening should be considered carefully and in relation to general climate patterns (such as wind pattern) to maximise the cooling benefits that could extend to the entire urban area. The collaboration among several ministries is crucial for the successful implementation of urban greening on a large scale.
Local scale urban greening 	Local urban greening involves the increase of the presence of midsize parks inside the urban area to provide areas of thermal comfort for leisure and recreation. They are commonly located close to residential areas or along seashores with a compact or linear shape.	Urban greening in local contexts is expected to provide thermal comfort within them, but little effect is expected far away from their boundaries. The combination of vegetation, shadowing and adequate ventilation can significantly increase the outdoor thermal comfort with respect to the nearby artificialised area.	The implementation of local urban greening should be carefully considered and in relation to the urban extension. These areas should be considered as providing thermal comfort inside them. They could be developed within specific urban development guidelines that enforce their presence in every new planning/project.

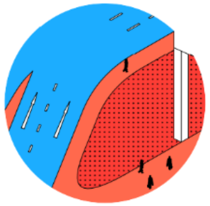
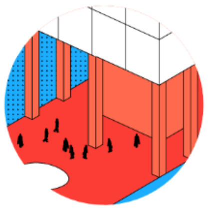
Microscale urban greening 	Microscale urban greening can be used to increase small vegetation presence inside the urban area. In addition to having vegetation around buildings, other uses can be pocket parks and green courtyards.	Despite the benefits on outdoor thermal comfort that can only occur in a small area when implemented adequately and/or interconnecting different microscale greening along the city, the effects on UHI could actually increase.	There can be two kinds of implementation: first, in developed areas where urban retrofitting is possible to improve the thermal comfort along pedestrian paths and in other pedestrian areas; second, in new urban areas to interconnect parks and bigger vegetation areas to create suitable thermal comfort pathways along the whole urban area.
Green parking lots 	This concerns reducing the amount of artificial material in parking lots while substituting them with ground vegetation (natural soil and grass) and/or trees and other vegetative infrastructure	The use of vegetative elements and/or soils with higher albedo has the effect of reducing the urban heat accumulation compared to conventional dark asphalt at parking lots. By decreasing the pavement temperature and extending the use of tree shadows, the heat accumulated by the cars can also be reduced.	Implementation should be focused on parking lots with little shadowing (low-rise building developments) where heat accumulation could be higher.
Tree species 	The selection of adequate species should be related to environmental tolerances, functional requirements, and urban design requirements in order for trees to obtain the best results for generating outdoor thermal comfort. For the environmental tolerance, aspects like climate, geology and topography have to be taken into consideration.	Different positive effects on heat accumulation can be achieved depending on not only the number of trees per square meter, but also their typology, size and adaptation to tropical areas. The previous mitigation measures have shown that trees can benefit the urban climate, but with varying results depending on how they are conditioned by their location and also by their actual characteristics.	It is required that urban design takes into careful consideration the exposure to direct solar radiation. On the whole, the aim is to look for thermal pleasure by developing an urban asymmetrical thermal environment dominated by cool spots in urban spaces (Emmanuel, 2016) and also enabling low-energy cooling indoors.
Urban farming 	Urban farms concern the practice of growing or producing food within urban areas. It can be installed in under-utilised urban spaces including rooftops, abandoned buildings and vacant lots. Urban agriculture has different climatic opportunities and constraints compared to rural agriculture.	Urban farms can serve as green islands within the urban landscape that can offer shade and protect impervious surfaces from the effects of solar radiation. Like other urban greenery, urban farms can produce similar local thermal comfort benefits and if highly extended to a relevant part of the urban area, it can lower the UHI effect and thus reduce building energy consumption for cooling.	Urban farming presents many benefits and opportunities. It helps to green the city, increase the amount of food grown and produced locally, thus preventing CO2 emissions in food transport from distant producers, and improving food security for this land-scarce island city. Suitable building codes, guidelines for new/ retrofit areas and/or economic policy can help develop green farming spaces.
Transport corridors 	The vegetation arrangement along transport corridors can provide shade to the infrastructure surface. The effect can vary depending on the vegetation density, height and species. But it is also key to combine the reduction of incoming solar radiation with the natural ventilation capacity of these spaces.	Vegetation can absorb incoming solar radiation and thus reduce heat accumulation in urban materials. At the same time, it provides shadowing (in the case of trees). Thus, considering local pedestrian outdoor thermal comfort, an increase in the number of trees makes sense. Transport corridors should be carefully designed with respect to UHI.	In planning for arranging vegetation along transport corridors, the exposure to direct solar radiation and wind enhancement should be considered carefully. A combination of different heights of vegetation elements together with their strategic location can allow for suitable airflow inside the transport corridor and thus pose higher benefits for this mitigation measure. T

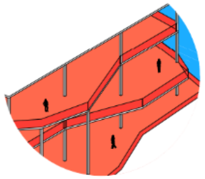
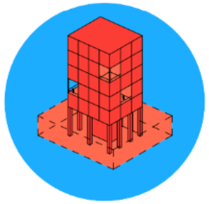
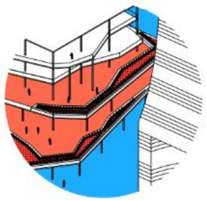
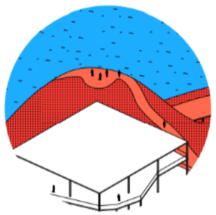
About 2. Urban Geometry

Measure	Description	UHI effect	Urban planning
Sky view factor 	The sky view factor (SVF) is defined as the ratio of the radiation received by a planar surface to the radiation emitted by the entire hemispheric environment. It is calculated as the fraction of sky visible from the ground. SVF is a dimensionless value that ranges from 0 to 1. For instance, an SVF of 1 means that the sky is completely visible and there are no obstacles around.	SVF conditions the amount of radiation received at the ground level during daytime (e.g. solar radiation) as well as the release of accumulated urban heat during the night (e.g. nocturnal cooling). Lower SVF can provide more shadow inside the street canyon during daytime and thus curtail the rise of ground temperature. However, trapping of the outgoing radiation during night-time can occur and thus the decrease of ground temperature will be lower during this time. Lower SVF can worsen the UHI during night-time but improve outdoor thermal comfort during daytime due to shade provided by urban elements. SVF also has a relevant influence on lowering surface temperature and thus reducing building energy consumption.	Implementation should be aided by the development of building codes and energy efficiency guidelines to ensure that solar heat gain is reduced. However, this should be balanced with indoor artificial light demand, which also requires a significant amount of energy.
Aspect ratio 	Aspect ratio (H/W) is the most important geometrical characteristic of a street canyon and is defined as the ratio of the canyon height (H) to the canyon width (W). It is usually calculated by dividing the mean height of buildings by the width of the street.	Similar to the Sky View Factor (SVF), aspect ratio conditions the incoming and outgoing radiation and thus the energy heat flux at the lowest level of a street canyon. The combination of low buildings and wide streets (or lower aspect ratio) can increase the entrance of wind flowing above the buildings and thus help remove urban accumulated heat and air pollutants. Such street canyons can also improve the nocturnal cooling of the ground surface. On the other hand, urban canyons with high aspect ratio can provide more shade during daytime and thus improve thermal comfort and reduce building energy consumption.	This measure can be combined with others such as passive design techniques for lasting comfort. It is important to evaluate the different options of the urban canyon aspect ratio to find the best fit that provides shading and increases wind flows. According to Mesa et al. (2011), the optimum ratio of the distance between buildings and the building height is between 2 and 3 (aspect ratio 1). The resulting aspect ratio may also affect the intensity and quality level of natural illumination reaching indoor spaces.
Mean building / tree height 	The relation between building and tree height will condition the amount of façade that is shaded by the trees and thus control the overheating of its surface	Trees reduce direct solar insolation thereby decreasing the surface temperature, both of building façades and in the tree surroundings. This way a reduction in UHI and an increase in local thermal comfort is expected together with benefits of indoor cooling energy demand.	Implementation should be aided by the development of building codes and energy efficiency guidelines. Adequate tree heights should be implemented in each area and other issues such as natural lighting should be considered.
Building form	Building form refers to the geometrical configuration and shape of a building or of multiple buildings. It can be linear, block or isolated punctual, and can be arranged in many different combinations.	The building form in combination with the arrangements of neighbouring buildings can contribute significantly to the formation of wind streams and the removal of urban heat accumulation through ventilation. Depending on the building	It is important that urban design considers the different options regarding building layout and façade orientation. The building form should be defined in relation to the direct solar radiation and thus shade the façades that are

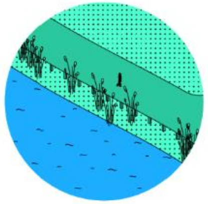
		form, it can also provide shade to itself or to its urban context and thus influence the energy consumption, reduce CO2 emission and improve outdoor thermal comfort.	mainly exposed to the sun. This way, higher indoor and outdoor comfort can be achieved, plus indoor energy demand can be reduced. This is essential in deciding the layout of buildings and the internal distribution in relation to the different occupation times during the day.
Variation between building heights 	The act of varying between different building heights and building forms (e.g. stepping building heights or podium structures) can improve wind capture with benefits of outdoor thermal comfort.	Wind speed varies with altitude that increases its intensity exponentially. Local outdoor thermal comfort can be enhanced by adequate air movement. In this sense, the variation between low- and high-rise buildings allows for increasing wind velocity due to the air dynamics between buildings.	New development or building retrofit should consider arranging buildings according to ascending heights with respect to wind direction to allow adequate wind to reach the rear blocks. An option would be to stagger building heights and void decks to increase the airflow. Also, downwash wind (bring upper wind to the ground level) triggered by the building geometry and layout allows for the ventilation of streets and generates air movement into the buildings.
Wider streets 	By widening the streets, the exchange of air inside the street canyons can be generated and increased at the same time. Allowing more air to come in creates effective wind corridors in the dense urban fabric.	The higher the air movement inside a street canyon, the higher the release of urban heat accumulation that will happen, thus reducing the UHI effect and building energy demand. Additionally, it permits a higher influence of non-urban breezes in the inner part of the city. Of course, outdoor thermal comfort can improve locally with increasing wind speed and air pollutants will have better dispersion conditions.	The implementation of street widening should be carried out in new developments with the help of building codes and urban design guidelines. Void decks at the ground floor of buildings or at different levels such as sky gardens can also increase the building permeability, in case streets are not wide enough and thus encourage the air flow through and around the buildings.
Avoid obstruction 	Obstructing the breezeway with buildings or other urban elements can block most of the wind to pedestrians thus affecting comfort and air quality. It can also minimise the air volume near the pedestrian level, which affects air quality. The effect of building layout, especially in terms of building site coverage, has a greater impact than building height on the pedestrian wind environment.	Any obstruction or stagnation of natural air movement might lead to a decrease in outdoor thermal comfort and an increase in UHI. To maximise the wind availability to pedestrians, towers should preferably be adjacent to the podium edge that faces the main pedestrian area/street so as to enable most of the downwash wind to reach the street level.	The obstructions can be avoided by stepping building heights in rows so as to create better wind at higher levels. Adopting a terraced podium design to direct downward airflow can help enhance the air movement at the pedestrian level and disperse the pollutants emitted by vehicles. Another option could be to align streets in parallel or up to 30° to the prevailing wind direction in an array of streets to maximise the penetration of wind through the district. Also aligning the longer frontage of building plots in parallel to the wind direction and introducing non-building areas and setbacks are appropriate measures.
Open spaces along	Open spaces along the seashore enhance the amount	The waterfront sites are the gateways of sea breezes and this	According to urban planning prospect, the open spaces

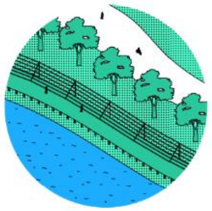
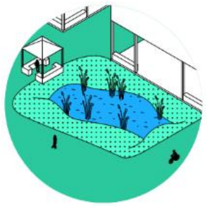
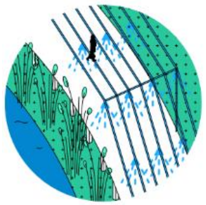
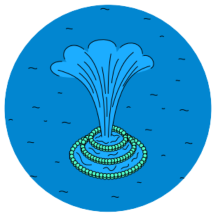
sea shore 	of wind entering the urban area with the effect of improving outdoor thermal comfort. In general, seashores are considered prime areas in a city with high density and are often excluded from public use.	can be enhanced for benefits of UHI and outdoor thermal comfort. They help regulate the urban climate by incorporating cold air within the urban fabric.	along the seashore should face the sea to offer residents beachside enjoyment while being exposed to maximum wind from the open sea to create a positive thermal sensation. To achieve this, incompatible land uses that obstruct the continuity of harbour front promenade and major infrastructure projects should be avoided. Also, an integrated network of open spaces and pedestrian pathways can allow for the better movement of air in a dense urban area.
Building porosity 	Building porosity can be achieved by generating adequate openings or gaps in buildings, either in horizontal or vertical direction. This strategy can maximise the air permeability of the urban area and minimise its impact on wind capture and air flow reduction.	Compact building blocks create stagnant air that worsens outdoor thermal comfort. In the tropics, a decrease in wind speed from 1.0 m/s to 0.3 m/s is equal to 1.9°C temperature increase, and outdoor thermal comfort under typical summer conditions requires 1.6 m/s wind speed. Therefore, according to Yuan and Ng (2012) building setbacks and building permeability are helpful in improving the pedestrian-level wind environment.	The provision of permeability closer to the pedestrian level is far more important than that at high levels as it helps to remove pollutants and heat generated at ground level. The permeability can be increased by creating voids in building blocks at ground level to improve natural ventilation for pedestrians and thus their comfort. Combining voids with appropriate wing walls permits air to flow through the openings of the buildings. Midlevel voids are especially relevant for very deep canyons or extremely tall building blocks.
Street axes orientation 	Choosing the appropriate geometry and the orientation of street canyons can improve outdoor and indoor environments, solar access inside and outside the buildings, the permeability to airflow for urban ventilation, and the potential for cooling of the whole urban system.	Street geometry and orientation influence the amount of solar radiation received by street surfaces and also airflow in urban canyons, which significantly affects local thermal comfort and building energy consumption. Streets aligned to breezeways can promote air movement into and within the urban areas, thus reducing UHI. An array of main streets, wide main avenues and/or breezeways aligned up to 30° to the prevailing wind direction maximises the penetration of prevailing winds and reduces the UHI effect.	This strategy should be considered during the first phase of the planning of a new development. It cannot be incorporated in urban retrofitting. The effort should be placed on the widening of streets orientated along the prevailing wind direction. Also, shortening the length of the street grid perpendicular to the prevailing wind direction minimises stagnation. It is important to explore the urban breezeway patterns to optimise the arrangement of street and corridor networks.
Well-ventilated sidewalks 	Well-ventilated pedestrian walkways can be achieved by aligning them parallel to the prevailing wind and positioning them in adequate locations.	The reduction in prevailing wind speed due to urbanisation reduces ventilation in walkways and can cause discomfort. Underpasses, sidewalks, skywalks and overpasses should be orientated and located in relation to the wind flow patterns, since wind flows are better at certain levels. At the same time, these pedestrian walkways should be protected from diagonal rain and sun radiation.	Pedestrian trajectories inside the urban area should be taken into consideration in the early stages of planning. Also, the technical aspects of walkways should be considered, such as materials used for paving. Multilevel pedestrian links and elevated walkways are important components of alternative walkway system that help in increasing pedestrian outdoor comfort. In high-density urban areas, carefully-designed walkway systems create a relatively pedestrian-friendly environment that also needs to distance people from vehicles, pollution and noise.
Building	The building arrangement refers to the adequate	A possible cause of increase in UHI is an improper building	It is necessary to include these issues in the first stage of

arrangement 	location of buildings with respect to each other and thus in relation to the prevailing winds to improve ventilation as well as shade where required.	arrangement that can reduce the wind speed and thus increase the thermal capacity of the city. It is important that the axis of the buildings should be parallel to the prevailing wind to avoid sea breeze obstruction. Inadequate arrangement can reduce wind speed and have an impact on building energy consumption. Similarly, exhausted heat from air conditioning has to be taken into consideration while arranging a group of buildings.	urban planning. An effective arrangement of buildings to improve wind ventilation is to stagger the arrangement of the blocks such that the rear blocks are able to receive the wind penetrating through the space between the blocks in the front row. The building arrangement can direct or redirect the wind flows. Generally, buildings with smaller footprints and low-rise buildings should also be considered to improve ventilation in the urban area.
Open spaces at road junctions 	The prevailing wind travelling along breezeways and major roads can penetrate deep into the district by the appropriate linking of open spaces. Such linkage and alignment can take place at road junctions in such a way as to form breezeways or ventilation corridors.	Linking open spaces with road junctions can produce higher benefits in reducing urban temperatures and improving thermal comfort outdoors. Outdoor thermal comfort can be improved as this linkage will provide abundant wind to pedestrians and cyclists crossing these junctions or to people resting in the open spaces.	An effective linkage of open spaces and road junctions can enhance suitable ventilation paths. In any case, the buildings along breezeways or ventilation corridors should be lowrise to avoid breezeway obstruction.
Guide wind flows with urban elements 	Guiding and increasing the wind flow through specific urban elements such as void decks can improve the wind volume near the ground and the urban air ventilation.	Introducing void decks and improving the building permeability on the ground not only improves the wind condition at the pedestrian level but it also adds value in mitigating UHI by lowering the air temperature.	The provision of building permeability nearer to the pedestrian level is far more important than that at high levels to improve the pedestrian comfort due to the stack effect. This can be achieved by creating voids at ground level to improve ventilation for pedestrians and the residential units at the lower floors.
Passive cooling systems	Passive cooling systems are design techniques that prevent heat from entering into the building or promote heat removal from the building envelope or	Higher UHI is expected if there is little emphasis on integrating passive cooling systems in the urban and building design. By utilising only mechanical systems such as air conditioners or	New neighbourhood planning should include passive techniques such as improved building arrangement, porosity, vegetation and coatings to reduce urban heat

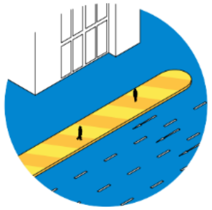
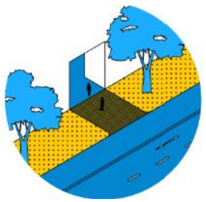
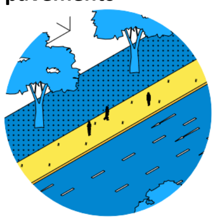
	open spaces through natural cooling. Cost-effective sources of passive cooling could be the orientation and arrangement of buildings and vegetation, water bodies and reflective coatings, but also the use and combination of open and semi-open spaces allowing cross-ventilation.	chillers as primary sources for improving indoor thermal comfort, there would be adverse impacts on UHI and outdoor thermal comfort.	accumulation. Also in the case of urban retrofitting, certain passive cooling systems could be considered.
Building surface fraction 	The Building Surface Fraction (BSF) is the ratio between the horizontal area of buildings (building footprint) on a given area and the total area. BSF is considered a physical parameter to measure Local Climate Zones (Stewart & Oke, 2012).	High density influences the ground space and the space between buildings. Lowering the BSF will provide more open space around the building volume and therefore decrease the air temperature by avoiding heat accumulation during the day as well as heat release during the night (Buchholz and Kossmann 2015). This will facilitate greater natural ventilation of pedestrian spaces and improvement in the outdoor thermal comfort.	Planners take into consideration the Gross Plot Ratio (GPR), which measures the ratio of the Gross Floor Area (GFA) of a building or various buildings to the land area of the site. By taking into consideration the surface fraction, planners can estimate the heat intensity caused by lowering or increasing the BSF.
Green plot ratio 	The Green Plot Ratio (GnPR) is a three-dimensional ratio between the greenery in a given area and the total area. It is measured through the Leaf Area Index (LAI). It includes vertical and horizontal landscaping, lawns and trees, raised planters and urban farms.	This strategy gives incentives to increase the amount of greenery in urban areas. Increasing the greenery and integrating it into the architectural design can provide cooling to the immediate surrounding environment and the surface temperature. Introducing building greenery on walls, balconies, sky terraces and roofs has a significant effect on the outdoor thermal comfort and in mitigating the UHI.	GnPR is part of BCA's Green Mark since 2005 and rates different building typologies by the amount and type of surrounding greenery such as grass, bush or tree.
Topography 	The topography can be an integral part of the urban fabric, which is not a direct component of microclimate but an indirect one.	The combination between the elevation of the terrain and the urban fabric influences the microclimatic phenomena such as wind drafts and rainfall, generating an indirect effect on UHI and outdoor thermal comfort. The effect of topography in UHI can be more appreciated when a topographic depression is found (Serrano et al. 2003) and also during daytime hours (Geiger et al. 1995 and Nitis et al. 2005).	Wall et al. (2015) shows evidence of urban design projects where natural and human made topographical features such as hills, buildings and vegetation were introduced to induce cool winds into the urban fabric.

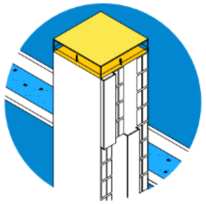
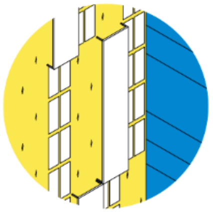
About 3. Water bodies & features

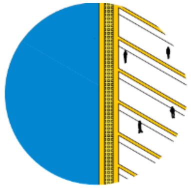
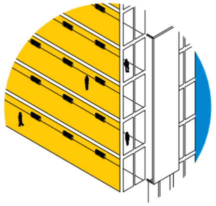
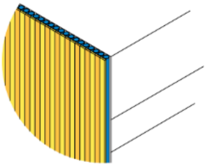
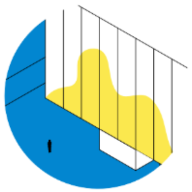
Measure	Description	UHI effect	Urban planning
Cool sinks 	Natural surface water accumulation can act as a cool sink to prevent the overheating of urban surfaces.	Large water masses can absorb thermal energy from the incoming solar radiation due to its heat capacity. Also, water evaporation is a sink for sun radiated energy. Thus, a mass of water can reduce the accumulation of heat and thus contribute to reduced UHI and improved thermal comfort. Additionally, if water bodies are sufficiently extended by, for example several square kilometres, local breezes can be developed and wind speed increased with benefits in thermal comfort and urban heat removal.	Implementation should be considered at an inter-ministerial context. Different agents should be involved in the design and implementation of this measure in relation to other requirements. Thus, the planning of new developments can consider the possibility of strategic natural water accumulation, which if combined with local wind flow patterns, can benefit nearby outdoor thermal comfort.
Blue and green spaces 	Combining blue and green mitigation strategies in urban areas can bring about integrated solutions and distinct benefits from their characteristics.	Water (blue) and vegetation (green) strategies can affect climate variables differently and thus the UHI effect. Differences between both do not only refer to the amount of energy dissipated but also on their suitability through the day. For example, water can have a nocturnal warming effect during certain periods of the year. Also, vegetation can provide shade during daytime and improve thermal comfort but during night-time it will trap heat at surface level and worsen nocturnal urban heat island.	Knowing the limitations of each mitigation measure and the benefit of combining them is crucial for developing ad-hoc urban design to protect and enhance the wellbeing of inhabitants by optimising ecosystem services. Thus, urban planning guidelines that include these issues would help their implementation.
Wetlands 	Wetlands are the link between land and water and they contribute towards flood control, carbon sink and shoreline stability. This measure concerns the conservation of natural water surfaces with high presence of vegetation and negligible surface overheating.	Water has negligible diurnal temperature variation compared to land surface and thus it does not accumulate heat during daytime hours. In this context, the proximity to wetlands with a high presence of vegetation can be more comfortable.	Care should be taken not only when developing natural areas that can provide thermal comfort, but also the surroundings where their effect can be extended, for example, cool air transportation due to wind.
Water catchment areas	Water catchment area is an area of land integrated into the natural landscape that collects rainwater and drains off into other water bodies. The accumulation of water catchment areas as a pre-emptive measure can prevent the overheating of urban surfaces.	Large water masses can absorb thermal energy from the incoming solar radiation due to its heat capacity. Also, water evaporation is a sink for sun radiated energy. Thus, extending water catchment areas can increase the non-heated surfaces and hence contribute to reducing UHI and improving the thermal comfort of residents outdoors.	Implementation should be considered at an inter-ministerial context. Different agents should be involved in the design and implementation of this measure in relation to other requirements. Thus, the planning of new developments can consider the possibility of strategic water accumulation.

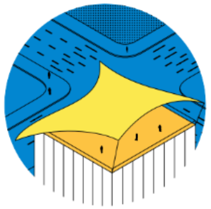
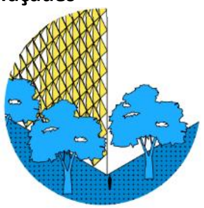
			
Ponds on roofs / ground floor 	Ponds are an accumulation of water that prevent the overheating of urban surfaces. They can be located on ground floor areas or on building roofs.	Water can absorb thermal energy from the incoming solar radiation due to its heat capacity. Also, water evaporation is a sink for sun radiated energy. Thus, a mass of water can lessen the accumulation of heat and thus contribute to reducing UHI. Additionally, reducing roof surface temperatures with the use of water bodies would lower energy demand, especially in low-rise buildings.	The implementation of water features on rooftops or ground floor should be aided by the development of building codes and energy efficiency guidelines. Also, the planning of new developments or urban retrofit can consider the possibility of strategic water accumulation both from a public and private perspective. In this sense, including the interaction of local wind with the water features would improve its performance regarding thermal comfort.
Evaporative cooling 	Evaporative cooling systems are devices that cool the air through the evaporation of water. It can increase locally the levels of humidity through water misting and/or spray.	Evaporative cooling dampens the positive effect on thermal comfort by eliminating heat or reducing temperature on the surface of the body's skin. In hot environments, evaporative cooling can play a role in creating a calming effect.	Since this measure provides benefits to the outdoor environment, the planning of new developments or urban retrofit could consider the possibility of including it locally so as to create cool spots that enable the enjoyment of the outdoors, both in public and private areas.
Fountains 	Fountains are watering surfaces to prevent overheating and increase locally the levels of humidity.	Water can prevent urban surfaces from heating due to its heat capacity and the evaporation process. Thus, a fountain can be considered a heat sink. In this sense, it can improve thermal comfort in the close surroundings similar to other water features, depending on its size, shape and water movement characteristics.	Strategic locations for fountains providing spray water are necessary if thermal comfort benefits are to be expected. One important consideration is the wind environment since it conditions the transport and impact of water spray

About 4. Materials & surfaces

Measure	Description	UHI effect	Urban planning
Cool pavements 	Cool pavements are made of materials that reduce their surface temperature by reflecting a significant percentage of solar radiation and releasing thermal heat into the environment. These surfaces are usually a light colour, or white.	Cool pavements are characterised by high albedo (high solar reflectance) and high thermal emittance. Consequently, this reduces the urban heat accumulation responsible for UHI phenomena, especially in hot climates. However, this measure could worsen local outdoor thermal comfort. The main positive effects of these materials are two-fold: one, reducing solar radiation absorbed by the pavements during the day, and two, releasing absorbed thermal heat into the atmosphere readily.	Cool pavements could be obtained by implementing lighter coloured asphalt on streets and roads and also by the use of cool tiles or special coatings on urban pavements. An incorrect implementation of this measure, especially in high urban density areas such as urban canyons, could cause outdoor visual and thermal discomfort for pedestrians and drivers as well as an increase of cooling loads in surrounding buildings. Nonetheless, cool pavements could be developed in both public and private spaces.
Permeable pavements 	Water retentive and porous pavement systems, which include additional voids compared to conventional pavements, allow water to flow into the ground or into water holding fillers. This helps to store runoff so as to avoid pooling or ponding on the pavement surface. From a thermal perspective, these pavements also enhance water evaporation and therefore remain cooler than conventional pavements.	A permeable pavement measure provides benefits for pedestrians' thermal comfort allowing a reduction of the surface temperature of the pavements due to water evaporation and reduction in overheated material. When applied on a large scale, it simultaneously contributes to UHI mitigation and also flooding risk reduction. It can also contribute to pollution control from surface runoff from roads and parking areas, and help with noise reduction.	This type of solution has become an important and integral part of sustainable urban drainage systems. Common applications can be public and private, such as vehicular access, parking, pedestrian access and bicycle trails (Scholz and Grabowiecki, 2007). Implementation varies greatly across specific designs, and can be integrated with vegetation factors.
Photocatalytic cool pavements 	Cool pavements are surfaces that have been treated, blended, coated, sprayed (before, during and/or after installation) with specific mixtures or additives that help them remain clean, and maintain a high level of solar reflectance over time. Generally, these treatments are based on photocatalytic properties.	Solar reflectance usually decreases over time, as soiling from traffic darkens the surfaces. Improving the self-cleaning capability of pavements and maintaining a high level of solar reflectance with photocatalytic treatments allows the original thermal and visual performance of the pavements to be retained. This helps maintain low values of surface temperature for pavements exposed to intense sun radiation and similarly, helps maintain low nearby air temperature values to improve pedestrian thermal comfort.	If implementation of photocatalytic cool pavements is not regulated under any standards, it can be implemented both for private and public pavements, or in renovated or new pavement scenarios.
Cool roofs	Cool roofs are typically white or lightly coloured reflecting surfaces that are able to decrease their surface temperature and consequently heat transferred into the buildings below. They can be useful for reducing cooling energy consumption and energy costs in buildings.	Cool roofs can increase the albedo of the urban environment if widely applied, presenting a relatively high heat island mitigation potential. Cool roofs are characterised by high solar reflectance, but also by high thermal emittance. These positive effects reduce building energy consumption for cooling - thanks to their capability for increasing thermal losses and decreasing corresponding heat gains during sunny days (Santamouris,	The implementation of a cool roof measure is considered financially and technically viable, providing a cost-effective solution to increase building energy efficiency. It can be implemented both on flat and sloping roofs using cool solutions such as natural cool gravels, cool membranes in single ply or liquid mixtures, cool coatings, cool tiles and more (Pisello et al., 2014; Pisello et al., 2015).

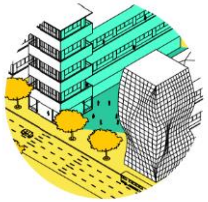
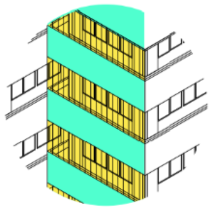
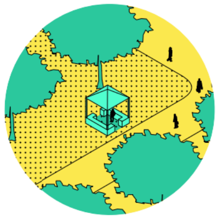
		2014; Akbari et al., 2006).	
Cool façades 	Cool façades are covering layers of building façades that limit the absorption of solar radiance. They help reduce the surface temperature of façades and cut both the heat transferred into the building, and the energy consumption needed for interior cooling.	The benefit of this solution consists mainly in increasing solar reflectivity and promoting emission accumulated heat using high thermal emissivity. The result is a reduction of both the building energy consumption for cooling and the temperature of the air in the cool façades proximity. The analysis of thermal effects on buildings and outdoor dense urban environments has shown interesting prospects for urban heat island mitigation (Doya et al., 2012). Thus, an improvement in outdoor thermal comfort and UHI is expected by the implementation of this measure on a large scale.	The implementation of this measure is considered financially and technically viable, especially for south-oriented façades. It could be implemented by following specific façade design to avoid visual and thermal discomfort for passers-by.
Photocatalytic cool buildings 	These are cool building envelopes such as cool roofs and cool façades that have been treated, blended, coated, sprayed with specific mixtures or additives that help building envelope surfaces remain clean and maintain a high level of solar reflectance unaltered in time. Generally, these treatments are based on photocatalytic reactions and they can be applied before, during and/or after installation.	Solar reflectance of cool roofs and cool façades decreases over time, as deposition from environmental agents darkens the surfaces. An improved self-cleaning capability can preserve a high level of solar reflectance to keep the original thermal and visual performance of such surfaces. This helps maintain low surface temperatures and reduce the potential building energy consumption particularly in hot climates where air conditioning is essential. The positive effects of this strategy in relation to the UHI phenomenon consist of limiting the potential increase of the phenomenon intensity and undesirable correlated effects.	The implementation of photocatalytic cool surfaces can be regulated by standards. The treatments can be white or light coloured and they can be implemented in both private and public buildings, and in building envelopes to be renovated or that are new.
Retro-reflective materials 	Retro-reflective materials are directionally reflective surfaces (non-diffusive surfaces) characterised by high albedo and the ability to reflect solar radiation back towards its source.	Retro-reflective materials contribute to the mitigation of extreme local overheating and UHI effects by lowering building cooling loads and electricity consumption (Synnefa et al., 2006). The decrease of building and urban surface temperatures, and consequently urban ambient temperatures, influence pedestrian thermal comfort in a positive way.	Suitable applications in dense urban environments need to consider the negative effects such as overheating and glare in nearby buildings. Implementation should be focused on roofs, façades, and pavements paying attention to the directionality of the reflected radiation.

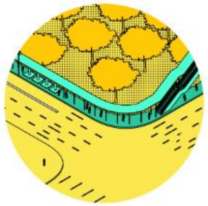
Phase change materials 	Phase change materials (PCMs) store and release massive latent heat during phase transition within a certain temperature range by increasing the building inertia and stabilising indoor air temperature.	PCMs help cut heat penetration into buildings and reduce the overall energy consumption, for both cooling and heating. It is considered a significant technology for the global warming solution (Lu et al. 2014). Indirectly, this solution will help mitigate UHIs and consequently improve the outdoor thermal comfort.	The integration of this measure needs to be done at building scale, incorporating the PCMs into the components of the building envelope, such as roofs, walls, floors, and transparent surfaces and so on. The efficiency and selection of PCMs are subject to the local climate where they are applied, since the transition temperature can vary.
Desiccant systems 	Desiccant systems control moisture and use latent cooling to maintain a comfortable and healthy indoor environment. By absorbing water vapour from the air, the dehumidifying effect moves the workload from latent cooling to sensible cooling and delivers improvements in building energy efficiency.	A desiccant (hygroscopic material) is energy-efficient for dehumidification in airconditioning systems in buildings (Gaoming Ge and Niu 2011). Desiccants remove moisture to reduce humidity and improve both air quality and energy efficiency. These systems offer thermal comfort in hot and humid climates along with lower primary energy resource consumption, compared to conventional cooling systems. The energy consumption savings allow reduced energy impact on the outdoor environment and therefore indirectly contribute to improving the outdoor thermal comfort and mitigating the UHI.	Not applicable as this solution concerns indoor application.
Water cooling façade systems 	Water cooling façade systems transfer heat by evapo-transpiration outside the buildings by means of water integrated within the building façades. Evaporative cooling is a heat dissipation technique.	Water cooling façade systems allow a reduction in urban heat accumulation and consequent emissions from a building by decreasing the surface temperature. This has a consequent influence on pedestrian thermal comfort when applied at pedestrian level.	Implementation should be focused on south-facing façades in particular where performance is enhanced by more intense solar radiation. Specific evaporative cooling solutions can be chosen and adapted for the purpose, in accordance with the architectural design of the building.
Thermochromic / selective materials 	This approach is suitable for building envelope application using reflective materials based on nanotechnological additives, such as thermochromic or selective materials. These respond thermally to their environment, changing colour (with reversibility) from darker to lighter tones according to the temperature increase. This passive cooling technique enables a decrease in heat gain by facilitating the elimination of excess heat in the indoor environment of a building to maintain high levels of thermal comfort.	Thermochromic systems allow the prevention of heat gains inside a building. The use of thermochromic coatings can both contribute to energy savings and provide a thermally comfortable building environment (Ma et al., 2001). They also contribute to improvements in the urban microclimate.	Implementation should be focused on building envelope and urban structures in areas characterised by non-negligible air temperature variation. In this sense, including this aspect in building codes could help with their implementation.

Dynamic and active roofs 	This measure concerns roofs that are characterised by the dynamic adaptation to environmental conditions, using manual, automatic or hybrid systems. The key purpose of these systems is to cool the roof	The advantage of this kind of dynamic measure is the ability to use roofs to adapt to the environmental conditions. This adaptation helps the roof maintain the optimal surface temperature and the building to exhibit better performance in terms of indoor cooling demand. This reduces CO_2 emissions from cooling systems. The implementation of this kind of solution within the city could mitigate the UHI phenomenon and, as a consequence, have a positive impact on the outdoor thermal comfort.	Moveable systems can be applied to the roof, according to the local regulation on dynamic and active systems. The principle of functioning can differ from one solution to another (automatic systems, water systems, manual systems, hybrid systems, etc.).
Dynamic and active façades 	This approach uses manual, automatic or hybrid system building façades that can dynamically change their configuration to let the building adapt to the weather conditions. The optimal adaptation improves the thermal-energy performance of the building.	The UHI mitigation, and consequently the improvement of outdoor thermal comfort, can be reached thanks to the use of dynamic building façades characterised by active systems that are able to improve the thermal-energy performance of the building envelope. Indeed, when the heat flux entering the building is reduced, the cooling energy consumption will be reduced accordingly, and less emissions would be released into the atmosphere by the cooling systems.	Implementation is related to building façades and can therefore be considered for both private and public applications. These solutions can be integrated into existing buildings or developed for new constructions.
	This measure improves the building envelope performance to minimise heat losses or heat gains through the use of high thermal-energy strategies such as specifying thick conventional insulation.	These solutions eliminate the risk of over-heating of the buildings during extreme heat periods. Therefore, the indoor cooling needs would be reduced, as well as the correlated emissions and heat released into the outdoor environment. The greater the use of this measure within a city, the greater the benefit for the urban environment in terms of UHI mitigation and improvement in outdoor thermal comfort.	Implementation should focus on building roofs and façades and with the help of adequate building codes. Both public and private buildings can be improved from the application of high performing building envelopes. Some strategies can be also applied on both new constructions and retrofit applications.

About 5. Shading

Measure	Description	UHI effect	Urban planning
Building orientation	Buildings can be positioned in relation to variations in the sun's path as well as prevailing wind patterns. An	Optimised building orientation can lower the sun exposure and therefore minimise solar heat gains through	The main orientation of the building should be within 30° of south. Houses oriented east or south will benefit from the

	adequate orientation can increase the building performance and provide shade on nearby outdoor structures such as sidewalks, public spaces and streets,	the façades. Depending on the building orientation, direct, diffuse, and reflected radiation can be blocked, limiting short-wave radiation on surrounding/ local outdoor spaces. Simultaneously, it can also decrease the surface temperature, contributing to the short-wave radiation reduction (Lin 2016). The orientation can also contribute to the shading of outdoor spaces and therefore increase the pedestrians' thermal comfort and reduce the air temperature.	morning sun. Those orientated west or south will catch the late afternoon sun – which can help delay the evening heating period. A location on a south facing slope optimises solar access whilst minimising overshadowing from adjacent buildings. It also allows for higher density planning.
Shading on buildings 	Building elements as shading devices can be installed outside or inside, on or around the building envelope. They can be fixed elements, such as canopies, brise-soleils, horizontal or vertical louvers, blinds, roof overhang, egg-crate; or moveable elements, such as sun baffles and shutters (Giguere, 2009).	These elements function to control direct solar radiation as well as block and diffuse the reflective radiation of building envelopes. They limit the heat gains and consequently improve the thermal comfort of both indoor and outdoor environments. They also increase the building energy performance by reducing the building peak cooling load, and therefore reducing the UHI effect.	Windows in façades facing east and west should be minimised and shading devices should be integrated to reduce solar heat gain. The most common shading elements used in the tropics are horizontal overhangs to block high-angle sunshine during midday and vertical fins to protect from low-angle sunshine during the morning and afternoon (BCA, 2010).
Permanent shading devices 	Permanent shading devices are solid and fixed structures. They are horizontal or vertical shades that protect people from harsh sunlight all day. Some types of fixed devices are urban pergolas, shade sails, framed canopies, shelters, or even solar cells applied on façades. They are mainly permanent structures.	Shading devices can control the intensity of solar radiation, but should not obstruct the breezeway and allow a refreshing sensation to guarantee comfort. The effect of this measure depends on the material, geometry, dimension and location of the device. It is imperative to study the sun-path to define the type and properties of the shading device.	Fixed devices can be applied to protect walkways, transport stops, park accesses, fixed urban furniture, or playgrounds. It is important that the design of fixed shading devices can balance the amount of shade and natural light.
Moveable shading devices 	Moveable shading devices are operable, manual and automated shades. They allow users to adjust the spatial properties according to personal needs. Some types of mobile devices are autonomous canopies and temporary tents.	This measure fulfils similar purposes as the fixed shading device. It can adapt to the sky conditions, solar angle and time of the day, reducing direct sun exposure during extreme weather conditions. Additionally, it offers spatial and temporal flexibility, but is limited in the sense of dimension, material and durability. It can have a positive impact on thermal comfort, especially in areas where permanent structures are not allowed or needed.	Mobile devices are commonly light and simple to install. They can be applied in areas where additional shading is needed during the daytime, for example in parks, sports fields, or temporary public spaces. During night-time they can be removed. This allows flexibility and variety of shaded and sunlit areas all-day round.

Smart shading devices 	Smart shading refers to shading devices that apply materials to transform their properties by external stimuli, also called 'shape shifting materials'. Their transformation is reversible and can be repeated.	Smart materials can change colour, shape or density according to the temperature, humidity and light of the outside environment. Smart shading devices can adapt to the climatic condition and therefore control the solar heat gain.	This type of measure can be implemented in many scales, from roofs for public spaces to entire building façades.
Shaded pedestrian spaces	Shading or the protection against direct sunlight of pedestrian spaces can be provided by buildings, canopies or trees. Important locations of shaded spaces are schools, hospitals, elderly facilities, transit stops, parks and plazas, recreational spaces, food centres and shopping areas.	Shading of outdoor spaces can effectively reduce the air and surface temperature while enhancing the thermal satisfaction of pedestrians. Increased shading on street level can control the amount of solar radiation absorbed by the ground floor surfaces.	The type of shading depends on the location, size, and function of the outdoor space. Different types of shading can have different impacts on pedestrians.
Shaded bicycle lanes 	The shading of bicycle lanes along designated lanes or along parks can be provided by buildings, trees, canopies or other existing infrastructure, such as bridges or elevated highways. They can shield cyclists from direct sunlight and high air temperatures, and help them have a comfortable ride, thus promoting active mobility.	Trees or permanent covers can provide shade along bicycle corridors. Such covers can block the direct solar radiation and protect from rain, and therefore contributing to cycling comfort.	The location and orientation of the bicycle routes during planning are crucial to provide sufficient wind breeze and sun shade. An example is to locate bicycle lanes under wide infrastructure structures that provide sufficient shade length and protection from heavy rainfall.

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