

2 Impacts, strategies and tools to mitigate UHI

Article 1: Impacts, strategies and tools to mitigate UHI. Submitted but not published.

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Abstract

The impacts of climate changes to cities, which are home to over half of the world's population, are already being felt. In many cases, the intensive speed with which urban centres have been growing means that little attention has been paid to the role played by climatic factors in maintaining quality of life. Among the negative consequences of rapid city growth is the expansion of the problems posed by urban heat islands, defined as areas in a city that are much warmer than in other sites, especially in comparison with rural areas.

This paper analyses the consistency of the UHI related literature in three stages: first it outlines its characteristics and impacts in a wide variety of cities around the world, which poses pressures to public health in many different countries. Then it introduces strategies which may be employed in order to reduce its effects, and finally it analyses available tools to systematize the initial high level assessment of the phenomenon for multidisciplinary teams involved in the urban planning process. The analysis of literature on the characteristics, impacts, strategies and digital tools to assess on the UHI, reveals the wide variety of parameters, methods, tools and strategies analysed and suggested in the different studies, which does not always allow to compare or standardize the diagnosis or solutions.

Key words

Climate change – Urban Heat Islands- Cities- Urban – Models

§ 2.1 Introduction

The attractiveness of cities and the diversity of economic and social opportunities available there, are the main drivers of the continuously increasing rate of urbanised areas during the last centuries. According to United Nations reports, around 54% of the world's population has been residing in urban areas (2014 figures), in comparison to 3% in 1950. Current projections show that urbanisation may increase to 66% by 2050 (United Nations Department of Economic and Social Affairs 2014). By occupying only 3% of the Earth's land (United Nations 2016), cities account for 60%-80% of total energy consumption and 75% of carbon emissions (United Nations 2016). Urbanisation means that these figures are also likely to increase.

In addition to the significant direct impact of cities on global climate change due to the substantial CO₂ emissions they release, there are also other indirect impacts due to unsustainable consumption, pollution and waste generation. Therefore, experts point out that a growing urban population is also likely to increase the direct influence of cities on the regional and global climate (Emmanuel & Krüger 2012, United Nations Department of Economic and Social Affairs 2014). There are also some health implications here to be considered: apart from the many links between climate change and health (Leal Filho et al 2016), extreme temperatures in many cities are known to be associated with many detrimental health effects (US Centres of Disease Control and Prevention 2012) and often with higher mortality (Mills et al 2015).

There is also a need to address urban sustainability matters at a regional scale (Echevarría Icaza and Van der Hoeven 2017), in order to ensure a social, economical and environmental balance between the cities and their rural surroundings (Péti 2010). However, when it comes to the assessment of climate change impacts and adaptation options, comparatively little attention is being paid to sub-regional and regional scale processes. Or to vulnerability, which is often overlooked (Cuevas, 2011). This, in turn, leads to a reduced willingness to engage on adaptation processes, which make extreme events, when they occur quite costly (Mechler, Hochrainer, Aachein, Salen, Wreford 2010).

Furthermore, political and social awareness often concentrate either on macro-scale climate modelling, with the main focus on greenhouse gas mitigation, or adaptation to climate change, or on disaster management where little attention is given to the exposure and responses of cities to climate change and extreme weather events (Rosenzweig 2011). As a consequence, regional climatic phenomena such as the identification of flood catchment areas or the urban heat island effect are not being appropriately assessed (Hebbert & Webb 2011).

The urban environment is known to have an influence on its climate as well. One of such effects is an urban heat island (UHI) (Kleerekoper et al. 2012), whose trends in Europe have been analysed by Santamouris (2007).

UHI can be formally defined as a metropolitan area, which is significantly warmer than surrounding rural areas (National Center for Atmospheric Research (UCAR) 2011). Most references indicate that during the summer in temperate cities, generally the UHI reaches its peak during the night (Oke 1987; IPCC 2001; Moreno García MC 1993; Kershaw 2010). The contribution of anthropogenic heat varies depending on location and season: during the summer it has a negligible contribution whereas during the winter it can have a significant one (Lee DO, 1984).

The phenomenon is associated with a variety of factors, among which mentioned can be made to changes in runoff, the concrete jungle effects on heat retention, changes in surface albedo, changes in pollution and aerosols, and so on (Solomon et al. 2007, Echevarría Icaza et al. 2016a, Echevarría Icaza et al. 2016b), combined with atmospheric conditions. These effects are to a large extent caused by changes in the land surface. The replacement of trees and vegetation by surfaces with less permeable materials, minimizes the natural cooling effects of shading and evaporation of water from soil and leaves (National Center for Atmospheric Research (UCAR) 2011). Waste heat from traffic, industries and air conditioners increase temperature and thus further exacerbate the heat island effect. Moreover, densely constructed buildings, from materials with large thermal admittance, and narrow streets, reduce air flow and natural cooling effects by holding and blocking heat from rising into the cold sky (National Center for Atmospheric Research (UCAR) 2011). Cities also have a larger surface area compared to rural areas and therefore more heat can be stored (Kleerekoper et al. 2012). The land use and the design of the peri-urban landscapes surrounding the cities, together with the design of the city boundaries (e.g. high constructions blocking wind paths versus green wind corridors) also influences the intensity of the phenomenon (Echevarría et al. 2016c).

Some recent studies such as Li & Bou-Zeid (2013) and Li et al (2015), have addressed the synergetic reactions of heat waves with UHIs which coupled with increased population density, exacerbates the problem in urban settings.

Heat islands can occur year-round during the day or night (National Geographic 2016). The UHI is the most obvious atmospheric modification attributable to urbanisation. It occurs in settlements of all sizes in all climatic regions (Roth 2013). Heat urban island was first observed in London by Luke Howard in 1833 (Chow et al. 2012). Today, it is the most studied climate effect of cities (Roth 2013).

UHIs have multiplied effects on climate and urban dwellers, mainly on local level. It increases summertime peak energy demand that elevates emissions of air pollutants and greenhouse gases, which in turn contribute to an even hotter UHI (US EPA 2015b; National Geographic 2016). Increased emissions lead to lower air quality compromising human health (US EPA 2015b). UHIs also impair water quality. Warm water ends up flowing into local streams: rivers, ponds, and lakes that stresses the native species that have adapted to life in a cooler aquatic environment (US EPA 2015b; National Geographic 2016). Keramitsoglou et al (2017) outlined the roots of urban thermal risk reduction whereas Lauwaet et al (2015) offered a detailed urban heat island projections for some cities.

However, the key issue is the effect of urban heat island on urban climate and surroundings. Consistent with the need to investigate this important topic, the aim of this paper is to analyse the different parameters, scales, intensities, health impacts, mitigation proposals and diagnosis tools, used to assess the UHI phenomenon across the globe, in order to highlight the huge disparity of methods, which can complicate the transferability of the results.

§ 2.2 Materials and Methods

In order to understand how consistent the different studies are, how comparable the results, and how formalised the procedures of analysis and tools, this study analyses and classifies UHI literature in three stages:

- Characteristics of the phenomenon in different cities across the world, identifying parameters analysed and mitigation proposals suggested based on the analysis.

- Analysis of different UHI mitigation strategies proposed, and description of the principle and effects.
- Analysis of digital UHI online tools, identifying geographical cover, scale of assessment, type of assessment and limitations.

§ 2.3 Results

§ 2.3.1 Trends on urban heat islands in cities round the world

Urbanisation impacts the climate on both regional and local levels. It results in differences between a city and rural area in cloud cover, precipitation, solar irradiation, air temperature and wind speed. The geometry, spacing and orientation of buildings and outdoor spaces strongly influence the microclimate in the city (Kleerekoper et al., 2012). Perturbation of surface energy balance caused mainly by reduction of evaporative cooling, release of anthropogenic heat and increase of solar radiation input due to decreased albedo. All these contribute to UHI (Zhao et al., 2014), which in turn exacerbate the impact of heat waves, periods of abnormally hot, and often humid, weather (US EPA 2015b). However, UHIs might also have positive effects in cities in cold climates, namely, a smaller number of snowfall and frost events, longer growing season as well reduced energy demand for domestic heating (Roth 2013).

The causes and impacts of the urban heat island effect have been well studied in different cities around the globe, and some examples are herewith documented (Figure 2.1).

- Example 1: USA. According to the EPA, many U.S. cities have air temperatures up to 5.6°C warmer than the surrounding natural land cover (National Center for Atmospheric Research (UCAR), 2011). Analysis of the regional temperature trends calculated from seven long-term observation stations for the summer and winter seasons between 1950 and 2014 identified an UHI effect in Reno, Nevada that is maximized during summer (June- August) (Hatchett et al., 2016). Debbage & Shepherd 2015 estimated the urban heat island intensities of the 50 most populous cities in the United States. Their findings indicate that the spatial contiguity of urban development, regardless of its density or degree of sprawl, is a critical factor that influenced the magnitude of the urban heat island effect. An increase of 10% of urban

spatial contiguity might enhance the minimum temperature annual average UHI intensity by between 0.3 and 0.4°C (Debbage & Shepherd, 2015).

- Example 2: UK. Kershaw et al. 2010 estimated the heat island effect in the UK cities. The obtained results showed that the UHIs are largest in the summer, but not for every city. For example, in small cities such as Leicester or York, the UHIs are very small and do not vary with season. The annual average UHIs for different UK cities range between 0.1 and 1.9°C, whereas in a summer period between 0.1 and 2.0°C, for example, in London it varies between 1.6°C and 1.9°C for summer (Kershaw et al., 2010).
- Example 3: Belgium. Lauwaet et al. 2016 examined the urban heat island of the country's capital, Brussels, for 2000–2009 and projected 2060–2069 climate conditions. The obtained results indicate that the presence of the urban heat island has an impact on extreme temperatures, especially during the night. Such temperatures are also expected to occur more frequently in the future. At the same time the authors project only very small change in the magnitude of Brussels' UHI in the near future. Overall, the mean night-time UHI of Brussels accounted to 3.15°C for the 2000–2009 (Lauwaet et al., 2016).
- Example 4: The Netherlands. Echevarria et al. 2016c made a comparative analysis of heat related parameters (storage heat flux, vegetation index, land surface temperature, albedo, sky view factor and coolspots) retrieved through satellite imagery analysis of six Dutch cities: The Hague, Delft, Leiden, Gouda, Utrecht and Den Bosch. The analysis revealed that the hotspots of the six cities were located in the seventeenth century city centres. The increase of the albedo of all roof surfaces comprised within the hotspot boundaries was estimated to reduce the UHI effect by 1.5°C. For the cities of The Hague, Delft and Leiden the maximum UHI (based on hobby meteorologists data) was estimated to range from 4.8°C to 5.6°C (Hove et al., 2011). The UHI of the city of Amsterdam was analysed by Van der Hoeven and Wandl 2015 who produced a set heat related maps: landuse, imperviousness, social vulnerability, building vulnerability. The nocturnal air temperature images present air temperature differences of above 7°C.
- Example 5: Greece. Greece's capital, the city of Athens, is characterised by strong heat island effect, mainly caused by its geographical position and its accelerated industrialisation and urbanisation during the last decades. The UHI in the city is mainly linked to limited green and open space areas, lack of water evaporation, the high heat storage capacities of building and surface materials, air pollution as a result of dense traffic and nearby industries, and intense air conditioning (Kourtidis et al. 2015). According to Santamouris et al. 2007, the ecological footprint of the additional CO₂ emissions caused by the presence of the heat island effect ranges 1.5–2 times the Athens's political area of 2,929 km², whereas the maximum potential ecological footprint, provided that all buildings are air conditioned, is approximately 110,000 hectares (Santamouris et al., 2007).
- Example 6: Germany. An example from Germany is provided by the city of Stuttgart, located in the Neckar basin, surrounded by steep hill slopes, and with an area of 207,4

km². The city is located at around 240 m above sea level, whereas the surrounding hills reach up to 500 m. This particular topography worsens the UHI effect as well as the air quality. The mean annual temperature will be increased by 2°C in the climate projections for 2071-2100 and the Great Stuttgart region will experience more than 30 days heat stress by 2100 (Adapt, 2015). In such context, preserving and enhancing existing green infrastructure surrounding the city becomes critical. The Climate Atlas of the Region of Stuttgart is one of the best-known examples of integrating climate knowledge into spatial planning. The city of Stuttgart has around 600,000 inhabitants, and its metropolitan region has around 2,600,000 inhabitants. This is primarily an industrial region and has had a long tradition of air quality concern, which is probably the triggering factor for its climatic awareness. Its 2008 Climate Atlas City of Stuttgart (Office for Environmental Protection, Section of Urban Climatology, 2008) highlights cold production areas, air catchment areas, as well as different breeze systems. The most important cold production green infrastructure area is located near to the western part of the city, and has a surface area of around 1,000 ha. One important characteristic of this climate buffer is that it is actually connected to a larger territorial landscape between the cities of Leonberg, Sindelfingen, Vaihingen and Boblingen.

- Example 7: Malaysia. Morris et al. 2015 investigated the existence and distribution of UHI in the administrative capital of Malaysia, Putrajaya. The city that is built on the garden-city concept. The obtained results have shown that UHI intensity of Putrajaya varies temporally and spatially. It increases during the night to a peak value and then diminishes in the morning with a negligible value during mid-day. During the night the UHI ranges from 1.9°C to 3.1°C. The overall effect of urbanized local climate zones heating of Putrajaya is Normalised by the total amount of area reserved for vegetation (Morris et al., 2015).
- Example 8: India. Borbora & Das 2014 assessed the urban heat Island intensity (UHII) during the summertime in Guwahati, a small but rapidly growing city of India, where humidity conditions are high. The findings show the existence of UHII above 2°C. The highest magnitude of daytime urban UHII accounts to 2.12°C while highest night-time UHII to 2.29°C. They also found that that the formation of daytime UHII of =1.5°C is fairly common. Therefore, the authors conclude that with incremental decrease in green cover associated with urbanisation, will enhance the UHI phenomenon that will result in substantially higher level of discomfort for dwellers (Borbora & Das, 2014).
- Example 9: Japan. According to Fujibe 2011, in some cities in Japan, the increase in annual extreme minimum temperature exceeds 10°C/century. The studies also revealed widespread urban warming (the extended heat island) around Tokyo and other megacities such as Osaka and Nagoya in the afternoon in summer. The obtained results are explained by the enhanced surface heating over a large urban area, and a reduction of sea breeze penetration caused by increased surface convergence. An analysis of meteorological data indicated the existence of anomalous temperature

changes. Locations with population density of 100 to 300 inhabitants per km² has the anomalous trend of 0.04°C /decade (Fujibe, 2011).

Some trends are also seen in Africa (Taylor, 2016) where efforts to handle the problem are seen. Indeed, numerous mitigation strategies are being employed as a response from city authorities across the world to the adverse effects caused by the urban heat island phenomenon. Some of them are introduced in the next section of this paper.

Country	Reference	City
USA	National Center for Atmospheric Research, 2011	
	Hatchett et al. 2016 Debbage & Shepherd, 2015	Reno, Nevada 50 most populous cities in the US
UK	Kershaw et al. 2010	
Belgium	Lauwaet et al. 2016	Brussels
The Netherlands	Echevarria et al. 2016 b	The Hague, Delft, Leiden, Gouda, Utrecht and Den Bosch
	Hove et al. 2011	The Hague, Delft and Leiden
	Van der Hoven and Wandl 2015	Amsterdam
Germany	Office for Environmental Protection, section of urban climatology, 2008	Stuttgart
Malaysia	Morris et al. 2015	Putrajaya
India	Borbora & Das 2014	Guwahati
Japan	Fujibe 2011	Tokyo, Osaka and Nagoya

FIGURE 2.1 Overview of a set of literature on UHI distributed by country.

Air Temperature Difference	Summer	Winter	Period of analysis	Parameters analysed	Mitigation measures suggested
5,6	X	X	1950-2014	Spatial contiguity, density and sprawl.	Spatial contiguity critical factor UHI. An increase of 30% in spatial contiguity might increase annual UHI by 0,3 and 0,4.
0,1 to 1,9	X	X			
3,15			2000-2009 and 2060-2069		
4,8 and 5,6	X			Storage heat flux, vegetation index, land surface temperature, albedo, sky view factor and coolspots	Hotspots of 5 of the 6 cities were located in the seventeenth century City Center. Albedo interventions on those could reduce the effect by 1,5
7	X			Land use, imperviousness, social vulnerability and building vulnerability.	
				Cold production areas, air catchment areas and breeze systems.	Preservation and enhancement of existing green infrastructure surrounding the city.
1,9 to 3,1				Vegetation surface	The overall effect of urbanised local climate zones is normalised by the total amount of area reserved for vegetation.
> 2				Green cover	The reduction of green cover associated with urbanisation, increases the UHI.
	X			Surface heating over large surfaces, sea breeze penetration, temperature change evolution per decade, density.	

§ 2.3.2 Strategies to reduce heat islands

By diminishing the accumulation of heat and applying cooling techniques, cities can reduce the temperature difference between urban and rural areas (Rotem-Mindali et al., 2015). There have been several attempts to produce catalogues describing not only the causes and impacts of UHI, but also suggesting mitigation strategies:

- In Quebec the Urban Heat Island Mitigation Strategies catalogue (Giguère M. et al., 2009) organizes the mitigation strategies around four sections:
 - Vegetation.
 - Sustainable urban infrastructure.
 - Sustainable stormwater management.
 - Reduction of anthropogenic heat.

It then also classifies by scale (building and urban planning) the mitigation measures. The building mitigation measures are classified in three sections: protection from solar radiation, minimization of heat infiltration, reduction of anthropogenic heat and maintaining comfortable thermal environment, whereas the urban planning and development measures are grouped in three areas: greening, urban infrastructure and reduction of anthropogenic heat.

This catalogue comprises short term mitigation measures such as ensuring the access to the so called “cooling centres” which are any airconditioned public buildings that can accommodate public (shopping centres, schools, cultural centres...), the creation of air-conditioned shelters for outdoor workers (CSST, 2004) or even the access to aquatic facilities (including pools and misters) in natural environment or public installations (Raymond et al., 2006).

- The catalogue developed within the framework of the UHI project which was implemented through the Central Europe Programme co-financed by the ERDF (Vienna University of Technology, 2014) structures the actions in four packages:
 - Buildings.
 - Pavements.
 - Vegetation.
 - Street morphology.

Its classification does not organize the mitigation actions by the immediacy of its effect (short, medium or long term effect), and in turn in its introduction a clear distinction is made between adaptation measures and mitigation measures. Adaptation measures are considered measures where the direct intervention of users is necessary -clothing, air conditioning (Solecki et al., 2005)....- and that do not have any positive effect on the outdoor thermal comfort, or even that have a negative one -heat released by air

conditioning (Hsieh et al. 2007, Wen and Lian 2009). In turn, the mitigation strategies are considered well prepared and consistently applied actions. This is the reason why the mitigation measures presented include less actions than other catalogues.

- The Yamamoto compilation study (Yamamoto, 2006) organizes the mitigation strategies in three blocks:
 - Reduction of anthropogenic heat release.
 - Improvement of artificial surface covers.
 - Improvement of urban structure.

And introduces important characteristics for each mitigation strategy:

- Scale (individuals, buildings, ward, city).
 - Period (short, medium or long term).
 - Degree of effect (on sweltering nights or on daytime temperature rise).
 - And administrators of the actions (individuals, business institutions, local governments...).
- There are other catalogues that attempt to keep updated the review of the UHI mitigation literature, such as the catalogue of strategies for tropical Singapore, which focuses in improving the outdoor thermal comfort in the tropical climate (Cooling Singapore, 2017).

The conclusion of the review of the above-mentioned catalogues is that even though the structure of the catalogues varies, there is a consensus in the nature of the UHI mitigation strategies. Below a summary of these.

§ 2.3.2.1 At building scale

- Choice of Roofing Materials: The choice of roofing colour can contribute to temperature reduction by approximately 12%. Roofing materials with high albedo reduce absorbed solar heat and make a house less warmer that results in lower energy consumption (Nuruzzaman, 2015). Studies in Singapore demonstrated that the city-scale deployment of cool roofs can greatly reduce the near-surface air temperature and surface skin temperature during the daytime (Li & Norford, 2016).

- Use of Green Roofs: The wide conversion of the black roofs into green roofs can have positive effects on micro- and urban scale as well provide better storm-water management- improving water retention by 7% to 10%, also leading to improvements of air quality and increases in urban biodiversity (Susca et al., 2011).
- Reduction of anthropogenic heat production: Anthropogenic heat generated by exhaust heat from outdoor AC units also contributes to the formation of UHI. Appropriate nocturnal cross ventilation, window shading, appropriate building insulation (Déoux, 2004) or the implementation of green roofs help decrease the use of energy for cooling and heating by between 20% and 25% depending on the construction materials used and whether or not green roofing is being used. The use of geothermal energy and radiant cooling systems, are alternative solutions to conventional air conditioning systems, which contribute to the reduction of anthropogenic heat.

§ 2.3.2.2 At city scale

- More Urban Green Vegetation: Vegetation provides shade, thermal insulation to keep the interior cool, manage noise and air pollution (Roth, 2013). According to Takebayashi & Moriyama, 2007, the sensible heat flux is small on the green surface (Takebayashi & Moriyama, 2007). Vegetation reduces the near-surface air temperature on average by of 1 – 4.7°C, particularly during night-time when the UHI intensity is high (Kleerekoper et al., 2012; Li & Norford, 2016). Assessments of the thermal load in terms of surface temperature in Tel Aviv demonstrated that the relatively low vegetation cover to free space ratio decreases the cooling effect of residential areas. Therefore, the authors recommend to ‘green’ areas within the private urban space instead of building new small-medium parks in metropolitan areas that are usually lack of free space (Rotem-Mindali et al. 2015). It is also important to note that increased urban green areas might potentially be offset by increased municipal water usage, especially, in the regions with scarce water resources, e.g. in Phoenix, Arizona, where per capita residential water use is significantly higher compared to other U.S. cities (Chow et al., 2012).
- Choice of Pavement Materials: The finishing materials of urban ground surfaces also have a major impact on the UHI effect (Gago et al., 2013). Replacing materials with new surface cover reduces the radiative heat gain in the material by about 18%-20% and improves evaporative properties of the urban surface (Roth, 2013). Cool pavements have substantially lower surface temperature and reduce sensible heat flux to the atmosphere. The current research trends in the field are focused on the development of highly reflective pavements and permeable pavements that use the cooling evaporation capacity of water (Santamouris, 2013).
- Urban structure: Changes in building development and design options might have a positive impact on reduction of building energy use and the UHI (Roth, 2013). The

distribution of the buildings and urban structures in a city affect the formation of the urban heat island, since this distribution usually determines the absorption of solar radiation and the formation of air flows (Gago et al., 2013). Designing building with considering wind properties can also lead to effective cooling of buildings in urban areas (Kleerekoper et al., 2012), reducing heat by about 25% depending on the area and properties of the building.

- Access to cooling centres: These are air conditioned public buildings: shopping centres, schools, cultural centres...As discussed at the beginning of section 2.3.2. these are controversial, as they provide shelter to vulnerable population, but in turn they contribute to the formation of the UHI due to the production of anthropogenic heat. Thus, they can be considered short term adaptation measures.
- Stormwater management infrastructure: Retention ponds (receive runoff water and infiltrate it into the ground, can be used as green recreational areas), infiltration trenches (receive runoff water and can be easily integrated in the urban environment), dry wells (receive runoff water and are covered with gravel and sand), reservoir pavement structures (collect water at the source, through pervious finishing materials).
- Reduction of anthropogenic heat: At city scale anthropogenic heat is produced either by buildings (section 2.3.2.1.) or by cars. Several measures can help reduce traffic anthropogenic: greener cars, improving public transit, reducing sprawl, increasing mixed-used development and by encouraging the use of electro-mobility.

§ 2.3.2.3 At regional scale

- More Peri-urban vegetation: The European Environment Agency urban adaptation document (EEA, 2012) suggests interventions to reinforce green infrastructure outside the city boundaries in order to manage the three main climate change phenomena threatening cities: heat waves, floods and droughts, which are projected to increase in frequency, intensity and duration (Barriopedro et al., 2011). Further, as far as governance is concerned, it also specifically highlights the importance of developing multi-level territorial spatial planning approaches to coordinate the responses to climate change challenges, from the city level through to national and EU levels. The regional level is the intermediate scale that links and connects cities with national territorial policies.
- Catering for Wind corridors: Wind corridors are designed to maximize the cool air transportation from natural cooling sources (typically green infrastructure) towards urban hotspots through advection (Echevarria et al., 2016c). Relevant examples of the study of the air circulation patterns applied to spatial planning are Climate Analysis Map for the Stuttgart region 2008 (Office for Environmental Protection, Section of Urban Climatology, 2008), the Urban climate analysis map for the city of Arnhem

(Burghardt et al., 2010) the Netherlands and the ones envisioned by the Land Use Plan 2020 of the city of Freiburg (City of Freiburg, 2013).

- Using the ecological functions of water bodies: Water might reduce temperature by evaporation, absorbing heat and transporting heat out of the area by moving, as in rivers. It has an average cooling effect of 1–3 °C to an extent of about 30–35 m. Such functions of water are already applied in Dutch cities (Kleerekoper et al., 2012). Hendel et al. 2016 assessed the thermal effects of pavement-watering in Paris during the summers of 2013 and 2014. The obtained results showed that pavement-watering has UHI-mitigation effects and is an effective measure to reduce maximum daily heat stress. The maximum reduction of 0.79 °C, 1.76 °C and 1.03 °C for air, mean radiant, UTCI-equivalent temperatures and UHI-mitigation of -0.22 °C have been recorded during the day (Hendel et al., 2016).
- Land use considerations: The average night-time land surface temperature of different land use patches varies depending on the size, shape and nature of the land use (forests, cropland, grassland, water surfaces, built areas and greenhouse areas) (Echevarría et al., 2016a). These should be taken into consideration when designing landscapes nearby to UHI hotspots.

§ 2.3.2.4 Raising awareness among residents

Apart from technical mitigation strategies, governments implement measures aiming directly at reduction of the climate discomfort of urban residents and their vulnerability to heat stress. The US EPA provides guidelines to the local governments to assist in the developing plans to adapt to heat. Among the main components are forecasting and monitoring, education and awareness, and heat wave response. Reliable weather forecasts allow city officials to warn citizens of heat waves in a timely manner and to prepare responses. Education and awareness efforts help to disseminate information about symptoms of excessive heat exposure and heat-related illness, recommended response and treatment, and potential risk factors (US EPA, 2015a). Bearing in mind that the economic and environmental effects of unilateral climate actions are limited, (Kiuila et al., 2016), these measures should ideally be implemented by groups of cities, so as to maximise their impacts.

These measures have the advantage of addressing the roots of the problem of UHI on the one hand, and inter alia reducing the changes of their detrimental impacts to human health on the other.

§ 2.3.3 Systematising estimation and adaptation measures to UHI

Several studies (Echevarria Icaza et al., 2016d) indicate that the need for deep climatological studies on the UHI is as critical as the need for quick, multidisciplinary, high level understanding of the impact of the phenomenon to ensure it is taken into consideration since the initial stages of the spatial design. Since the options to mitigate and or adapt to the UHI phenomenon are numerous, there have been several attempts to create tools for urban planners to obtain an overview of its actual effect and potential mitigation strategies available.

§ 2.3.3.1 The “Decision Support System” (DSS)

The “Decision Support System” (DSS) was developed in the framework of the UHI Project, co-financed by the European Regional Development Fund. It covers 8 metropolitan areas and mega urban regions in the Central Europe Region (Bologna/Modena, Venice/Padua, Wien, Stuttgart, Lodz/Warsaw, Ljubljana; Budapest and Prague). For each of these areas, the tool provides an overview of the extent of the phenomenon, and suggests mitigation actions at two different scales: the building and the urban ones, and analyses the feasibility of the implementation of measures affecting facades, roofs, surface lots, urban structure and urban green in existing structures and new constructions (Urban Heat Island project, 2014).

This webpage can be considered an interactive tool for urban planners, as these first select the location in which they are interested, the scale at which they wish to intervene, an economic assessment which is actually an online calculator and a checklist of the skills on which one chooses to be assessed (Figure 2.2). Based on these, a customised report is issued which consists of three main elements: a climate change assessment of the selected area, a set of normative applicable to the selected area and skills, a set of potential mitigation strategies. The final part of the report is common to all reports and consists of a description of the pilot actions undertaken within the UHI project and a list with the contact details of the partners involved in the project.

The climate change assessment of the area consists of a set of maps: one showing the change in the average annual mean temperature every decade (Figure 2.3), one showing the projected changes in the annual near-surface temperature for the periods of 2021-2050 (Figure 2.4), and 2071-2100 and finally one identifying the heat wave frequency for the period of 1961-1990 and 2071-2100 (Figure 2.5).



FIGURE 2.2 Screenshot of the interactive assessment configuration of the DSS tool.

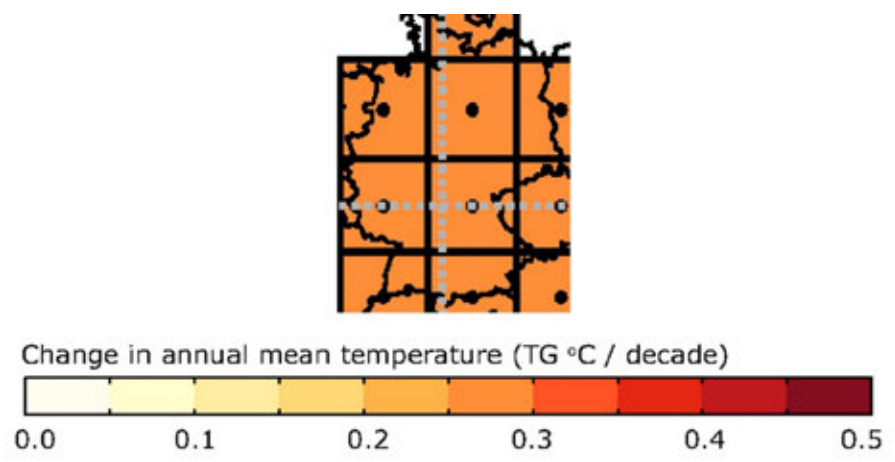


FIGURE 2.3 Screenshot of the customised map output showing the change in annual mean temperature per decade for the city of Stuttgart.

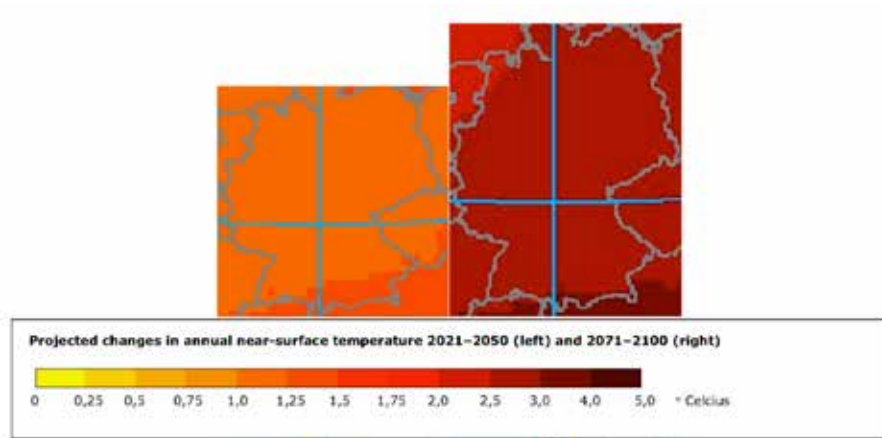


FIGURE 2.4 Screenshot of the customised map output showing the projected changes in the annual near-surface temperature for the periods 2021-2050 and 2071-2100 for the city of Stuttgart.

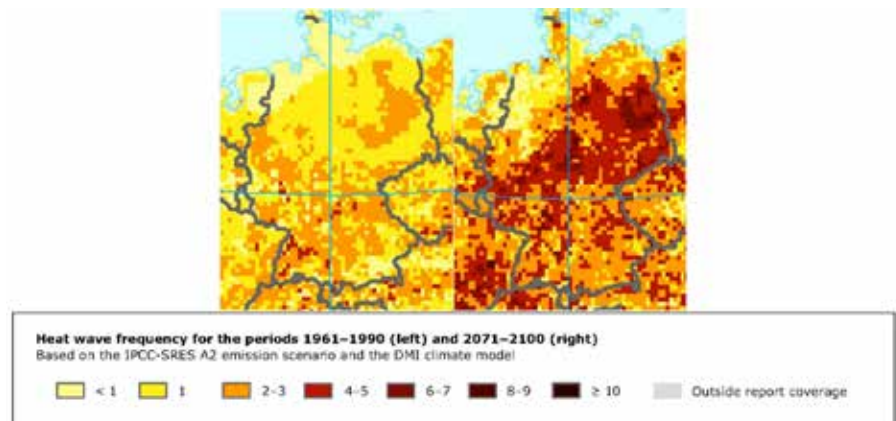


FIGURE 2.5 Screenshot of the customised map output showing the heat wave frequency for the periods 1961-1990 and 2071-2100 for the city of Stuttgart.

§ 2.3.3.2 The CE Urban Heat Island Atlas

The CE Urban Heat Island Atlas was also developed in the framework of the UHI Project, and is actually an interactive digital map which allows overlapping layers of parameters which play a role in the formation of the UHI phenomenon in the Central Europe region. The different layers available are: location of the project partners, air temperature, digital elevation model, land surface temperature (day and night), Normalised differential vegetation index, land cover (corine), and urban atlas land use (Figure 2.6).

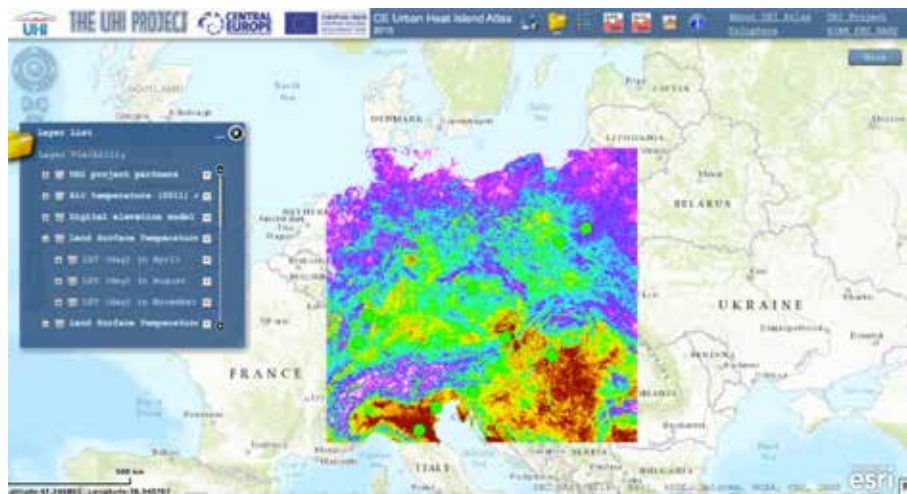


FIGURE 2.6 Screenshot of the CE Urban Heat Island Atlas.

§ 2.3.3.3 The STAR tools

The STAR tools was developed within the framework of Green and Blue Space Adaptation for Urban Areas and Eco Towns (GRaBS) project (The Interreg IVC EU program) which aims to improve the planning and development policy making in the context of climate change. It has been developed of the North West region of England and it includes a surface temperature tool and a surface runoff tool, which allows to estimate the impact on surface temperature and surface runoff for several land use scenarios under different temperature and precipitations scenarios (STAR tools, 2016).

This webpage can be considered an interactive tool for urban planners, as these can select the location in which they are interested, the land cover scenario they wish to analyse (where buildings, major roads, other impervious surfaces, green and blue surfaces and bare soil or gravel areas can be differentiated) as well as the temperature scenario for the 2050´s they wish to consider (10, 50 or 90% probability level) (Figure 2.7). Even though the tool can be used at different scales, it is best used at neighbourhood scale. The output of the surface temperature tool, is an exportable spread sheet (Figure 2.8) indicating the maximum surface temperature estimated based on the selected land cover and temperature scenario considered.

STAR tools
Surface temperature and runoff tools for assessing the potential of green infrastructure in adapting urban areas to climate change

Step 2: Amend the input values Surface temperature tool

The input values for the parameters needed to run the tool are set out below. Amend the values for your study area(s) if desired. Use the tabs on the left hand side to view and amend the input values for each of your study area(s) selected in step 1. Set up new land cover scenarios if desired and rename them.

Study area(s):

Drawing layer: 1

Drawing layer: 2

Land cover scenarios

Land cover scenario 1

Buildings	15 %
Major roads	20 %
Other impervious surfaces	30 %
Green and blue surfaces	20 %
Bare soil or gravel surfaces	20 %
Total	100%

Temperature scenarios

Baseline temperature (1991-1999) 20 °C

2050s High temperature - 10% probability level 22 °C

2050s High temperature - 50% probability level 23 °C

2050s High temperature - 90% probability level 25 °C

Temperature scenario-dependent parameters

Further parameters

Recommendation 1 (author, including user referring to your results) STAR tools, or in full as below:
 The authors: grabs & the university of manchester (2017) STAR tools: surface temperature and runoff data for assessing the potential of green infrastructure in adapting urban areas to climate change.
 Part of the EU Horizon H2020 project: Urban Greening in the Netherlands (101019041).
 If you have any comments or would like any further information please contact: star@grabsforliving.nl / acknowledgements@grabsforliving.nl

FIGURE 2.7 Screenshot of the input values that should be incorporated by the user, which refer to the land cover scenario for the selected area, the considered temperature scenario

STAR tools

Surface temperature and runoff tools for assessing the potential of green infrastructure in adapting urban areas to climate change

Step 3: Results

Surface temperature tool



Please complete our questionnaire.

In order to help us justify any future development of the STAR tools we would be grateful if you could take a minute to fill in a short questionnaire so that we can capture some information on who is using the tools and for what purposes.

The maximum surface temperatures for the study area(s), land cover scenario(s) and temperature scenario(s) you defined are presented below.

The results can be displayed in a number of ways using the dropdown boxes provided. This lets you compare results for your different study areas, land cover scenarios and temperature scenarios in a meaningful way. See here for an example of how you can interpret the results. You can also print the results as they are displayed on the screen and export the results to Excel (as displayed on the screen or all results).

Maximum surface temperatures (°C) are currently displayed for land cover scenario Land cover scenario 1

Columns labels: Study areas

Row labels:		Drawing layer: 1	Drawing layer: 2
Temperature scenarios	Baseline temperature (1981-1990)	29.5	29.5
	2050s High temperature - 10% probability level	30.8	29.5
	2050s High temperature - 50% probability level	31.3	30.1
	2050s High temperature - 90% probability level	32.8	31.1

[Print](#)
[Results as displayed on screen](#)
[Export to Excel](#)
Input data and results as displayed on screen
[Export to Excel](#)
Input data and all results

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Built here @ University of Manchester, ASB, and to the courtesy of AHRC 2017
UK Climate Projections 2009 @ Crown Copyright 2009

[Return to surface temperature tool](#) [Go to surface runoff tool](#)

[Return to step 2: Amend the input values](#) [Go to step 2: Amend the input values](#)

[Return to step 1: Define your study area\(s\)](#) [Go to step 1: Define your study area\(s\)](#)

Recommended citation (including when referring to your results): STAR tools, surface temperature and runoff used for assessing the potential of green infrastructure in adapting urban areas to climate change. Part of the EU Horizon H2020 project: urban-green (101019669).
If you have any comments or would like any further information please contact urban-green@man.ac.uk / urban-green@man.ac.uk

FIGURE 2.8 Screenshot of the input values that should be incorporated by the user, which refer to the land cover scenario for the selected area, the considered temperature scenario

§ 2.3.3.4 The “London unified model” (Londum)

The “London unified model” (Londum) developed within the Lucid program (Lucid, 2016) is a city wide climate atmospheric model at 1km grid, which features city wide air temperature maps at 1.5 m height. It has been developed for the city of London which estimates the impact of the volume on long and short wave radiation (reflection, shadow, conduction of heat into the building and calculation of the flux into the atmosphere) (Figure 2.9) (Hamilton et al. 2012; University College London, 2012).

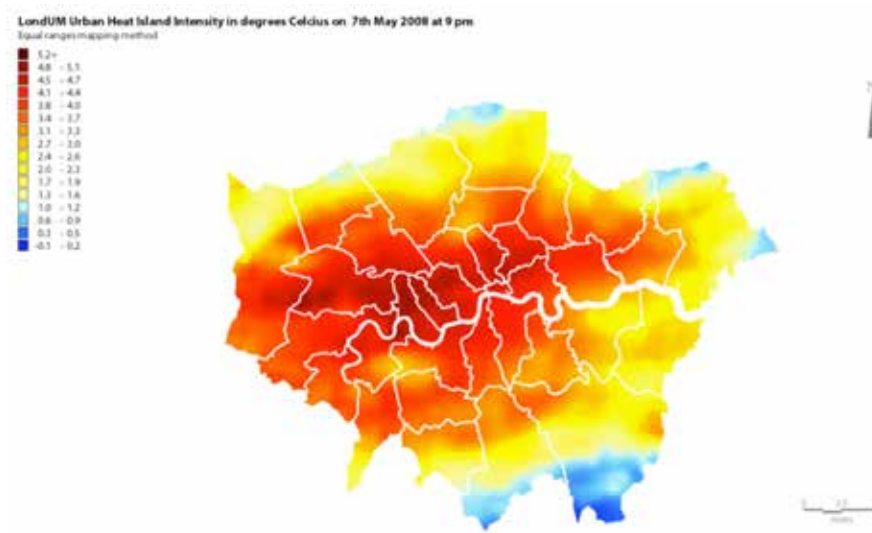


FIGURE 2.9 Screenshot of the output map of Londum model estimating the Urban Heat Island Intensity on May 2008 at 9.00 PM.

§ 2.3.3.5 The ADMS model

The ADMS model is an atmospheric dispersion model which was also developed within the Lucid program for the city of London and which features the perturbation on temperature and humidity at neighbourhood scale model based on the building volume and surface covers (it considers albedo, evapotranspiration and the thermal admittance of surfaces) (Figure 2.10). (Hamilton et al., 2012; University College London, 2012).

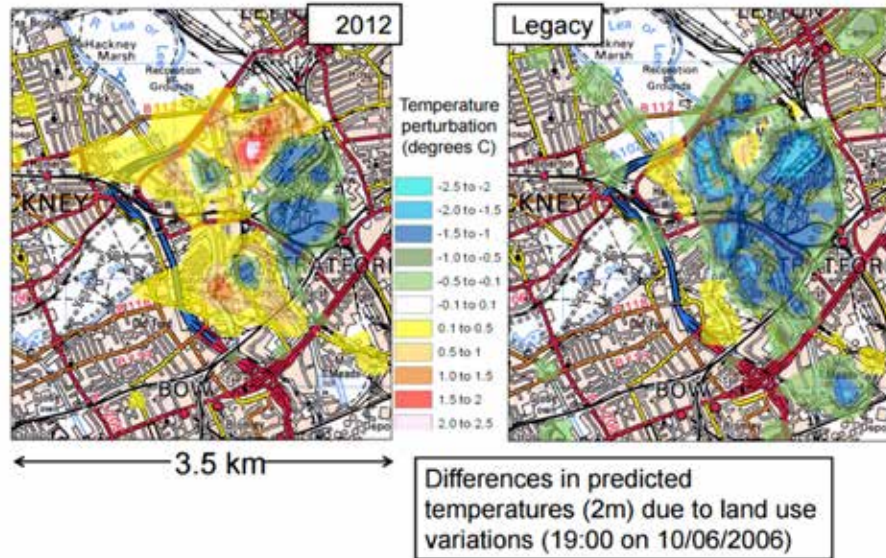


FIGURE 2.10 Screenshot of the output map of ADMS model estimating the temperature changes due to land use variations on the Olympic Parkland site development.

§ 2.3.3.6 The LSSAT

The London site-specific air temperature prediction model (LSSAT) predicts on an hourly basis the air temperature at discreet locations within the city of London (based on input data from one meteorological station for the time the prediction is required and historic measured air temperatures within the city). It allows testing building performance compared to neighbourhood, city or regional weather (Figure 2.11) (Hamilton et al., 2012).

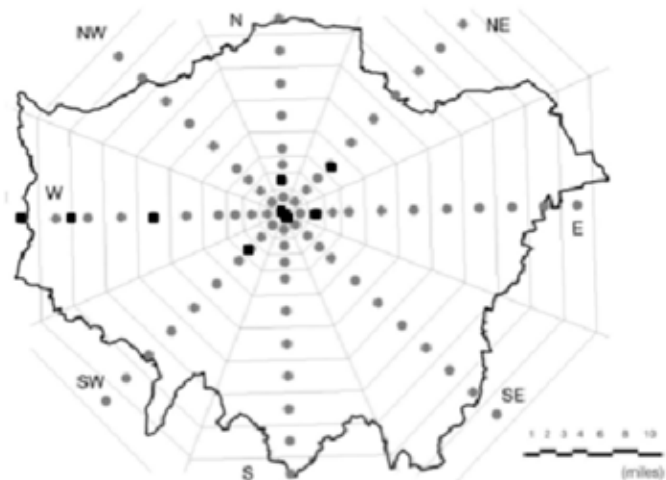


FIGURE 2.11 LSSAT model, fixed temperature stations along the 8 transects of the Greater London Area. Measurement locations are marked in squares.

§ 2.3.3.7 EPA Mitigation Impact Screening Tool (MIST)

EPA Mitigation Impact Screening Tool (MIST) (EPA, 2016) is a software tool developed by the US Environmental Agency to provide an assessment of the impacts of several UHI mitigation strategies (mainly albedo and vegetation increase) on the reduction of the urban air temperatures, ozone and energy consumption for over 200 US cities (Sailor DJ and Dietsch N, 2007). The tool is currently unavailable, it was disabled by EPA due to the need to update the methodology and data inputs. Nevertheless, the authors have analysed how it functioned, as it attempted to provide a practical and customised assessment for the UHI reduction.

As for most interactive tools, the first step is the selection of the city. The latitude, the cooling degree day (CDD), the heating degree day (HDD), the population, the mean annual temperature and the typical peak (1 hour) ozone can be adjusted manually (Figure 2.12).

FIGURE 2.12 Screenshot of the input values that should be incorporated by the user, which refer to the selection of the city, and the corresponding city parameters (which can be adjusted manually).

The second step consists in the selection of the mitigation strategy and its quantification. The two options available consist in the modification of albedo and or the modification of the vegetation. The level of mitigation change is considered to be uniform across the selected city, it does not allow discriminating surfaces (roof tops from pavements), nor does it discriminate neighbourhood strategies within cities (Figure 2.13).

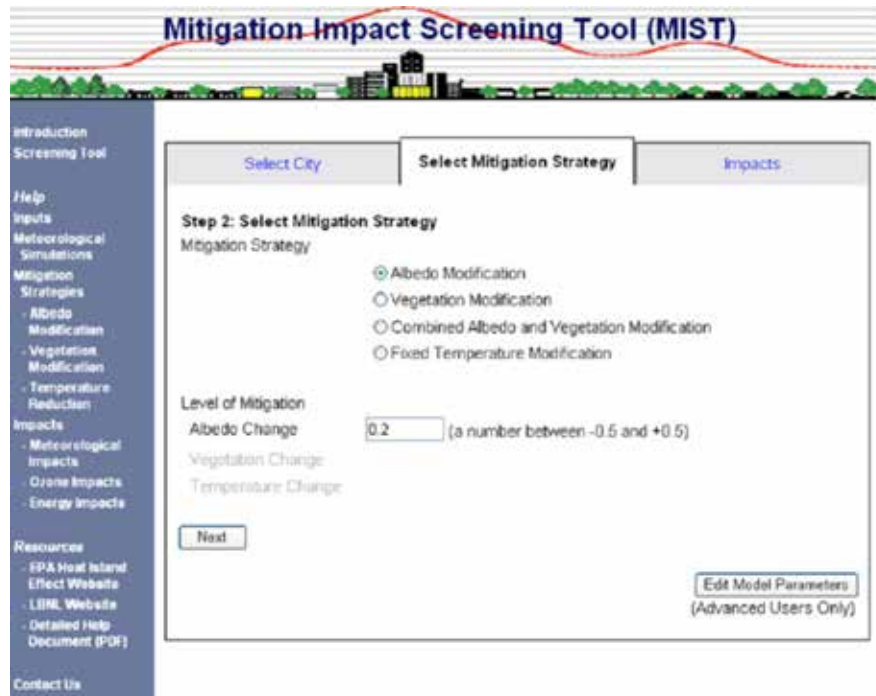


FIGURE 2.13 Screenshot of the mitigation strategy selected and its quantification. The mitigation strategy options are mainly albedo and vegetation modification or a combination of both.

The final step is the impacts estimation of the selected strategy in the selected city. The tool calculates the effect of the mitigation strategy on the reduction of the mean city temperature, the cooling degree days, the heating degree day, the typical 1hr and 8hr max ozone and on the energy consumption (Figure 2.14).

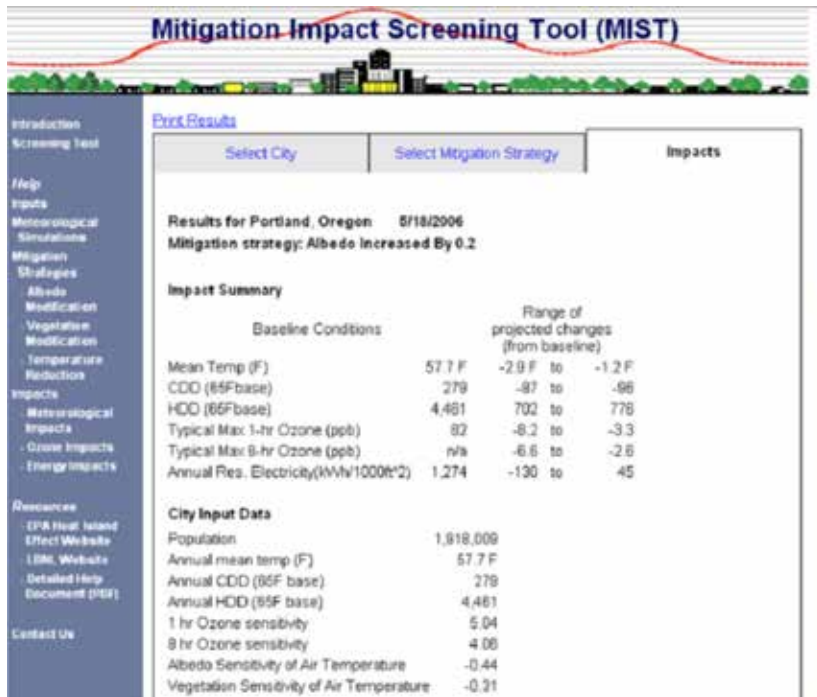


FIGURE 2.14 Screenshot of the impact estimation for the selected city and mitigation strategy.

§ 2.3.3.8 The Urban Microclimate tool

The Urban Microclimate tool is being developed at MIT, in order to control UHI to allow not only an increase of the thermal comfort but also a reduction of the energy use. It will be integrated in Rhinoceros, thus allowing ensuring urban planners workflow continuity.

UHI assessment TOOL	Geographical cover	Scale of the assessment
Decision Support System (DSS) UHI project	Bologna/Modena, Venice/Padua, Wien, Stuttgart, Lodz/Warsaw, Ljubljana, Budapest and Prague.	Supra-metropolitan
CE Urban Heat Island Atlas UHI project	Central Europe region	Regional
STAR tools GRaBS project	North West region of England	Neighbourhood
London unified model (Londum)	City of London	City
ADMS model	City of London	Neighbourhood
London site-specific air temperature prediction model (LSSAT)	City of London	Neighbourhood
EPA Mitigation Impact Screening Tool (MIST)	U.S.A. 230 cities	City

FIGURE 2.15 Overview of different digital UHI tools available

Type of assessment	User input parameters	Tool output
Phase 1: Mapping Urban Heat. Phase 2: Understanding regulations and policies related to UHI (greenery: street or roof, material reflectance...)	1/Location, 2/Scale (building or urban) 3/Typology of the intervention (building, facade, roofs, surface lots, urban structure and urban green) 4/Economic assessment 5/Skills	1/climate change assessment (Change in annual mean temperature per decade, changes in annual near-surface temperature for 30 year periods and heat wave frequency), 2/a set of normative applicable to the selected area and skills, 3/a set of potential mitigation strategies
Phase 1: Mapping Urban heat related parameters.	1/Location	1/Air temperature 2/ Digital elevation models 3/Land surface temperature 4/ Land cover regional scale (corine) 5/Urban land use.
Phase 4: Testing conceptual design	1/Location 2/Land cover proposal (% of buildings, major roads, other impervious surfaces, green and blue surfaces and bare soil or gravel surfaces) 3/Temperature scenario for 2050 (Baseline temperature, 2050's 10% probability level, 50% probability level or 90% probability level)	1/Maximum surface temperature
Phase 1: Simulation map of the Urban Heat Island of the existing city. Phase 4: Simulation map of the Urban Heat Island of the projected city.	1/ Volume (Reflection, Shadowing, conduction of heat into the buildings, flux of heat into the atmosphere). Provided by the tool for the city of London.	1/Urban heat island intensity (air temperature at 1,5m height)
Phase 1: Simulation map of the Urban Heat Island of the existing city. Phase 4: Simulation map of the Urban Heat Island of the projected city.	1/Location 2/Surface cover (Albedo, evapotranspiration, thermal admittance).	2/Air temperature variations -due to land cover- at 2m height.
Phase 1: Air temperature mapping at a particular time. Phase 4: Air temperature prediction based on intervention proposed.	1/Location	1/Hourly prediction of air temperature based on site specific transects (Global solar radiation, cloud cover, wind velocity and relative humidity)
Phase 4: Testing the mitigation effect of the selected mitigation strategy.	1/Location 2/The latitude 3/the cooling degree day (CDD) 4/the heating degree day (HDD) 5/the population 6/the mean annual temperature 7/the typical peak (one hour) ozone 8/Mitigation strategy (albedo or vegetation modification)	Calculation of the effect of the mitigation strategy 1/Reduction of the mean city temperature 2/Cooling degree days 3/the heating degree day 4/the typical 1hr and 8hr max ozone 5/The energy consumption

The type of assessment of the analysed tools has been classified in 4 phases (Figure 2.15): phase 1 corresponds to the phase where the existing situation is analysed (current UHI mapped or mapping UHI related parameters), phase 2 corresponds to the analysis of the existing regulations or policies in force affecting UHI, phase 3 is the development of the concept design and phase 4 is the UHI assessment of the proposed conceptual design. Tools that provide mainly an assessment on phase 1 are actually databases, that provide an assessment on UHI related parameters for a specific location. Tools that provide an assessment on phase 4 are simulation tools, which allow to test the efficiency of specific design proposals. Each of the tools requires different input parameters from the user (on the intervention to be tested) and provides different outputs and in different formats (urban heat island intensity, maximum surface temperature, applicable regulations).

These tools are valuable attempts to improve the understanding of the UHI for urban planners and decision makers, however the limitation of these tools is always geographical, as the accuracy of the assessment is directly connected to the quality of the input data, the resolution of the used maps and the complexity of the simulation models used.

Finally, each of the tools uses different input data and technologies (satellite imagery, meteorological stations measurements, meteorological model simulation algorithm...), and assess the user's proposal based on: surface cover, volume and land use parameters.

Surprisingly none of the tools provide an estimation on the benefits of the implementation of the UHI mitigation measures on populations health, which would help decision makers the direct benefits of such actions on populations health.

§ 2.4 Conclusions

A wide variety of cities -with different sizes, geographical characteristics, urban structures and in different climatological zones- are affected by the UHI phenomenon. The revision of related literature shows how broad the range of analysed parameters is -spatial contiguity, density, sprawl, storage heat flux, vegetation index, land surface temperature, albedo, sky view factor, coolspots, land use, imperviousness, social vulnerability and building vulnerability, cool wind paths,...- and how varied the suggested mitigation proposals are -increase of urban green, enhancement of peri-

urban natural vegetation areas, consistent roof albedo modification in specific areas, maximising cooling properties of water bodies, raise social awareness, of influence the building and urban design-

In terms of health impacts of UHI, most of the health problems and fatal incidents take place during times of thermal extreme. In particular, persons with preexisting diseases, especially cardiovascular and respiratory diseases, are more often affected. In both sides of the scale, i.e. the very old, and the very young, are the most susceptible to such health problems. The effects of UHI on health are however difficult to quantify, because specific data about it is limited, and cases are poorly reported. Therefore, more attention should be paid to documentation in the occurrence as part of public health policies and measures.

Most of the UHI studies are site specific investigations, and the extrapolation of the results to other climate zones, geographies and urban areas might be challenging. In order to be able to provide a high level, first diagnosis on the phenomenon, several investigation groups have attempted to build UHI tool kits which provide a general UHI overview of the impact and potential solutions for specific regions, which can be taken into consideration by all parties involved in the process of construction and development of the urban environment (urban planners, politicians, economists, architects, teachers, citizens, ..). However, these remain isolated cases, for specific locations and they do not quantify the effect of the measures on populations health.

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Conflicts of Interest: The authors declare no conflict of interest.

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