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Global Facility for Disaster Reduction and Recovery

Analysis of
Heat Waves and
Urban Heat Island Effects
in Central European Cities and Implications for Urban Planning

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About this report

This report provides an overview of the urban heat island (UHI) effect in Central European cities and its implications for sustainable development. Directed at policy makers, practitioners, and the wider public, the report explains the UHI effect and its drivers, as well as potential risk management and adaptation measures to address them. One of the report’s key messages is that in the context of cities and changing climate, policy and investment decisions can be facilitated by scientific approaches that provide information on current and future climate, and that increase understanding of measures to reduce UHI effects. Along with potential adaptation measures, this report also highlights the need to increase public awareness of, and emergency preparedness for, urban heat impacts on people and societies. The report also includes a number of city examples and case studies, selected based on availability of information, and relevance for other cities in the region.

In introducing adaptive and preparedness policy options, this report also promotes the integration of disaster risk management approaches in the urban context. This integration is illustrated through a roadmap for increased resilience to urban heat. This roadmap highlights the key steps that cities can take to better understand the scope of UHI effects and in turn integrate this information into broader resilience or urban development plans and strategies. In the process of planning and implementing specific adaptation measures for urban heat, cities would have to consider a range of aspects, including technical, institutional, regulatory, social, environmental, financial, and many others, which go beyond the scope of this report. A glossary of key terms used, along with further references, is provided at the front and at the back of this report respectively.

ADAPTATION
Actions taken to manage climate risk to an acceptable level, taking advantage of any positive opportunities that may arise. Adaptation options are possible measures and actions that can be implemented to improve adaptation to climate change.

ALBEDO
The fraction of solar radiation reflected by a surface or object, often expressed as a percentage.

ANTHROPOGENIC
Made by people or resulting from human beings or activities.

EARLY WARNING SYSTEM
The set of capacities needed to generate and disseminate timely and meaningful warning information to enable individuals, communities, and organizations threatened by a hazard to prepare and to act appropriately and in sufficient time to reduce the possibility of harm or loss.

ENSEMBLE
A group of parallel model simulations used for climate projections. Variation in the results across the ensemble members gives an estimate of uncertainty. Multi-model ensembles that include simulations by several models also include the impact of model differences.

IMPACTS
Effects on natural and human systems. In this report, the term "impacts" is used to refer to the effects of physical events and climate change on natural and human systems.

IMPERVIOUS SURFACE
Surface covered by water-resistant materials such as asphalt, concrete, or stone, resulting in reduced evaporation and hence higher heat loads and increased storm-water runoff.

INVERSION
An increase of air temperature with height.

AbCd efgH iJklMn

CITIZEN WEATHER STATION A weather station set up by an amateur observer, for example located in the owner's garden. The owners can submit their observations to online platforms, making data available for various applications.

CLIMATE
Climate is usually defined as the average weather, or more rigorously, as the statistical description in terms of the mean and variability of relevant quantities over a period of time ranging from months to thousands or millions of years. Variability may be due to natural internal processes within the climate system (internal variability), or to variations in natural or anthropogenic external forcing (external variability).

CLIMATE SCENARIO
A plausible and often simplified representation of the future climate, based on an internally consistent set of climatological relationships that has been constructed for explicit use in investigating the potential consequences of anthropogenic climate change, often serving as input to impact models.

HAZARD
The potential occurrence of a natural or human-induced physical event that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, and environmental resources.

HEAT STORAGE
The residual term in the surface energy balance wherein a layer or volume has a gain of heat resulting in a temperature increase depending on the heat capacity of the material.

HEAT WAVE
A period of abnormally hot weather. Heat waves and warm spells have various and, in some cases, overlapping definitions. A detailed description is provided in Chapter 6.

LOCAL CIRCULATION SYSTEM
Wind flow patterns typical for a local area, usually on a spatial scale between 10 and 100km.

LONGWAVE RADIATION
This radiation originates by thermal emission from the Earth's surface and its atmosphere out to space.

MITIGATION
The lessening of the potential adverse impacts of physical hazards (including human-induced impacts) through actions that reduce hazard, exposure, and vulnerability; in terms of climate change, a human intervention to reduce the sources or enhance the sinks of greenhouse gases.

RESILIENCE

The ability of a system and its component parts to anticipate, absorb, accommodate, or recover from the effects of a hazardous event in a timely and efficient manner, including through ensuring the preservation, restoration, or improvement of its essential basic structures and functions.

RISK

The potential for consequences where something of value is at stake and where the outcome is uncertain, recognizing the diversity of values. Risk is often represented as probability of occurrence of hazardous events or trends multiplied by the impacts if these events or trends occur. Risk results from the interaction of vulnerability, exposure, and hazard.

THERMAL STABILITY

The most stable conditions in the atmosphere occur during a temperature inversion.

THERMAL STRESS

A condition when temperature becomes too extreme for the body to manage.

THERMOREGULATION

A process that allows the living body to maintain its core internal temperature.

TROPICAL NIGHTS

Days where the minimum of air temperature does not fall below 20.0°C.

UNCERTAINTY

An expression of the degree to which a value or relationship is unknown. Uncertainty may originate from many sources, such as quantifiable errors in the data, ambiguously defined concepts or terminology, or uncertain projections of human behavior. Uncertainty can therefore be represented by quantitative measures (e.g., a range of values calculated by various models) or by qualitative statements reflecting the judgment of a team of experts.

URBAN CANYON

Defined as the space above the streets and between the buildings.

URBAN ENERGY BALANCE

The exchange of surface energy fluxes, primarily heat, in urban areas.

URBAN HEAT ISLAND

The relative warmth of a city compared with surrounding rural areas, associated with changes in runoff, the heat retention, changes in surface albedo, and so on. The full definition is provided in Chapter 1.

URBAN HEAT LOAD

Excessive heat conditions in urban areas. The term „heat load" is sometimes used in literature as a synonym for „heat stress", which is related to human thermal comfort.

URBAN MICROCLIMATE

A local set of atmospheric conditions in a relatively small area (typically up to 100 m) that differ from those in the surrounding areas.

URBAN-RURAL GRADIENTS

The difference in temperature between the urban and surrounding rural regions.

op Qr Stu VWxYz

PARAMETRIZATION

In climate models, the technique of representing processes that cannot be explicitly resolved at the spatial or temporal resolution of the model (sub-grid-scale processes) by relationships between model-resolved larger-scale flow and the area- or time-averaged effect of such sub-grid-scale processes.

PREPAREDNESS

Capacity of entities to anticipate, cope and recover from the negative impacts from disasters and emergencies.

PROJECTION

A potential future evolution of a quantity or set of quantities, often computed with the aid of a model. Projections are distinguished from predictions in order to emphasize that projections involve assumptions—for example, about future socioeconomic and technological developments that may or may not be realized—and are therefore subject to substantial uncertainty.

SCENARIO

A plausible and often simplified description of how the future may develop based on a coherent and internally consistent set of assumptions about driving forces and key relationships.

SKY VIEW FACTOR

A geometric ratio that expresses the fraction of the radiation output from one surface that is intercepted by another.

SOIL SEALING

A process for changing the nature of the soil and covering it by impervious materials, such as concrete, metal, and tarmac.

SUMMER DAYS

Days where the maximum of air temperature is equal or higher than 25.0°C.

WASTE HEAT

It is the unused heat produced by machines, objects (such as automobiles or air conditioning) or processes (industry) transferred to the surrounding environment, contributing to the UHI effect.

VULNERABILITY

The propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts, including sensitivity or susceptibility to harm and lack of capacity to cope and adapt.

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Executive summary

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, heat waves—extended periods of unusually high atmosphere-related heat stress—accounted for 68 percent of natural hazard–related fatalities among the European Economic Area countries and five percent of economic losses. Direct health impacts of heat are high among vulnerable populations, including children, the sick, and the elderly. Indirect impacts of heat include productivity loss, risk of fires, impact on water resources and agriculture, and power cuts. 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.[i]

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 UHI effect results from the interaction of different physical processes. Temperatures are higher in densely built urban areas than in surrounding areas, due to extensive sealed-surface coverage and small share of vegetation. With more than 50 percent of the global population currently living in urban areas, urban land use changes impact local climate and urban air temperatures, and these impacts are enhanced by anthropogenic (industrial and socioeconomic) activities. Reduced air circulation and limited cooling at night contribute to cities being warmer and more prone to excess heat during heat waves than, rural areas, while building materials used in cities facilitate the absorption of solar radiation and thus exacerbate heating.

Sustainable urban development and climate-resilient spatial planning play an important role for climate change adaptation in urban areas. The intensity of the UHI effect depends on many factors, such as the size and structure of the city; heat emissions from buildings, industry, and vehicles; topography; and climate and meteorological conditions, including airflow. Anthropogenic heat emissions alone, such as waste heat from cooling systems, can locally increase air temperature by an additional 1–3°C. Understanding how land use and climate trends lead to changes to the local climate is critical for future development plans and climate adaptation strategies, and can help decision makers find optimally cost-effective, evidence-based, and consistent solutions for sustainable cities.

Many complementary tools are available to help integrate climate information into policy-making and urban planning. Modeling can help us understand urban climate processes for given urban areas and surfaces, and can focus on different spatial scales and terrains. Building-scale models help to inform architectural and engineering design. Micro-scale models are used in construction projects for large building blocks or districts, or open (green) space designs, while city-scale models provide information for strategic urban planning and climate adaptation actions. Simulations can identify critical zones with increased environmental risks, such as hot spots, and can serve to support efforts to mitigate the UHI effect and improve urban climate, through such means as ventilation, greening, air pollution monitoring, and water and energy management. Finally, given that urbanization can lead to environmental changes beyond the local scale, regional-scale models are used to understand processes on different spatial scales and interactions within the climate system.

Cities seeking guidance on managing heat waves and the UHI effect can make use of a vast range of data for in-depth analysis. Urban climate analysis can use extensive meteorological observation networks and data sources from remote sensing as well as from so-called citizen weather stations (CWS), set up by citizens or private companies. Crowdsourced data have gained in importance in past years. This trend is expected to continue in the future, as ownership of weather stations connected to the Internet of Things will increase. After quality control, meteorological data measured by CWS can provide results complementary to those of stations belonging to national meteorological services networks.

Supported by these tools and data, cities have access to many solutions to mitigate the increasing risk of heat waves and its enhancement by the UHI effect. Adaptation measures broadly fall into two categories: nature-based and technological solutions. Nature-based solutions refer to green city approaches, which increase the coverage of vegetation to provide better cooling and shading, and blue city approaches, which use water for cooling effects. Technological solutions include white city approaches, which use “cool” materials to enhance reflection and reduce the absorption of solar radiation. The success of specific measures depends on local conditions; and in many cases, combining these measures may be most appropriate and bring the highest benefits. Many of these measures also provide multiple benefits, such as space for recreation, increased energy efficiency, and human comfort.

Urban climate models can be used to quantify the effect of different adaption options while considering local climate conditions and urban structure. Simulations and scenarios can help identify critical zones in the city in current and future climate and thus support the prioritization of adaptation plans. Furthermore, they can also help evaluate the effectiveness of urban planning measures to reduce the heat load before construction, and support communication and consensus-building among different stakeholders, both of which are critical for the success and sustainability of specific preventive and adaptive measures.

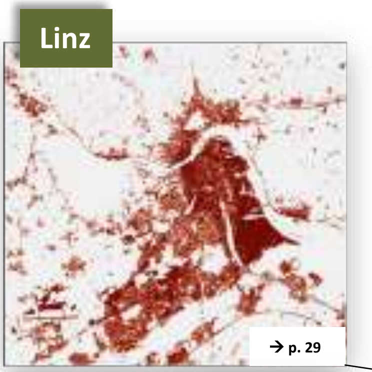
In parallel to climate adaptation at the city level, improved preparedness and awareness are needed to tackle the risks of heat waves. Heat health warning systems and heat health action plans help to address, manage, and reduce health-related risks. Warning systems include threshold values for issuing warnings, a system of graded alerts, and the communication of the alerts to the general public or target groups. Following recent heat waves, many national and local governments in Europe have implemented heat health prevention plans, which have contributed to saving lives and reducing damage.

This report concludes with a roadmap with actions for increased resilience to urban heat. The roadmap focuses on the critical steps that can help decision makers understand the drivers of heat waves and UHI effects in their city, the scope of risk (including people and assets exposed), as well as the impacts of heat waves on specific areas or population groups. In parallel to other considerations, this critical risk information can form the basis for identifying the most effective use (or combination) of solutions, including green, blue, or white city measures, and for developing and implementing an action plan with agreed actions, investments, and monitoring and evaluation to improve urban planning and preparedness. Available urban climate analytics and modeling tools can support the overall process for better results. This framework is part of a risk management approach applicable to multiple hazards (such as earthquakes, floods and storms) faced by municipalities. The integration of these concepts can help to minimize climate change and other hazard–related loss to public, private, and combined investments, leading to more sustainable urban development and planning, and, ultimately, more resilient economies and societies.

Abbreviations

CWS	citizen weather stations
DHMZ	Croatian Meteorological and Hydrological Service
EEA	European Environment Agency
HHAP	heat health action plan
HHWS	heat health warning system
RCP	representative concentration pathway
UHI	urban heat island
WHO	World Health Organization
WMO	World Meteorological Organization
ZAMG	Zentralanstalt für Meteorologie und Geodynamik (Austrian National Weather Service)

Linz



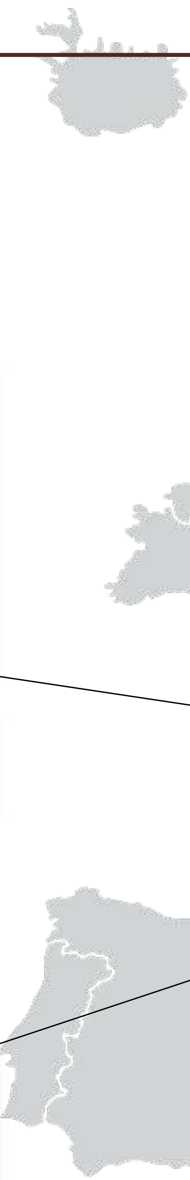
→ p. 29

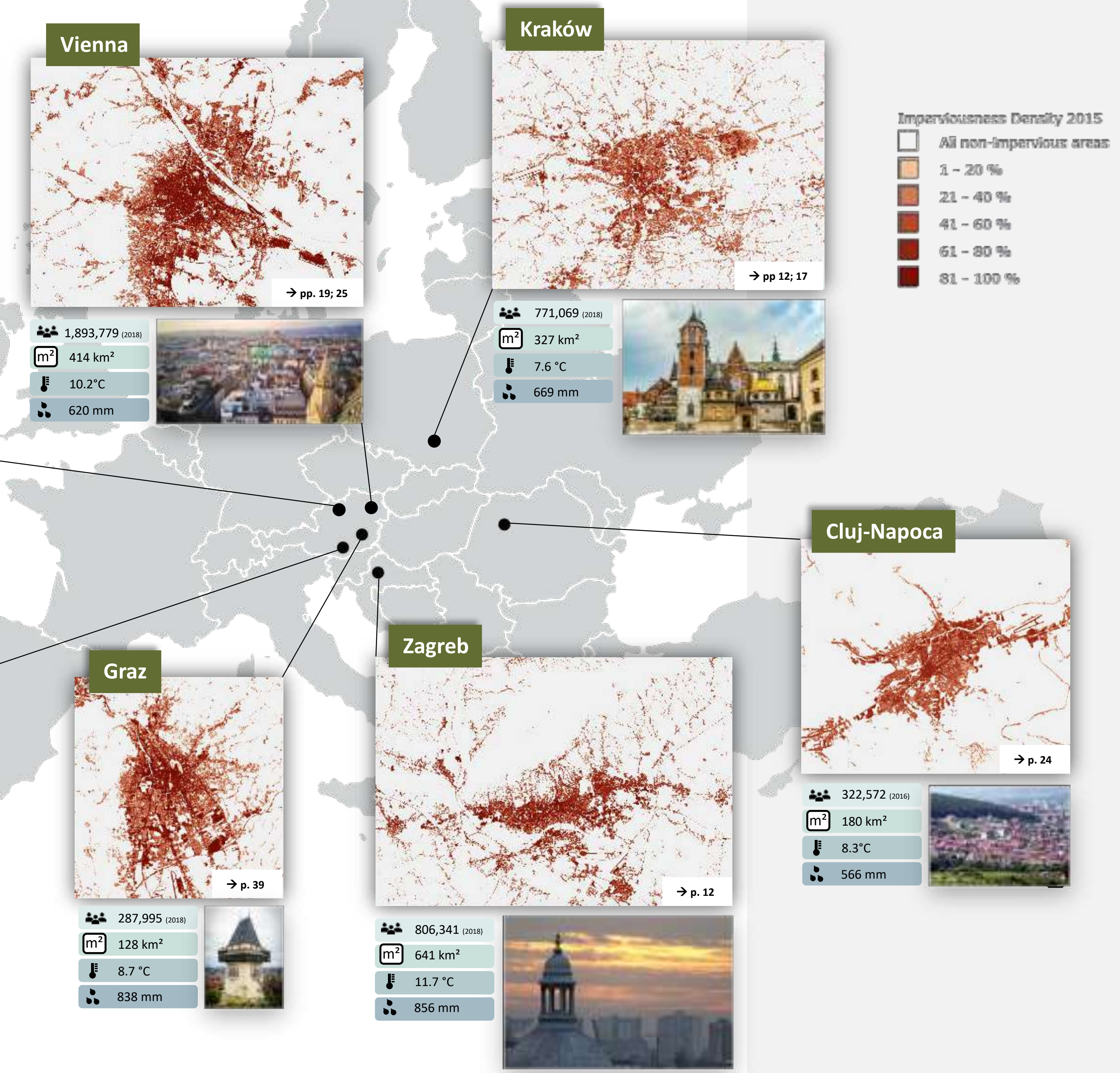
205,613 (2018)
m² 96 km²
8.8 °C
754 mm

Klagenfurt

→ pp. 40; 41

100,851 (2018)
m² 120 km²
8.2 °C
885 mm





Geographic and demographic factors, and climate information for a sample of Central European cities. Urban areas are characterized by high imperviousness. Credit: ZAMG/Kainz based on data for Imperviousness Density 2015 from Copernicus Land Monitoring Services (https://land.copernicus.eu/pan-european/high-resolution-layers/imperviousness/status-maps/2015), CRU TS4.01 and ZAMG climatological data for the period 1971—2000 (Harris and Jones 2017; https://climatecharts.net) and city population data (see References).

Population
Area
Mean annual temperature
Mean annual rainfall

1

CITIES IN CHANGING CLIMATE

Urban areas experience more excessive heat than their rural surroundings due to the urban heat island (UHI) effect. Understanding the processes and evaluating possible changes occurring in the local climate is important as the first step for sustainable urban development and climate-sensitive urban planning. Along with key definitions and an overview of the impacts of UHI effects, this chapter provides examples from Zagreb and Kraków focusing on understanding the importance of UHI effects for urban development.

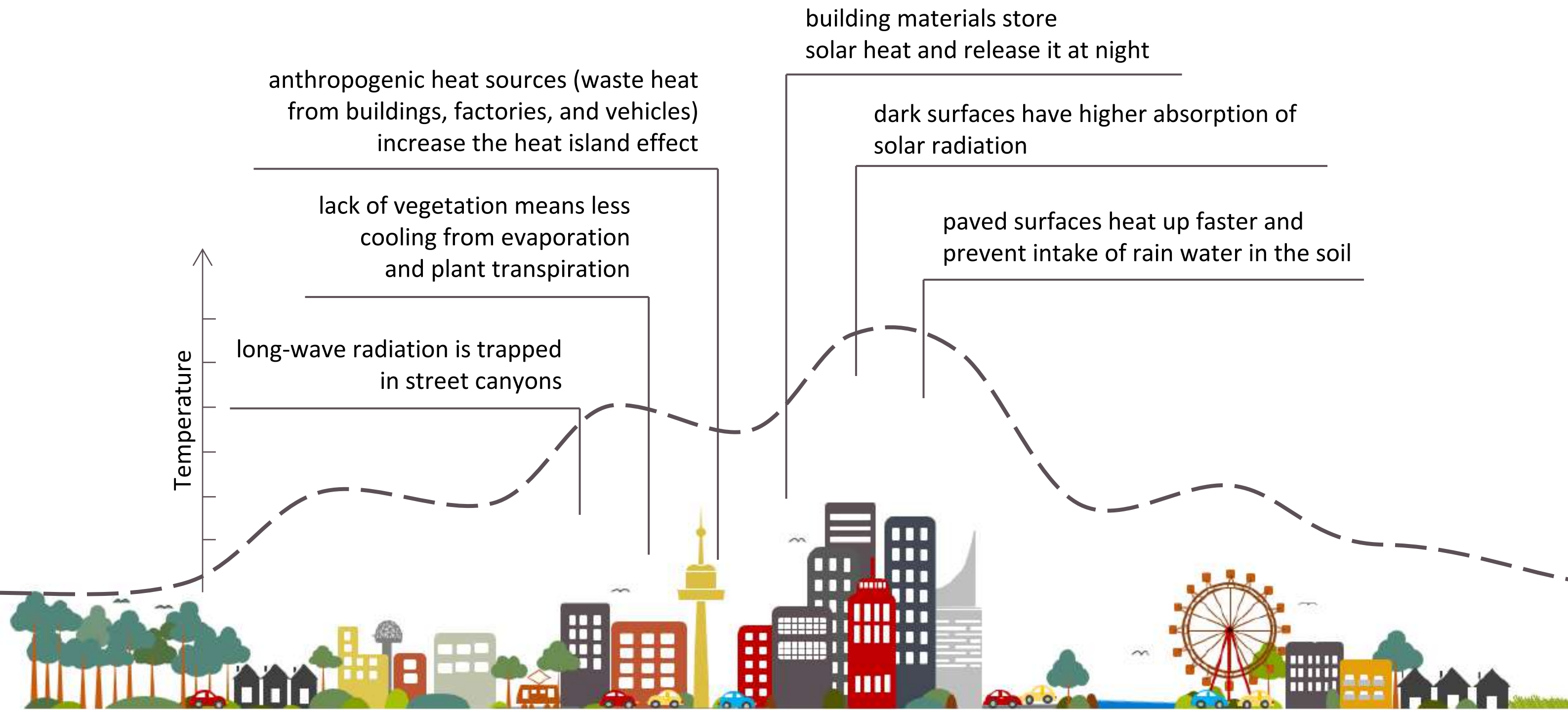


Figure 1. Schematic illustration of the urban heat island effect and factors that contribute to higher temperatures in urban areas. The heat load is typically lower in the rural surroundings than in dense built-up areas. The graphic also illustrates parks, water surfaces, forests, and open spaces that can create cooler areas within the city. Credit: ZAMG/Hollósi.

THE DRIVERS OF THE UHI EFFECT

Climate change is one of the most significant environmental and societal challenges that the world is facing today. Cities, along with urban populations concentrated in densely built-up areas, are highly vulnerable to climate change impacts, such as negative consequences of extreme heat events (Rosenzweig et al. 2011). In addition to an observed warming trend, the so-called **UHI effect** is a typical feature associated with urban climate, which further enhances the excessive heat in cities. The UHI effect results from the interaction of different physical processes (Figure 1). The modifications of energy balance in the built-up environment in terms of land cover and land changes—as well as the additional release of anthropogenic heat combined with less vegetation, reduced air circulation, and reduced nocturnal cooling—contribute to cities being warmer than their surroundings and more prone to excess heat (Oke 1978). Urban building materials often have high heat capacity and thermal conductivity, enabling a greater absorption of solar radiation. Retained heat is then released during the night as long-wave radiation, but the cooling is slowed due to urban structures. The **intensity** of the UHI depends on many factors: the size and structure of the city; anthropogenic emissions related to waste heat from buildings, industry and vehicles; topography; climate zone; and meteorological conditions (Oke 1982). In cities with flat relief, land cover and land use play an important role in determining spatial temperature differences. Analyzing UHI in cities located in a valley, on a slope, or on a hilltop requires more attention due to different processes caused by **complex terrain**. Topography affects the local wind conditions and has an impact on temperature inversion in height. Therefore, the UHI can either be weakened or strengthened. Additionally, the UHI has strong temporal variations dependent on climate conditions and human activities. Studies in Central Europe show that maximum

UHI values developed at night and do not show a relationship to the city size (Santamouris 2007). Maximum UHI intensity varies between 1–12°C and the highest values correspond to anticyclonic periods of weather, while much larger variations (more than 10–15°C) are rarely observed due to local wind circulation reinforcement that mixes air and limits the extent of UHI. **Weather factors** that have the largest influence on the UHI intensity are wind speed and cloudiness. If incoming solar radiation is decreased by clouds, temperature differences and therefore UHI intensity are also subsequently decreased. Such weather conditions help to improve human thermal comfort both in the city and in surroundings. Humidity plays an important role as well. Cities in regions with variable wet and dry seasons have larger temperature differences during the dry period. Due to their small share of vegetation, built-up areas also have less water evaporation, which contributes to increased surface and air temperatures. The UHI phenomenon refers either to differences in air temperature at two-meter height (atmospheric UHI) or to surface temperatures (surface UHI). **Surface temperatures** vary more than air temperatures during the daytime and tend to be greater when the sun is shining. Due to seasonal variations in the solar radiation, the magnitude of surface UHI shows greater intensity in the summer period, partly because of the land cover. On a hot summer day, dry urban surfaces placed in direct sunlight can be up to 25–50°C hotter than the air (Berdahl & Bretz 1997), while the temperatures of shaded or moist surfaces remain similar to that of the air. The UHI can have **secondary impact** on local meteorology, including the modification of local wind patterns; and due to convection provided by extra heat, additional shower and thunderstorm activity can be greater than usual (Shepherd 2005). The influence of UHI on ecosystems has been observed as well, e.g., extension of the growing season (about 15 additional days) in urban areas compared to the surroundings (Dallimer et al. 2016).

HEAT-RELATED RISKS AND IMPACTS

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. In order to determine long-term changes in heat load, many factors need to be considered, such as historical development, modification in urban structure, increase in population, and related anthropogenic heat production or changes in weather patterns. Given that global and regional warming are leading to more frequent and more intense extreme hot periods, heat can already be considered as a severe hazard for people in higher-vulnerability groups. **Overheating** of buildings during prolonged heat waves and associated negative impact on residents have been identified as a public health issue (Figure 2), as extreme temperatures are considered among the deadliest hazards in Europe (WMO 2014). Cities in particular are susceptible to heat-related health impacts because of the high density of population, with many people exposed to high temperatures over a long period. The UHI effect during heat waves leads to a low recovery potential, particularly due to high nighttime temperatures and insufficient cooling. **Direct impacts** of heat on human health can range from fatigue and discomfort to heat cramps, heat exhaustion, heatstroke, and death. The effort of the human body to release heat and keep the body temperature around 37°C puts an extra strain on the cardiovascular system (Havenith 2005), which can aggravate existing health conditions. Apart from these direct impacts**, indirect impacts** are also possible: e.g., an increase in accidents, labor productivity losses, increased risks of forest fires, impacts on water resources, transport restrictions, agricultural losses, and power cuts (UNEP 2004). Regarding the health effect of heat waves, **particularly vulnerable groups** include the elderly (Fouillet et al. 2006), due to changes in their thermoregulatory system (Kovats & Hajat 2008; WHO 2011), as well as infants, whose thermoregulation is still immature and whose dependency level is high (WHO 2011). 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 poses 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 (Casanueva et al. 2019). Loose social contacts and a large number of single and lone-pensioner households in cities constitute an additional risk. As climate change makes heat waves more frequent and intense, as cities grow, and as the population in many countries ages appreciably over the next 50 years (Confalonieri et al. 2007), the numbers of deaths due to heat waves can be expected to increase if no measures are taken.

PREVENTING HEAT IMPACTS

Early warning systems, awareness and appropriate spatial planning can reduce negative impacts of heat events. For more information, see Chapter 6 on heat warning systems and Chapter 7 on climate adaptation measures.

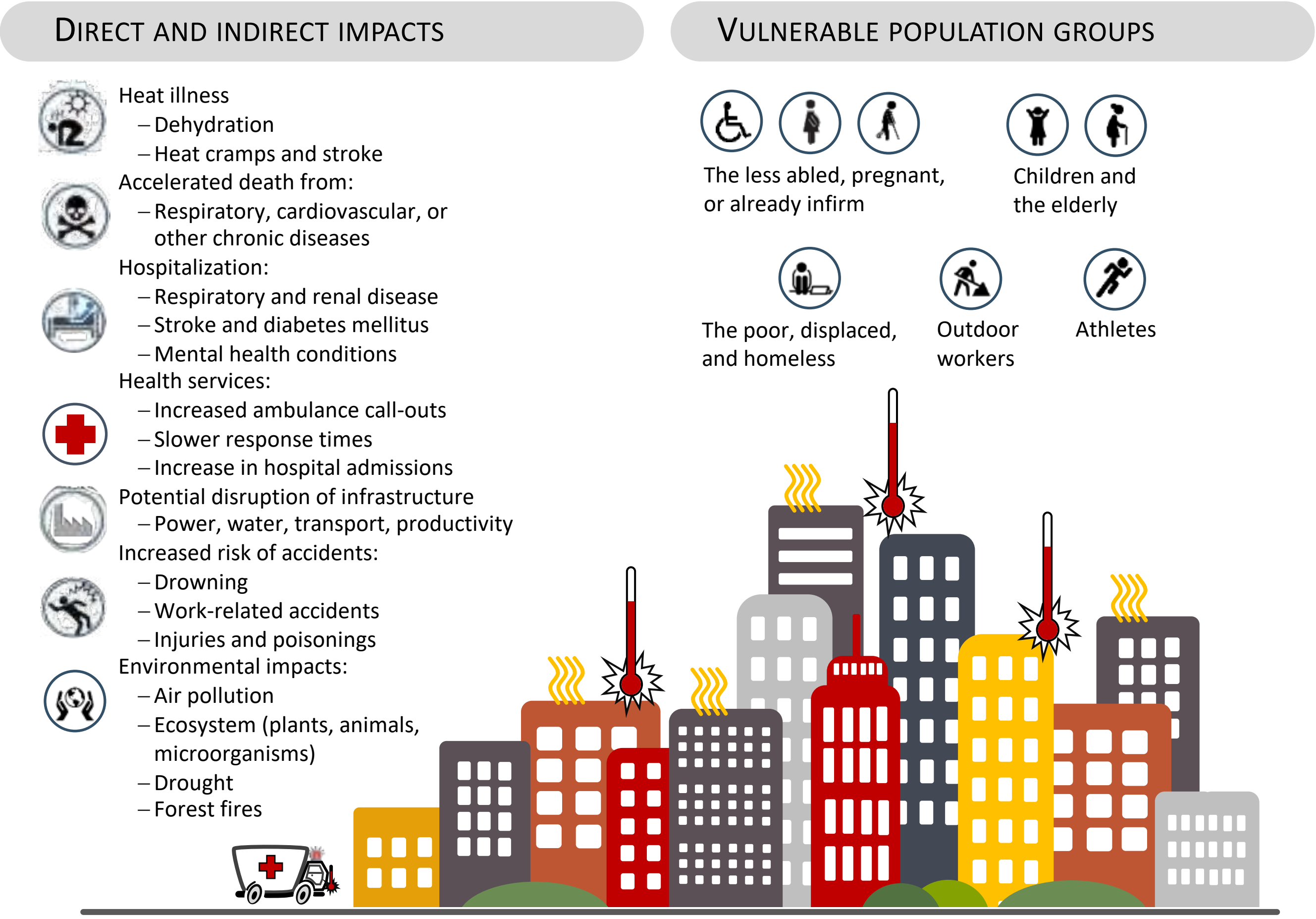


Figure 2. Direct and indirect health effects and the population groups most vulnerable to extreme heat. The extent and form of the impacts depend on (among other things) the timing, intensity, and duration of the extreme heat event; the level of adaptability of the population; and possible actions taken to prevent negative effects of heat. Credit: ZAMG/ Hahn and Hollósi, based on WHO, "Information and Public Health Advice: Heat and Health", https://www.who.int/globalchange/publications/heat-and-health/en/.

Example from Zagreb

806,341 (2018)

641 km²

79.4 summer days

15.6 tropical nights

Zagreb is the capital and largest city of Croatia, as well as popular tourist destination especially in the summer months. Zagreb's climate is continental with maritime influence. The 20th century has seen a warming trend with an increase in mean annual temperature of +0.07°C per decade. The warming of Zagreb has become more pronounced in the last decades (MZOIP 2010). Between 1901 and 2008, the majority of warm temperature indices (e.g. summer days, warm nights) had an upward trend, while a majority of cold temperature indices (e.g. frost days) had a downward trend. The observed trend in heat load can be attributed to regional climate warming, but also to urbanization and the associated UHI effect. The UHI formation in Zagreb is controlled by the city's topography (Nitis et al. 2010) and morphology resulting in intense summertime land surface temperatures (Kovacic 2014). Atmospheric circulation (particularly upslope and downslope wind patterns forming at the slopes of the nearby mountain Medvednica during the summer anticyclonic conditions) can alter thermal stress and air quality in urban areas (Klaic et al. 2002). The local UHI-induced circulation directed toward the city center can be strengthened in the late afternoon due to the increased urban-rural temperature difference. This local circulation effects the downslope thermal circulation by enhancing the upward air movements on the southern hillsides, and further contributing to generated thermal stress.

Example from Kraków

771,069 (2018)

327 km²

56.4 summer days

0.6 tropical nights

Kraków, Poland, is located in the valley of the Vistula river with diversified relief and land cover. Like many cities in Central Europe, Kraków developed around the historical center, and its infrastructure has gone through intensive spatial development in the second half of the 20th century. Land surface temperature, mapped through satellite imagery, indicates that hot locations are mainly in the city center, along the main transport arteries and industrial zones (Walawender et al. 2014), while cold locations include forests, city parks, and water reservoirs. Although highly dependent on land cover types, the thermal structure is influenced by additional factors, such as emission of anthropogenic heat, insolation of the surfaces depending on land relief and shape of buildings, and seasonal changes in vegetation and weather conditions. Despite relatively small height differences (about 100 m), relief is an important factor influencing urban climate in Kraków, as it forces the formation of a cold air lake in the valley floor (outside densely urbanized areas) and air temperature inversions (Bokwa et al. 2015). The cluster analysis of air temperature measurements, conducted between 2009 and 2013 in 21 urban and rural locations across various landforms, shows several types of nighttime thermal structures, including elements that display the formation of the inversion layer, cold air reservoir, and the UHI peak zone.

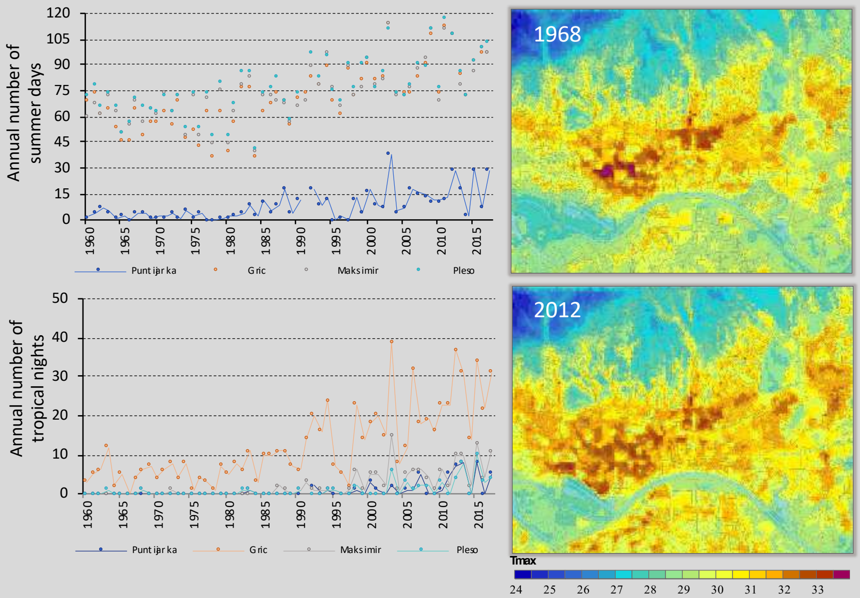


Figure 3. Left: Time series of climate indices in Zagreb (summer days, Tmax ≥25°C; tropical nights, Tmin ≥20°C) showing a warming trend. Source: DHMZ, https://meteo.hr. Right: Spatial variability in daily maximum temperature (T_{max}) based on the urban climate model and land use data from the year 1968 (top) and 2012 (bottom). Note expansion of areas with excessive heat caused by urbanization. Source: CroClimGoGreen Project, Zagreb, Croatia, https://www.pmf.unizg.hr/geof/znanost/klimatologija/ccgg.

Heat load in the city of Zagreb shows a warming trend, especially for nighttime temperatures in the city center, as well as expansion of areas with excessive heat caused by urbanization (Figure 3). Expected regional warming together with potential expansion of the city could contribute to the intensification of UHI, increased thermal stress, and air pollution in Zagreb, making UHI a serious environmental problem. Sustainable urban planning and development is needed for Zagreb, building on an understanding the parameters and processes contributing to UHI intensity and possible mitigation strategies.

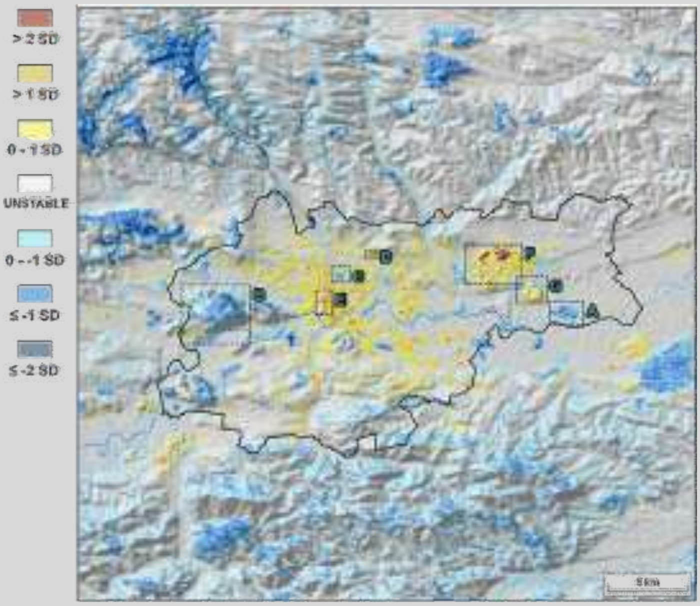


Figure 4. Thermal stability (SD) based on surface temperature in the agglomeration of Kraków (shaded relief in the background). Characteristic cold and hot spots: (A) water reservoirs of former gravel excavation sites in Przylasek Rusiecki, (B) Wolski Forest, (C) Rakowicki Cemetery, (D) "Krokus" Shopping Center, (E) Kraków Old Town, (F) steelworks in Nowa Huta, and (G) slag heap in Pleszow. Source: Walawender et al. 2014.

The atmospheric UHI of cities located on variable landforms with diverse land cover is characterized by a complex thermal structure, which results from the interaction of urban energy balance and processes induced by the relief. The terrain-induced processes may also include upward or downward wind flows or air temperature inversions. Krakow is one of the cities which displays such characteristics. Figure 4 shows hot and cool areas in Kraków. The air temperature changes rapidly during the day and the UHI is one of the urban climate elements contributing to temperature variations.

2

FUTURE SCENARIOS

A key step in understanding UHI effects is to consider future scenarios. Global temperatures are projected to increase by 3–6 °C by the end of the century if greenhouse gas emissions continue to rise. Depending on the emissions and global climate development, the heat load in urban areas is expected to increase further. This chapter highlights key projections, and provides an example of future projections for Kraków.

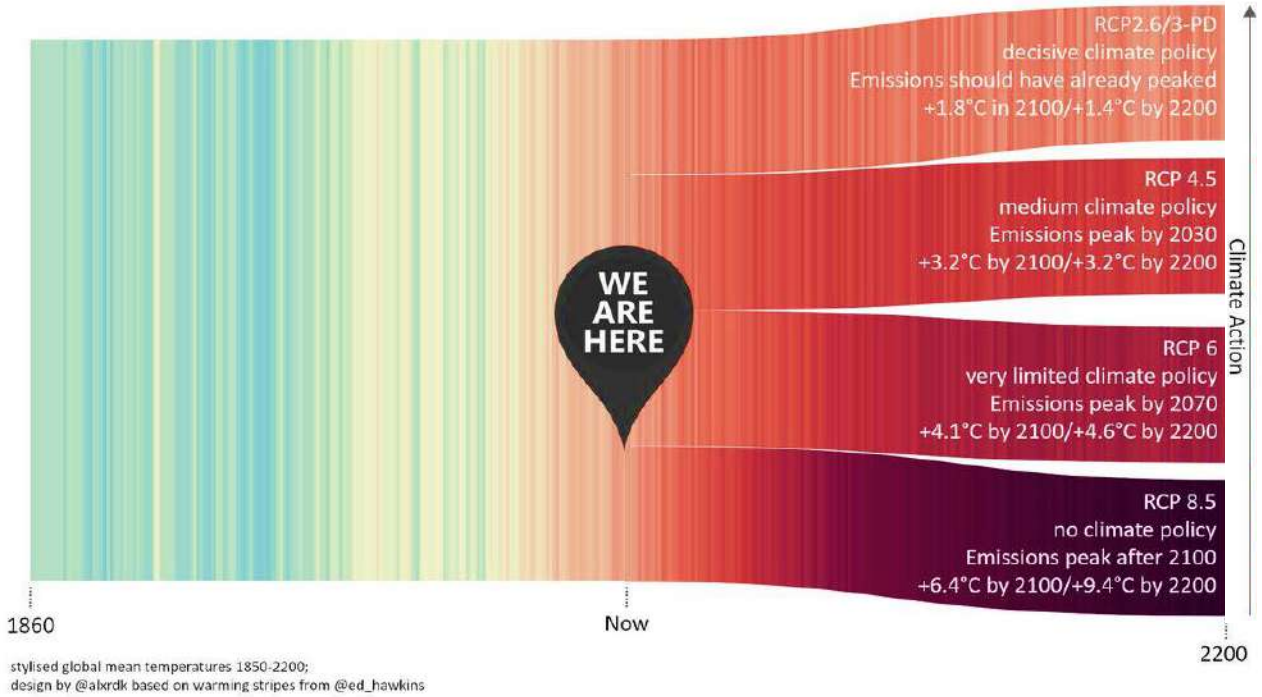


Figure 5. Stylized global mean temperature anomalies from 1860 until 2200. The future development depends on the climate action scenario: decisive climate policy reducing greenhouse gas emissions limits warming, whereas temperatures will continue to rise under the worst-case scenario RCP8.5. Credit: Hawkins and Radtke.

GLOBAL CLIMATE PROJECTIONS

The Earth's future climate depends strongly on the development of greenhouse gas emissions. Several scenarios describing future emissions consistent with various socioeconomic assumptions are available, describing a range of climate outcomes (Figure 5). These so-called **representative concentration pathways (RCPs)** extend from RCP2.6 (van Vuuren et al. 2011), consistent with decreasing greenhouse gas emissions after 2020 (decisive climate action), to RCP8.5 (Riahi et al. 2011), in which greenhouse gas emissions continue to increase under a worst-case scenario. Intermediate scenarios, RCP4.5 (Thomson et al. 2011) and RCP6.5 (Masui et al. 2011), are consistent (respectively) with emissions peaking in 2030 under an active climate change mitigation scenario, and in 2070 under a limited climate change mitigation scenario. These assumed climate scenarios form the basis of climate projections. Such projections are based on numerical simulations performed using climate models and describe the Earth's climate in future decades. Since the late 19th century, global mean surface temperatures have been observed to increase; and for all scenarios, global mean temperatures are projected to increase further in the future (Stocker et al. 2013). Toward the middle of the century, the temperature's increase compared to 1986–2005 is estimated to be 1.4°C under scenario RCP4.5; the estimate for the worst-case scenario is 2.0°C. For the end of the century, these numbers are 1.8°C and 3.7°C respectively. Except under RCP2.6, warming will continue beyond 2100. However, the climate does not change uniformly around the globe. Indeed, the annual average land temperature over Europe is projected to increase more than the global mean (Collins et al. 2013). To study regional climate in more detail and at a finer scale, regional climate models are used to

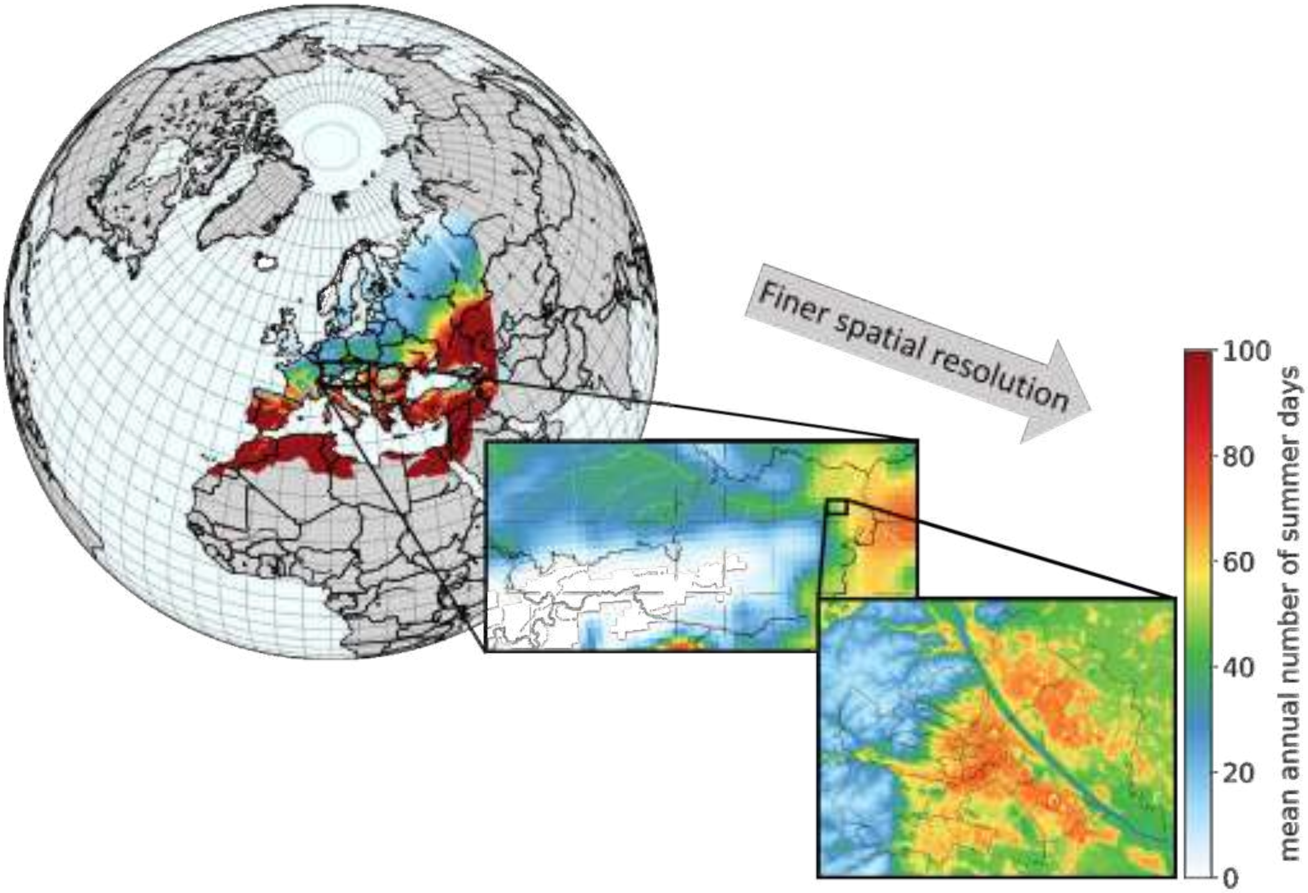


Figure 6. Global – regional – local: A chain of different climate models is used to downscale coarse global results to urban scales, increasing the spatial resolution from 100 km to 100 m in order to capture the increase in the number of the summer days on a finer scale. Credits: ZAMG/de Wit and Kainz.

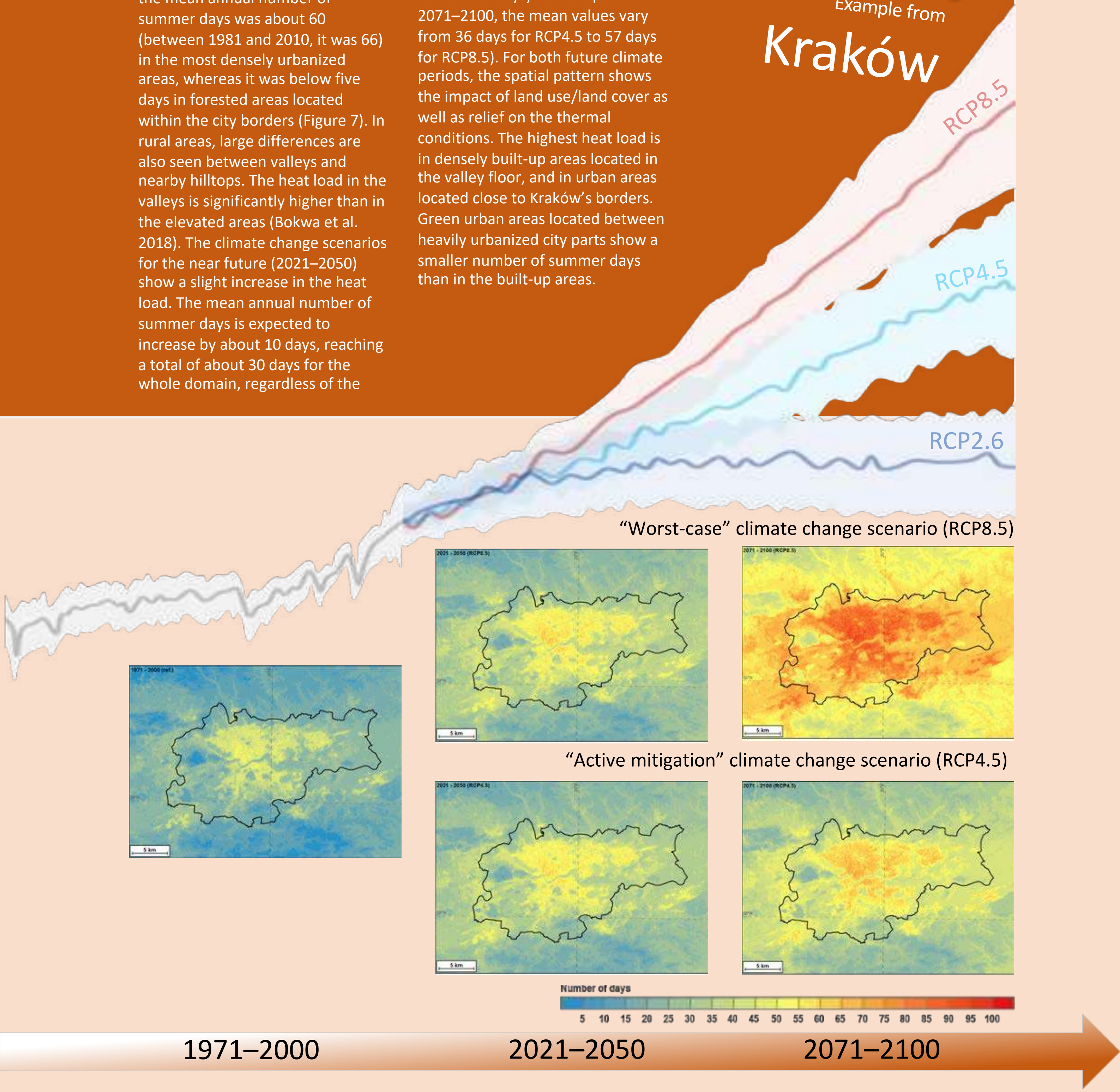
downscale results from general circulation models representing the global scale (Figure 6). For Europe, the EURO-CORDEX initiative (Jacob et al. 2014) provides a suite of regional climate projections with a spatial resolution of 12 km. These simulations, in turn, form the basis for urban climate simulations at even higher resolution.

FUTURE URBAN CLIMATE

Urban climate models, such as MUKLIMO_3 (Sievers 2016), can be used for a wide range of applications. They not only make it possible to study the implications of climate change for the heat load at **city scale**, they also help identify the spatial distribution of the heat load under current climatic conditions, thus revealing potential hot spots. To define the spatial pattern of heat load at urban scales, climate indices such as mean annual number of summer days (days with maximum temperatures exceeding 25°C) can be used. Using specific methods (e.g. the cuboid method from Früh et al. 2011), the long-term aspects of urban heat load for different climate scenarios can be projected. The following example shows the development of the urban heat load in Kraków, Poland, under RCP4.5 (intermediate scenario) and RCP8.5 (worst-case scenario). Using the ensembles of regional climate simulations from EURO-CORDEX as a base, the heat load expressed by the mean annual number of summer days is determined for the reference period (1971–2000), the near future (2021–2050), and the end of the century (2071–2100).

Example from Kraków

In Kraków, between 1971 and 2000, the mean annual number of summer days was about 60 (between 1981 and 2010, it was 66) in the most densely urbanized areas, whereas it was below five days in forested areas located within the city borders (Figure 7). In rural areas, large differences are also seen between valleys and nearby hilltops. The heat load in the valleys is significantly higher than in the elevated areas (Bokwa et al. 2018). The climate change scenarios for the near future (2021–2050) show a slight increase in the heat load. The mean annual number of summer days is expected to increase by about 10 days, reaching a total of about 30 days for the whole domain, regardless of the scenario (for the period 1971–2000 it was 17.6 days). For the period 2071–2100, the mean values vary from 36 days for RCP4.5 to 57 days for RCP8.5). For both future climate periods, the spatial pattern shows the impact of land use/land cover as well as relief on the thermal conditions. The highest heat load is in densely built-up areas located in the valley floor, and in urban areas located close to Kraków's borders. Green urban areas located between heavily urbanized city parts show a smaller number of summer days than in the built-up areas.



"Worst-case" climate change scenario (RCP8.5)

"Active mitigation" climate change scenario (RCP4.5)

Figure 7. Mean annual number of summer days in Kraków for 1971–2000 (left) and future climate projections for the time period 2021–2050 (center) and 2071–2100 (right) using the model simulations for the RCP4.5 (bottom) and RCP8.5 (top) scenarios. Source: Adapted from Bokwa et al. 2018.

3

IMPACT OF URBANIZATION AND ANTHROPOGENIC HEAT

This chapter focuses on demonstrating how urbanization and anthropogenic heat contribute to UHI effects. Greater built-up of urban areas leads to more energy consumption and can negatively affect the local climate. In light of climate change, sustainable urban development and reduction of anthropogenic emissions are required, as shown with an example from Vienna.

Example from Vienna

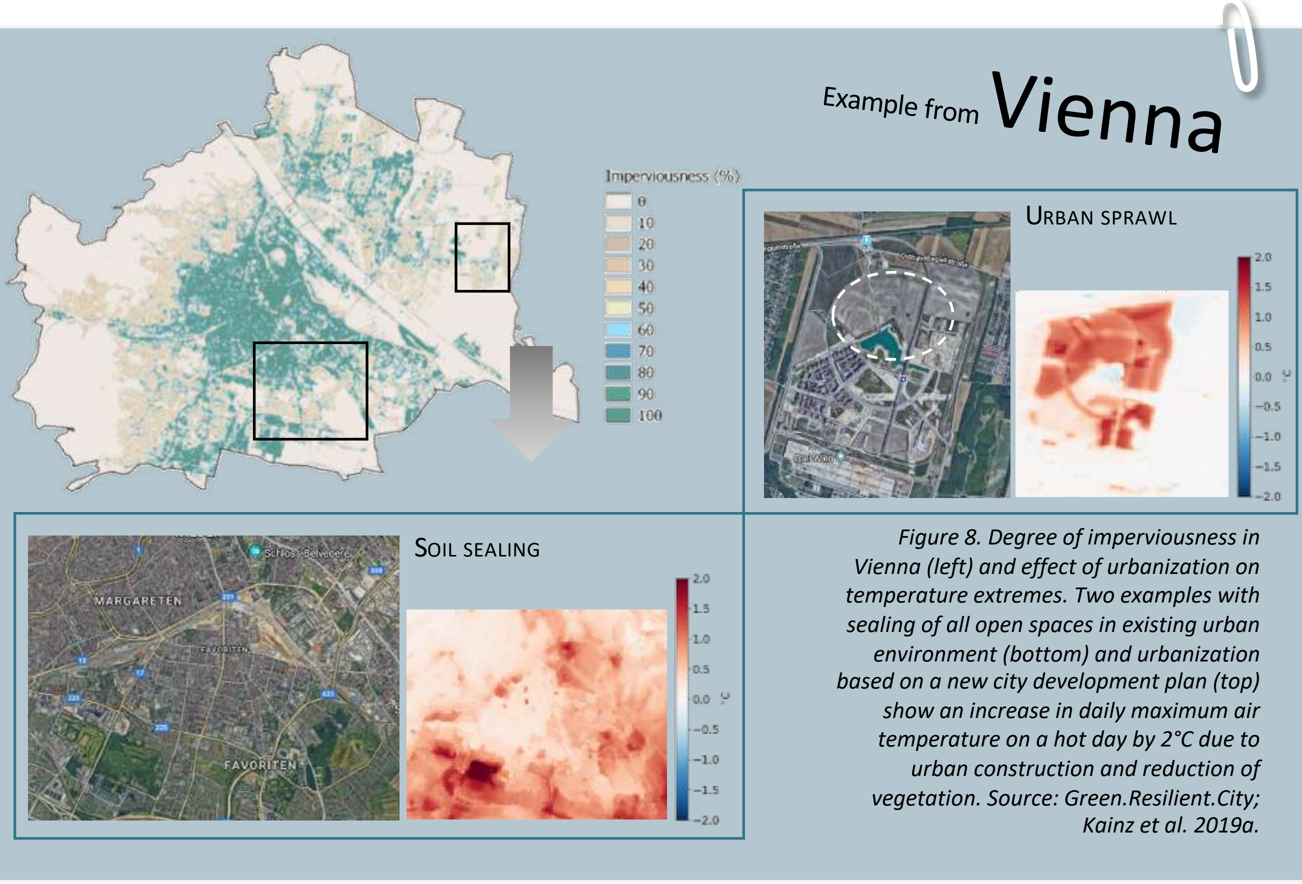


Figure 8. Degree of imperviousness in Vienna (left) and effect of urbanization on temperature extremes. Two examples with sealing of all open spaces in existing urban environment (bottom) and urbanization based on a new city development plan (top) show an increase in daily maximum air temperature on a hot day by 2°C due to urban construction and reduction of vegetation. Source: Green.Resilient.City; Kainz et al. 2019a.

UHI EFFECT AND CITY GROWTH

Modification and changes in land use and land cover play an important role in determining local climate characteristics (Oke 1973; Landsberg 1981). They affect new developing areas as well as the existing urban environment, where building construction and increasing soil sealing can lead to intensification of the UHI effect. Based on observational time series data from the 20th century, an obvious warming trend due to urbanization was already recorded in many cities (Chrysanthou et al. 2014). City growth—both in terms of densi-fication and urban sprawl—induces higher heat load, which in the future is expected to superimpose on regional climate warming (Guerreiro et al. 2018; Smid et al. 2019). To understand the role of **long-term land use changes** in cities and help estimate changes in thermal conditions resulting from regional climate change and urbanization, it is useful to combine high-resolution urban climate model simulations using historical and future land use data with climate information. Modeling the effects of new buildings and level of imperviousness on urban temperature provides useful information regarding future urban plans and may serve as a scientific basis to optimize spatial development strategies and facilitate selection and implementation of climate adaptation options.

URBANIZATION IN VIENNA

The city of Vienna is projected to grow, with a total increase in population of 289 thousands (+15.5 percent) during the period 2018–2048 (Bauer et al. 2018). The city is urbanizing rapidly and this is evident in the densification of the existing built-up areas and sprawl of the city toward the northeast and southeast (Figure 8). The following examples show the effect of urbanization on the spatial distribution of heat load, both historically and relative to

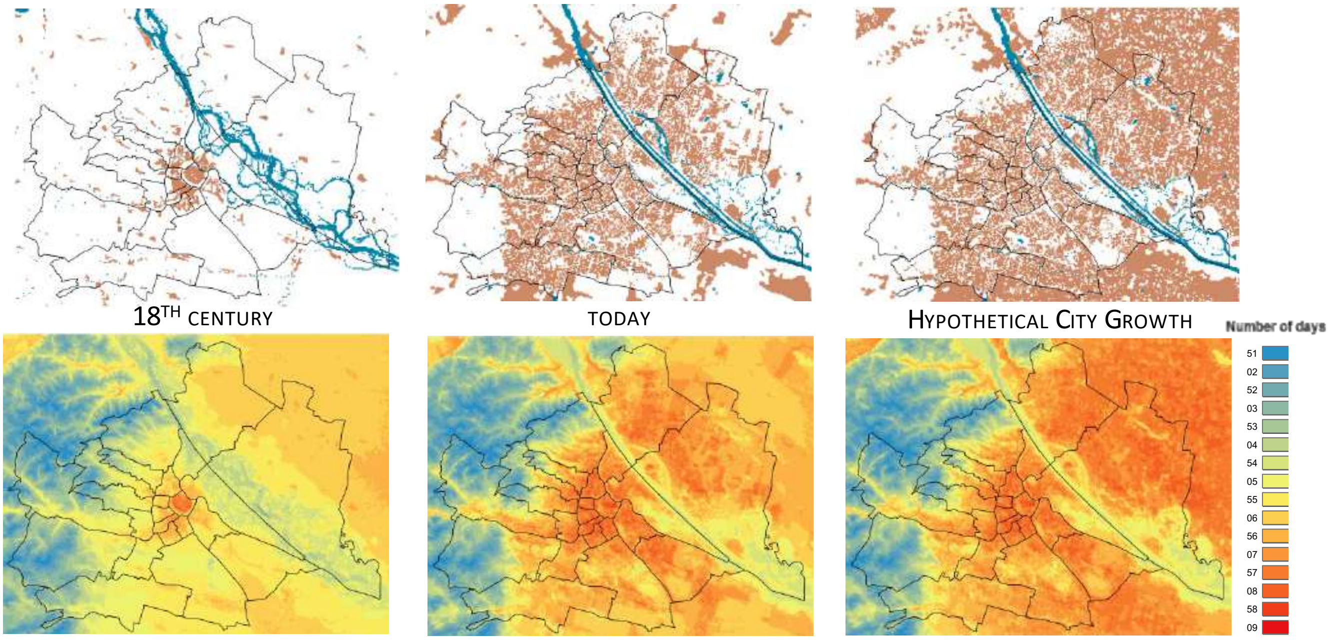


Figure 9. Building distribution in Vienna (top) and modeled mean annual number of summer days (Tmax ≥ 25°C) in Vienna (bottom). The bottom maps use climatological data for the period 1981–2010 based on historical maps of the First Military Mapping Survey of the Austrian Empire, from the period 1764–1787 (left), a current land use survey provided by the Vienna city administration (center), and hypothetical city growth in the northeast and southeast (right). Adapted from Zuvela-Aloise et al. 2013, 2014.

future development plans. The relationship between long-term modification in urban climate and large-scale urbanization was investigated by modeling the spatial distribution of heat load based on current urban structure and land use data reconstructed from the geographical maps of the period 1764–1787; see Figure 9 (Zuvela-Aloise et al. 2014). The modeling results indicate that the intensity of the UHI in the historical city center might have been similar to today's values due to the high-density built-up construction with fortification walls. The spatial structure shows a complex thermal pattern as a response to exerted land use modification and reveals expansion of areas with excessive heat load; this can be attributed to the city growth and is comparable to observational data from to the period prior to year 1850. These results illustrate the long-term consequences of urbanization. In the future, if the city were to follow a similar rate of urbanization, the urban heat load could be expected to be largely spread on the surrounding rural environment. Due to the interaction of land use and local wind conditions, neighboring city areas might experience more extreme heat as well (Zuvela-Aloise et al. 2013). On a short time scale, which considers many building projects in planning, avoiding worst-case scenarios is of crucial importance. This is illustrated by two case studies of future city development: (i) the new developing area of Aspern Seestadt in the east and (ii) further soil sealing in the densely built-up area south of the city center. The modeling results show that in case no greening is planned in new construction or all green and open spaces are paved in the existing urban environment, the maximum air temperature on a hot day will be higher (Reinwald et al. 2019). Aspern Seestadt is one of the largest urban development projects in Europe, and therefore the planning process is putting special emphasis on sustainable and green building, and energy efficiency. It can thus serve as a role model for future sustainable urban development (www.aspern-seestadt.at).

ANTHROPOGENIC HEAT

The formation of UHIs is not only due to a city's fabric and geometry. Heat emitted by human activities—such as cooling or heating of buildings, industrial processes, and transportation—also plays a key role (Figure 10). These anthropogenic heat emissions can increase air temperatures by approximately 1–3°C (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. Modeling studies have shown that during prolonged heat periods, air conditioning usage can increase urban air temperatures up to 3°C locally (de Munck et al. 2013). Sales of air conditioners have increased dramatically over the last few years (Davis et al. 2015). This increase, primarily driven by sales in middle-income countries, is explained by rising temperatures as well as income growth. In addition to adversely affecting the urban microclimate, this rise in air conditioning adoption results in increased energy need, especially on hot days during times of peak energy consumption, and thus puts additional strain on the power grid, making it more vulnerable to power outages or blackouts (Steininger et al. 2015). Furthermore, if this increased energy need is covered by electricity generated by the burning of fossil fuels, then it contributes directly to climate change through the increased emission of greenhouse gases. To adapt to increased temperatures in a sustainable way, it is important to consider cooling solutions that do not lead to further greenhouse gas emissions (Matthies et al. 2008) and to limit the anthropogenic heating of the urban fabric while at the same time guaranteeing **indoor thermal comfort**. Improved building insulation or the use of smart shading solutions can help reduce solar gain, thereby keeping buildings cool and decreasing cooling needs. Cool roofs, green roofs, and vertical gardens have also been shown to reduce indoor air temperatures. An additional advantage of these measures is their positive cooling effect on the urban microclimate.

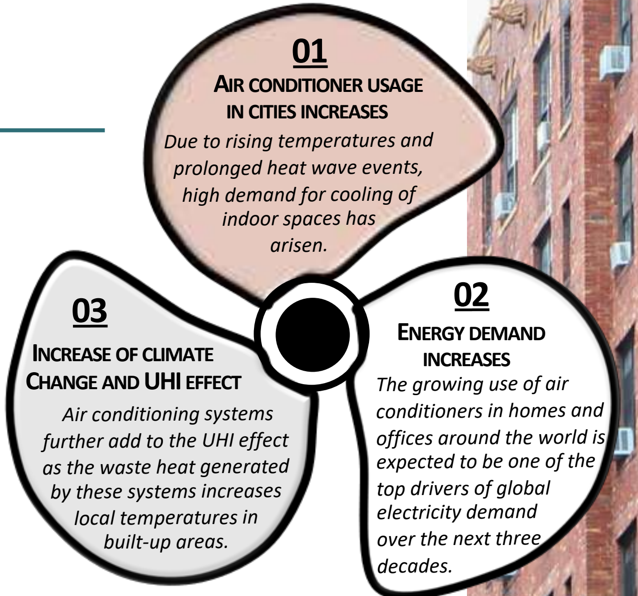


Figure 10. Anthropogenic heat feedback cycle. Credits: ZAMG/Hollósi and de Wit.

4

DATA SOURCES

Having considered climate change projections, urbanization and anthropogenic heat, this chapter highlights some of the data which can help cities better analyze 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 the use of various data sources include Cluj-Napoca and Vienna.

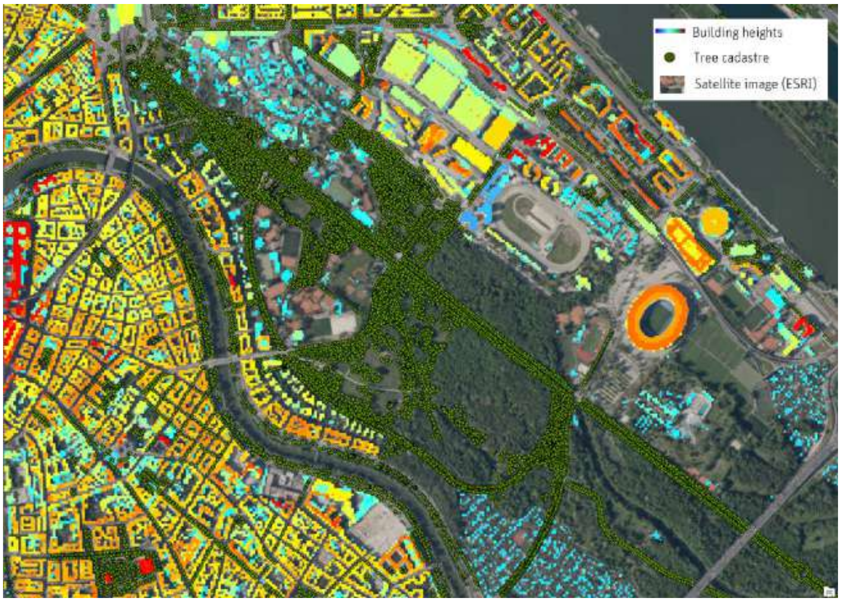


Figure 11. Satellite image and tree cadastre, building footprints, and height layers (using photogrammetry) in the area of the Viennese public park Prater. Source: City of Vienna.

MONITORING NETWORKS

Urban climate effects are generally investigated by examining the differences in meteorological elements measured and observed in rural and urban areas. Long-term monitoring records, for several decades or more, are particularly important in climate analysis in order to appropriately capture temporal variability. National weather services operate monitoring networks and provide essential meteorological data (e.g., on air temperature, wind, humidity, precipitation), which are also available on European scale (van Engelen 2008). Due to the diversified urban fabric, simple urban-rural gradients are often not sufficient to evaluate the urban climate and microclimatic differences found within the city area. For the investigation of small-scale variations, dense monitoring station networks are needed. However, the establishment of an appropriate operational **monitoring system** with high-quality equipment is often very cost-intensive, and other sources of information can be helpful to fill the data gaps. Recent trends show that utilizing alternative networks of **citizen weather stations** (CWS) can provide promising supplemental information for urban climate analysis (Chapman et al. 2017). In order to evaluate specific aspects of urban climate, observations can also be made within the scope of **measurement campaigns** using fixed or mobile stations, like temperature sensors attached to transport vehicles (Brandsma & Wolters 2012; Yokobori & Ohta 2009). Such measurements can be designed to investigate additional meteorological parameters such as radiative components or air turbulence and can be adjusted to record data in shorter time intervals. These alternative observational sources have higher spatial density than traditional monitoring networks, but are more limited in duration of measurements than traditional networks, which are operational at all times.

REMOTE SENSING DATA

Among data sources that may be used to visualize relative hot and cold surface spots are satellite data. Surface UHI studies based on **remote sensing** data have been conducted for several decades (e.g., Pongrácz et al. 2010). Examples include observations with the MODIS instrument aboard the Terra and Aqua satellites, which provides land surface temperature observations with a spatial resolution of one km, or Landsat EMT+ data with a 60 m resolution (e.g., LANDSAT-8). Even higher spatial resolutions can be obtained with airborne thermal imaging using aircrafts or automated flying devices. The remote sensing data provide many important insights into the spatial structure of UHI, especially in areas with low-density monitoring networks. Beyond meteorological observations, diverse satellite-based products that provide imagery of urban structures, land cover, and biophysical characteristics are extremely important in understanding processes, such as the relationship between vegetation and surface temperature (Guha et al. 2018). Ongoing developments in technology have led to several projects and programs that aim to overcome the weaknesses of existing land cover and land use data sets and offer improved spatial and thematic services on regional, national, and European scales. Products of Copernicus Land Monitoring Services, (https://land.copernicus.eu) the European Environmental Agency, etc. can support cities with harmonized information in order to make them more resilient and sustainable.

In recent years, through their open data policies, several cities have made high-quality 3D information accessible to the public; see Figure 11 for the example of Vienna.

Despite the many advantages of remote sensing observations, which enable investigation of cities' spatial patterns and thermal characteristics, researchers still face challenges in using satellite data for urban climate analysis (e.g., limitations in case of cloudiness, as well as in spatial resolution or temporal availability).

It is important to note that satellite-derived thermal data obtain surface temperatures instead of air temperatures; these can be markedly different, so the interpretation of the results must be done carefully (Tomlinson et al. 2011).

Example from Cluj-Napoca

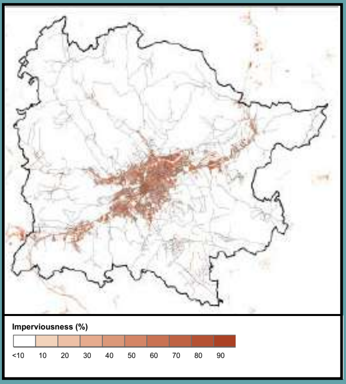
322,572 (2016)

180 km^2

64.2 summer days

0.2 tropical nights

The thermal conditions in Cluj-Napoca, Romania's second-most populous city, have been analyzed based on satellite imagery (Herbel et al. 2018). 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, such as products provided by Copernicus Land Monitoring Services, can provide complimentary information to guide sustainable urban planning (Figure 12).



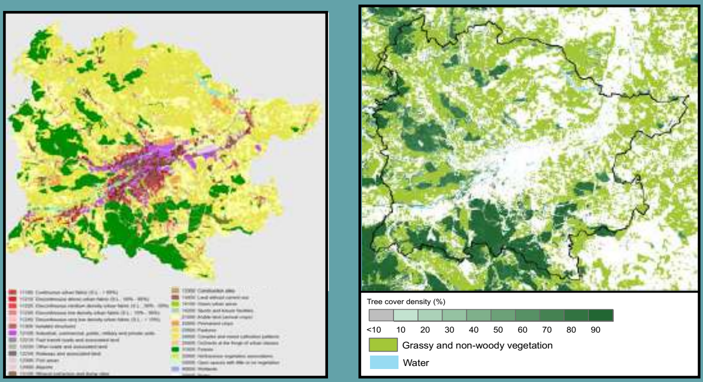


Figure 12. Cluj-Napoca spatial data available from Pan-European data sets: Urban Atlas 2012 (bottom left), Tree Cover Density 2015 with green and water areas (bottom right), and Imperviousness Degree 2015 (top right) of EEA and Copernicus Land Monitoring Services, available at: https://land.copernicus.eu/pan-european.

Example from Vienna

1,893,779 (2018)

414 km^2

64.1 summer days

4.0 tropical nights

Quality-controlled, crowdsourced CWS air temperature observations were used to study the temperature distribution in Vienna, Austria, for an 11-day high-temperature period in August 2018 (Feichtinger et al. 2020). The statistical quality control was based on the procedure developed in a previous study (Napoly et al. 2018), further optimized by incorporating two additional steps to address the specific issue of radiative errors using solar radiation data from non-CWS reference stations. In Vienna, 1,357 unique stations were available during the study period, of which 1,083 stations passed the full quality control procedure. This represents a major improvement in the spatial resolution of available temperature data compared to the currently available operational network. The quality-controlled CWS are comparable to the urban climate models simulations and provide a valuable data source for further studies.

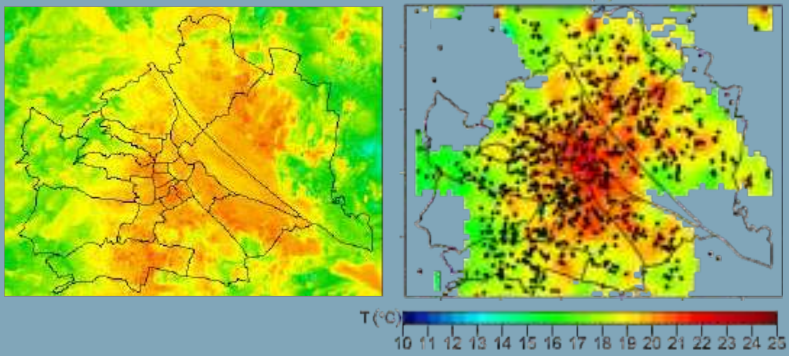


Figure 13. Spatial distribution of air temperature in Vienna, on August 17, 2018, at 00:00 UTC, based on MUKLIMO_3 model simulation (left) and CWS measurements (right) based on Feichtinger et al. 2020.

ALTERNATIVE DATA SOURCES

Although the UHI intensity may be determined by comparing urban and rural air temperature measurements, for a detailed investigation of the spatial heat load pattern more observations are necessary. However, even in cities with a relatively dense observational network, additional data sources are needed for high-resolution urban heat load studies. Urban climate models are among the available tools to obtain high-resolution information; however, they need to be validated, and various observational data sources may be used as an alternative to traditional meteorological observational networks. One example is the use of **crowdsourced data** from CWS (Figure 13). The unknown quality of these measurements is compensated for by the large number of available observations, which impose a stringent statistical quality control. Crowdsourced data have recently gained importance in urban climate research (Meier et al. 2017), and this trend is expected to continue, as ownership of weather stations connected to the Internet of Things is expected to increase. After application of the quality control, CWS meteorological data provide results comparable to those of national meteorological service networks, and discrepancies between these data sets could be explained by differences in station location relative to the urban structure.

5

URBAN CLIMATE ANALYSIS AND TOOLS

Building on the information about various sources of data available to improve UHI analyses, this chapter presents the key numerical models and tools that can be used to analyze urban climate and to support integration of climate information in urban planning. Advanced modeling approaches for the city of Linz are included as an example.

Research studies on UHI are characterized by a large variety of methodological approaches depending on the focus of interest. Investigations aim to understand the comprehensive processes of the UHI phenomenon both in space and time.

MODELING APPROACHES

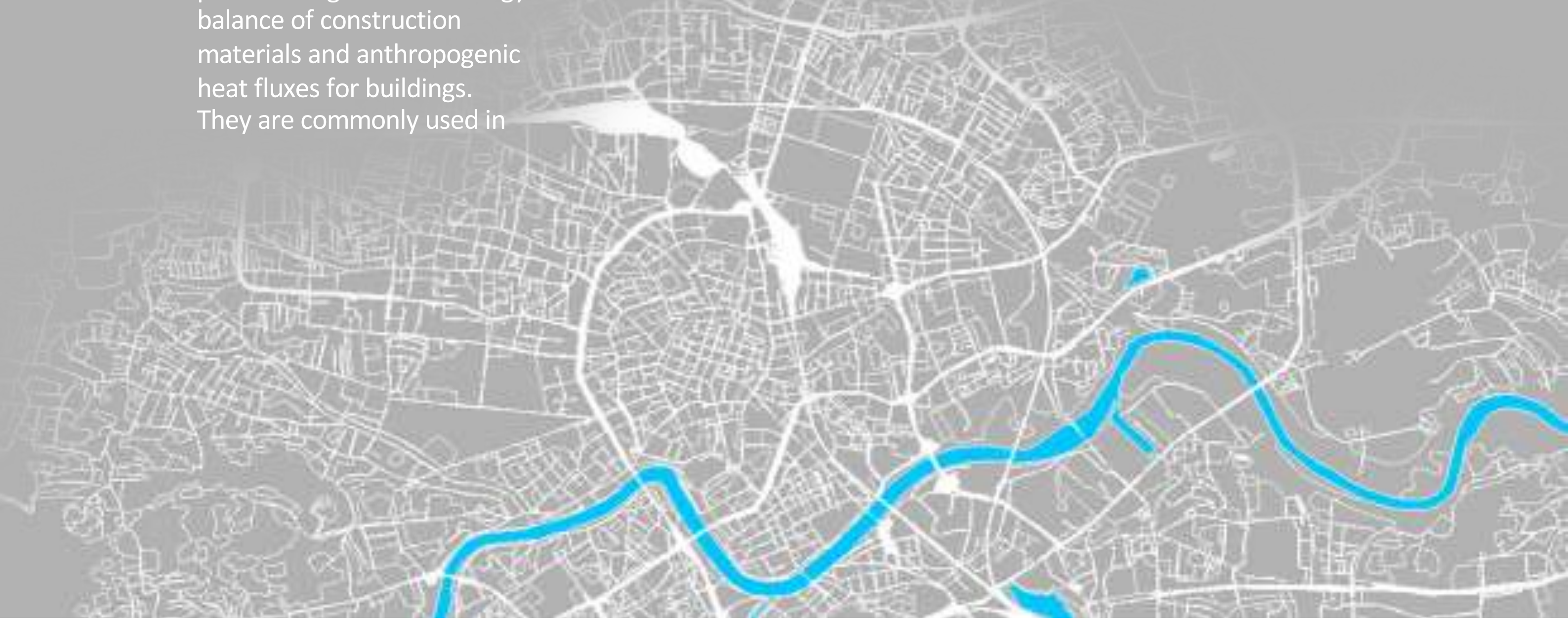
Numerical modeling is a fundamental tool for understanding urban climate processes, such as the exchanges of energy, mass, and momentum within the urban boundary layer or at the urban surface. Urban climate model simulations allow an analysis of urban climate under future urban and/or climate development scenarios, and can help urban planners to find optimally cost-effective and science-based solutions for sustainable and future-oriented cities. There is a wide spectrum of models in terms of spatial scales and applicability to various problems (e.g., Grimmond et al. 2010, 2011).

Building-scale models can provide insight on the energy balance of construction materials and anthropogenic heat fluxes for buildings. They are commonly used in architectural and engineering design (e.g., Reinhart & Davila 2016). However, these models can be applied only to an isolated building volume and neglect the influence of neighboring areas and surroundings on building performance.

Micro-scale models are widely employed to represent the interaction of resolved buildings with their surrounding environment. In most applications, the impacts of different parameters—such as building orientation, surface materials, vegetation and tree planting scenarios, human comfort, and urban ventilation—are investigated. These models are especially useful for the planning of building construction projects or the design of open spaces. They are, however, limited in spatial extent, covering areas ranging from several building blocks to a whole district (e.g., Bruse & Fleer 1998; Matzarakis et al. 2007). Larger-scale applications often involve extensive computational costs.

City-scale models enable the analysis of atmospheric and surface processes covering the area of an entire city. They can thus meet specific needs for strategic urban planning and development of climate adaptation strategies on a higher regulatory level than individual urban projects (e.g., Sievers 2016). Simulations carried out by city-scale models can help to identify critical zones in the city with increased environmental risks, such as hot spots, and can serve to support urban-scale UHI mitigation policies. These include evaluation of urban climate for protection of ventilation pathways, greening plans, air pollution monitoring, and water and energy management.

Regional-scale models in recent years have implemented higher spatial resolutions and can be used to investigate urban climate on short and long temporal scales, including variations in climate forcing and land use changes. These models parameterize urban processes to include the



modifications in energy balance (Masson 2000; Salamanca et al. 2010) and due to these simplifications are often less suitable for the evaluation of specific urban development plans. However, they provide exceptional opportunity to understand processes on different spatial scales and interactions within the climate system, such as feedbacks between the atmosphere, soil, water bodies, wind circulation patterns, and anthropogenic emissions.

In seeking to fully understand and describe the UHI phenomenon, it is important to understand that no single method is sufficient for all applications, and that these techniques and tools have to be considered as complementary approaches (Mirzaei 2015).

SPATIAL-TEMPORAL BEHAVIOUR

It is well documented that the UHI effect can significantly vary in space and time (Oke 1995; Oke et al. 2017). Temperature heterogeneity of urban areas can be explained by the heterogeneity of surface variations, morphology, or human activities (Chapter 1). The meteorological situation (e.g., cloudy and windy conditions) has an immediate impact on UHI development, while some features (e.g., effect of solar radiation) can be delayed due to inertial effects (Figure 14). Several studies analyze variations of both air and surface UHI in the context of changes in land use and land cover characteristics. In evaluating spatial behavior, the **intra-urban variability** in UHI is significantly related to building characteristics, imperviousness, and green surface fractions. Green and water areas can effectively reduce the intensity of UHI and amplitude of daily variations due to shadowing and thermal inertia. However, water surface might have reverse effect if they are warmer than the environment. During the daytime, the intra-urban variability can mainly be determined by the absorption of solar radiation by various urban surfaces, differences in wind velocity, and shadowing effects. At night, open spaces cool faster, whereas dense building areas and urban canyons cool more slowly due to the aggregated heat load and the trapping of outgoing long-wave radiation through the small sky view factor.

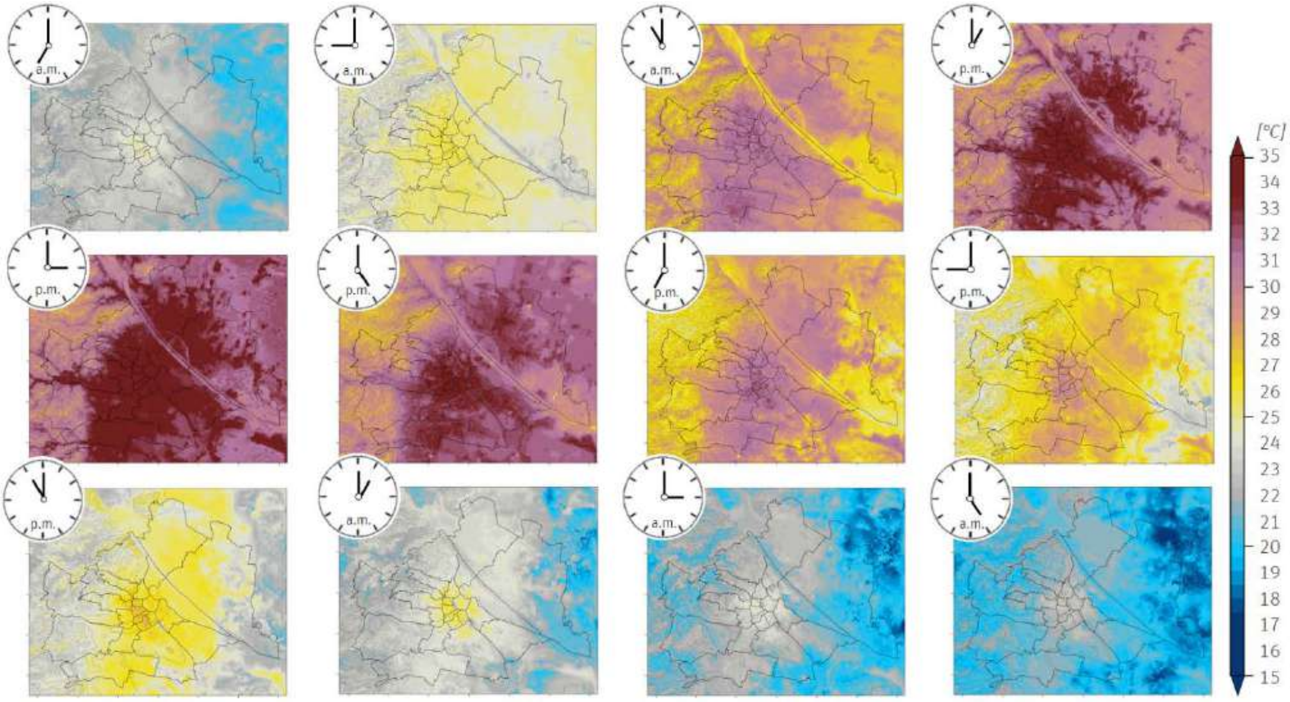


Figure 14. Spatial and temporal variability of the UHI in Vienna on the hottest day of the heat wave of 2015 (August 12) at 100 m horizontal resolution (clocks show Central European Summer Time). Adapted from Bokwa et al. 2019.

AIRFLOW

The heat exchange between buildings and air can change the intensity and patterns of airflow in urban areas. Wind patterns are also affected by canyon-like structures as well as by high-density built-up areas, where the surface roughness is relatively high. These phenomena lead to reduced airflow in urban areas that can strengthen the UHI effect. Prevailing wind and local air circulation are considered important factors in the mitigation of the negative effects of UHI. In atmospheric conditions characterized by high temperatures and low wind speed, **thermally induced local circulation systems** (UHI circulation) are of particular importance, as they create a country-to-city gradient with increased fresh air supply and provide a better air quality, especially in densely built-up areas. In addition, orography or other topographic configurations, such as coastal areas or river valleys, play a significant role in inducing local wind systems (Figure 15). Different topographic settings can reduce but also magnify the intensity of the UHI circulation as well, regulating the effects on air temperature and the dispersal of pollutants positively or negatively in urban areas. If a city is located at the base of a slope, for example, the cool air on the windward side can be blocked due to buildings. Therefore, it is of crucial importance to consider ventilation zones for long-term urban planning. Apart from its UHI mitigating effect, wind can generate discomfort and safety issues for pedestrians. In recent years, **human wind comfort** became an important factor in planning and creating more comfortable and functional buildings (e.g., Janssen et al. 2013). High building constructions and complex forms as well as funnel-like gaps between buildings or parallel rows of smooth-faced buildings can increase gustiness at pedestrian level and produce problems of wind discomfort around buildings.

Example from Linz

Relief plays a significant role in the development of local wind systems, as illustrated in the city of Linz, Austria. Figure 15 shows the formation of a nocturnal cold airflow along a valley to the north of the city as a consequence of its terrain structure. The so-called Haselgrabenwind (drainage flow from the Haselgraben valley) has been studied in detail (Mursch-Radlgruber 2003). It shows a specific airflow and wind behavior, with high peaks of wind speed during the first half of the night supporting fresh air movement in the urban area.

205,613
(2018)

96 km^2

55.8
summer days

0.5
tropical nights

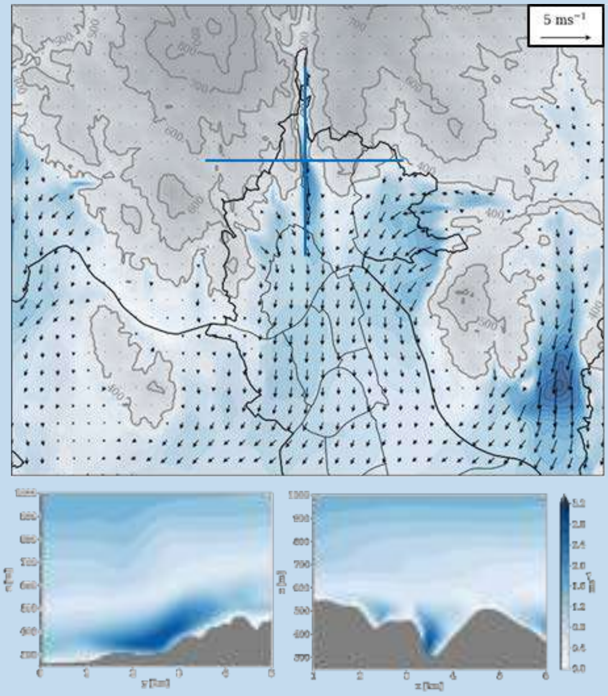


Figure 15. Formation of a nocturnal cold airflow along a valley to the north of the city of Linz based on a model simulation using the urban climate model MUKLIMO_3. Adapted from Kainz et al. 2019b.

6

HEAT WAVE IMPACTS AND WARNING SYSTEMS

Heat waves can have severe impacts on human health. A better understanding of UHI also considers the preparedness and response aspects to excess heat. With various examples across Europe, this chapter provides an overview for heat health warning systems and heat health action plans, both of which can help cities to address, manage, and reduce the health-related risks.

HEAT WAVE

A heat wave is an extended period of unusually high atmosphere-related heat stress, which may have **adverse health consequences** for the population. Heat is not only important during the daytime, but also during the night, as it can lead to a cumulative build-up of heat load with little respite during the night. Currently, there is no universally accepted definition of heat waves (Perkins & Alexander 2013; Robinson 2001), but in general they are periods of at least two or three days with unusually hot weather, which can adversely affect human and natural systems (WMO & WHO 2015). Air temperature alone with reference to maximum and minimum temperature may be sufficient to define heat waves, but it is generally not a representative indicator of the **human thermal environment**.

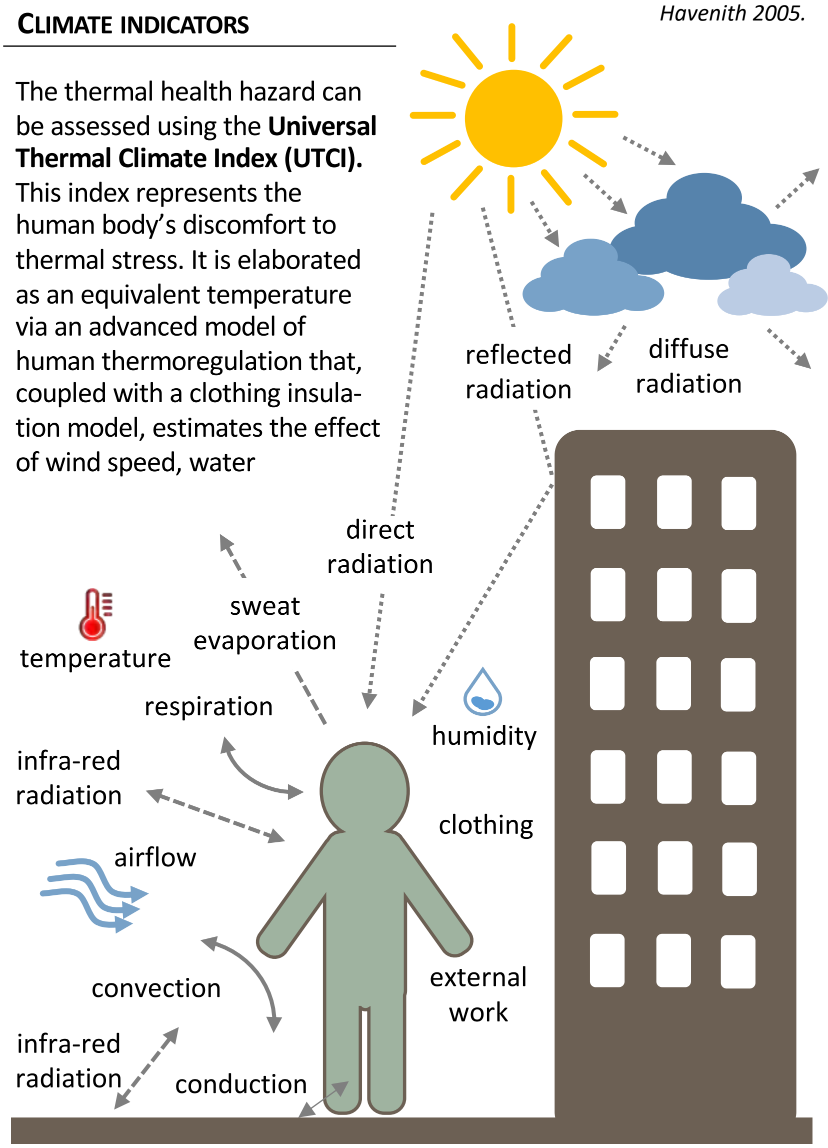
HUMAN COMFORT FACTORS

Human thermoregulation, and in particular the ability to keep the body temperature around 37°C, is affected not only by air temperature but also by meteorological variables like air's moisture content, wind speed, and radiation levels (Havenith 2005). Heat, which is produced as a result of metabolic activity plus potential other heat gains (e.g., through solar radiation), can be released through convection, conduction, respiration, radiation, and evaporation of sweat (Havenith 2005; Figure 16). When the air temperature is high, the main way to lose heat is through sweat production and evaporation. This cooling effect is compromised in humid conditions (WHO 2004). Therefore, indices to describe thermal comfort usually consist of combinations of dry-bulb temperature and different measures for humidity, wind, and/or radiation.

CLIMATE INDICATORS

The thermal health hazard can be assessed using the **Universal Thermal Climate Index (UTCI).** This index represents the human body's discomfort to thermal stress. It is elaborated as an equivalent temperature via an advanced model of human thermoregulation that, coupled with a clothing insulation model, estimates the effect of wind speed, water vapor pressure, and short- and long-wave radiant fluxes on human physiology (Di Napoli et al. 2019). Other indicators, such as physiological equivalent temperature (PET) and perceived temperature (PT) or apparent temperature, can be used to evaluate human comfort as well (Matzarakis & Amelung 2008).

Figure 16. The parameters that effect outdoor thermal comfort. Credit: ZAMG/ Hollósi; adapted from Havenith 2005.



Recent heat wave events

European countries are strongly affected by heat waves (Figure 17; this natural hazard causes more deaths in Europe than any other (Figure 18). 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). In total, the 2003 heat wave caused more than 70 thousands deaths in Europe (Robine et al. 2008). European countries were also affected by heat waves during the summer of 2015 and 2019, when record maximum temperatures were recorded (NOAA 2015; WMO 2019). Southern and southeastern Europe was greatly affected by the heat wave of 2017 (Kew et al. 2018). 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 (Zaninovic 2011). It was also shown that 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). 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 in Cluj (Herbel et al. 2018).

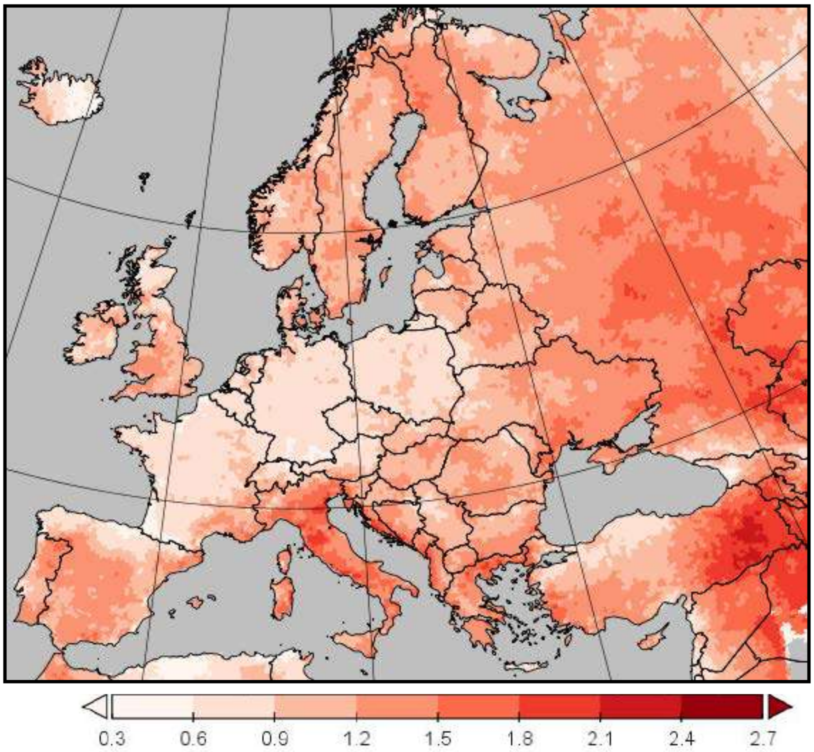


Figure 17. Annually averaged frequency of heat waves with durations of six days or greater exceeding the 90th percentile of daily maximum temperature in the months April through September, based on 1971–2000 E-OBS data. Source: E-OBS ECA&D (van Engelen et al. 2008).

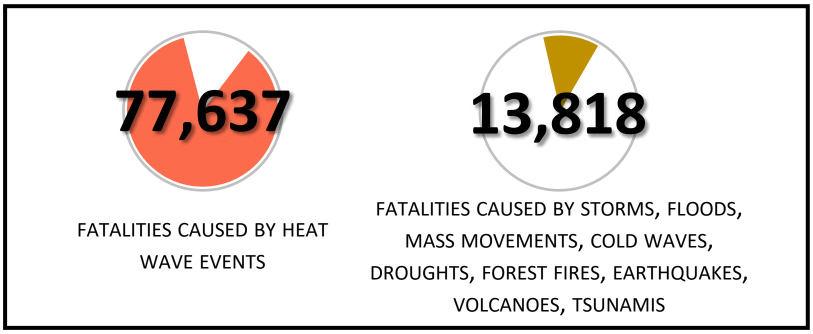


Figure 18. Of all the natural hazards affecting the EEA member states in the period 1980–2017, heat waves account for some 68 percent of the fatalities and about five percent of total economic losses. Source: EEA 2019.

HEAT HEALTH WARNING SYSTEMS

Heat health warning systems (HHWSs) and **heat health action plans (HHAPs)** constitute the means to address, manage, and counteract the health-related risks of heat waves. HHWSs, which are often part of a wider HHAP, were developed in many regions to better inform people about upcoming hot weather conditions and thus to reduce the negative impacts of heat waves on human health. Guidance on how to develop HHWSs has been issued jointly by the World Meteorological Organization and the World Health Organization (WMO & WHO 2015). A HHWS usually comprises weather forecasts, a method to assess the heat-health relationship, the determination of **threshold values to issue warnings**, a system of graded alerts, and the communication of the alerts to the general public or specific target groups (WMO & WHO 2015; Casanueva et al. 2019). Ideally, a combination of weather elements related to the human sensation of heat should be used as a risk indicator. Appropriate thresholds must be established for that combination, considering both daytime high and overnight low values, and being related to the climatic variability common to the area. The effect of duration should also be included. The thresholds may represent absolute values (e.g., maximum temperature exceeding 30°C) that are specific for a particular region. Alternatively, the thresholds may be relative (e.g., temperature exceeding the 98th percentile of the maximum temperature) and apply to all regions. The benefit of this latter approach is that heat wave health assessments would be similar across communities for relative temperature effects.

Casanueva et al. (2019) provides an overview of 16 existing HHWSs in Europe. While before 2001 only one operational HHWS was in place in Europe (in Lisbon), most European countries started to implement a HHWS after the 2003 heat wave. The variables and thresholds used in Europe to issue warnings are very diverse (Table 1). In most countries, warnings are triggered based on maximum or mean temperature only. Some countries also consider minimum temperature when issuing a warning, and a few countries include other climatic factors, like humidity. Thresholds are often defined based on **epidemiological studies**, where climatic variables are set in relation to mortality (most countries) or to heat stress levels (e.g., Austria, Germany); or they are based on climatological extremes for the specific region (e.g., high percentiles).

Table 1. Heat warning system characteristics for different countries. PT: perceived temperature; Tmin, Tmax, Tmean: minimum, maximum, and mean temperature respectively. Source: Casanueva et al. 2019; DHMZ.

Country	Heat index	Criteria for warning	Target groups
Austria	PT and Tmin	PT > 35°C for at least three days and Tmin ≥ 20°C (subject to modifications)	Hospitals and health resorts, childcare facilities, mobile nursing services, medical and emergency organizations
Croatia (Zagreb)	Tmin and Tmax	Yellow: Tmin > 20.2 *or* Tmax > 33.7 Orange: Tmin > 21.3 *or* Tmax > 35.1 Red: Tmin > 22.9 *or* Tmax > 37.1 If both conditions satisfied, higher category is applied.	Public
North Macedonia	Tmax	Monthly thresholds for each of the four phases for 13 cities in six regions from May to Sep.	Retirement homes, general practitioners, workers
Romania	Tmax	Alert: Tmax: 35-38°C, Maximum response: Tmax: 35-40°C	-
Slovenia	Tmean and Tmax	Yellow: Tmax > 31°C Orange: Tmax > 34°C and/or Tmean > 26°C Red: Tmax > 37°C and/or Tmean > 28°C	Public (genera), civil defense in case of orange or red warning

THE ROLE OF METEOROLOGICAL SERVICES

National meteorological services provide weather forecasts, usually monitor the country-specific risk indicators, and inform the public about the exceedance of threshold values. In some countries they are also mandated to provide heat wave advisories, while in other countries the local public health agencies are responsible for issuing warnings (WMO & WHO 2015).

Thresholds to issue **warnings** are in most cases defined at country scale; however, some countries have defined region-specific thresholds (Casanueva et al. 2019). In many countries, heat health warning systems are established as part of the national heat health action plan (simplified example in Figure 19). At European scale, Meteoalarm (Figure 20) is the official website providing alerts on extreme weather. It receives information from the national weather services.

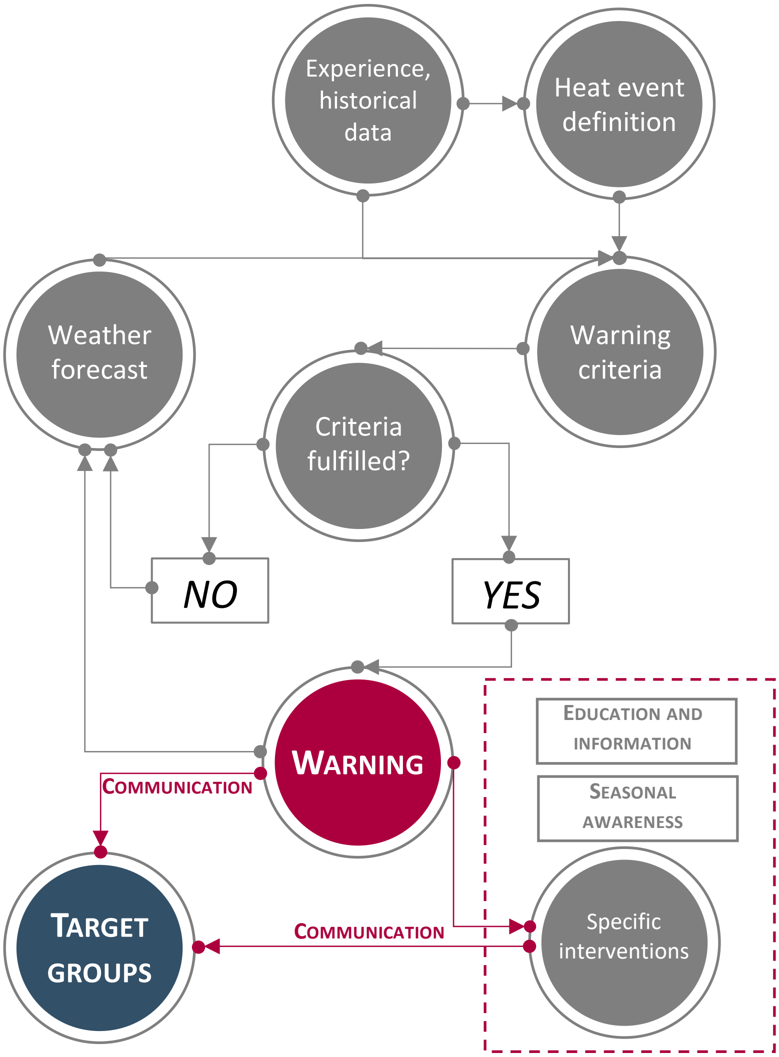


Figure 19. Simplified illustration on how to implement a HHWS as part of a wider HHAP (elements in the red box). Adapted from WMO & WHO 2015.

HEAT HEALTH ACTION PLAN

Apart from alerting the public when a heat wave is predicted (through HHWSs), it is crucial to inform people up front about the devastating effects heat can have on their health and about the appropriate measures to take. Therefore**,** **raising awareness and knowledge building** in general are important aspects of HHAPs beyond warnings. HHAPs usually also comprise the identification of vulnerable population groups (to make sure that they are being reached during an extreme event), the set-up of intervention plans and communication strategies (to ensure that warnings are issued and communicated to the right people and that all involved partners and organizations are informed and prepared), the determination of medium- and long-term **mitigation measures** (like recommendations for urban planners), and the definition of evaluation procedures. In 2004, the French authorities implemented local and national action plans that included HHWSs, health and environmental surveillance, reevaluation of the care of the elderly, and structural improvements to residential institutions. Across Europe, many other governments (local and national)

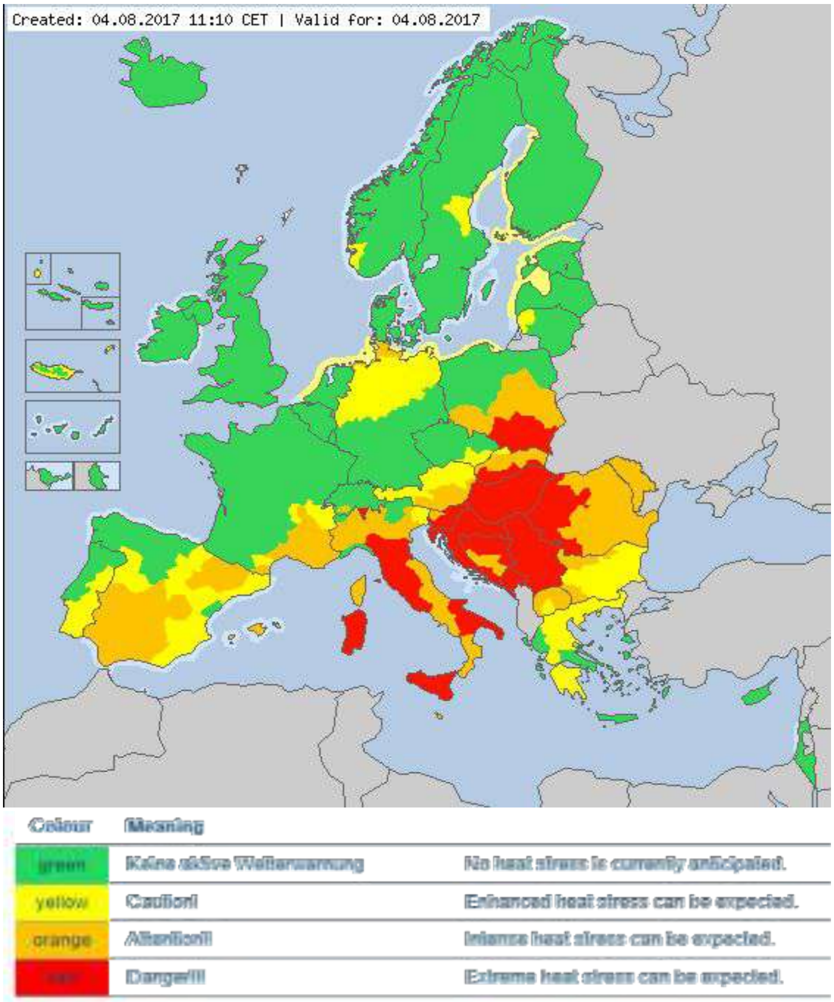


Figure 20. Meteoalarm, which provides relevant information needed to prepare for extreme weather expected to occur in Europe, issued the highest grade (red) warning for heat on August 4, 2017, for several countries, as displayed on the Meteoalarm website. Source: www.meteoalarm.eu.

have implemented heat health prevention plans (Casanueva et al. 2019). In Croatia, one of the priority measures was the implementation of the “Protocol on Treatment and Recommendations for Protection against Heat.” This important protocol allows coordination of several national and city services, with the DHMZ providing weather forecasts and warnings. In Austria, the national heat protection plan specifies the warning procedure at national level, while at local level, HHAPs (such as the one for Vienna) define in more detail different actions that are to be taken before the warm season, during the warm season, and during a heat event. As soon as heat stress is predicted, ZAMG sends an alert to the Ministry of Health and other relevant federal institutions. The federal states inform predefined institutions and groups, such as hospitals, care homes, childcare institutions, care givers, and the Red Cross. Guidelines on how to behave during a heat wave are available on the website of the Ministry of Health. In case of extreme events, the Ministry of Health and the Austrian Agency for Health and Food Safety (AGES) jointly set up a phone hotline to provide advice for the general public. The positive effect of such awareness strategies is evident, as shown by a study by Fouillet et al. (2008). By modeling the expected number of heat wave deaths in the period 1975–2003 in France and extrapolating the expected number of deaths for the 2006 heat wave, the study showed that the actual excess mortality was markedly lower than that predicted by the model. This reduced death toll could be attributed in part to increased awareness of the risk related to extreme temperatures, preventive measures, and the set-up of the warning system.

Besides implementing and strengthening warning and communication systems to prepare people for upcoming heat waves and thus reduce health effects through raised awareness and better preparedness, HHAPs can and should also comprise long-term strategies to alleviate the future impacts of heat events.

7

CLIMATE ADAPTATION MEASURES

Appropriate adaptation measures can reduce urban heat load and bring further benefits for the city. In light of climate change, both climate adaptation and climate mitigation strategies need to be included in urban action plans. Building on the information across the previous sections, this chapter introduces the concept of green, blue or white city agenda, along with examples from Graz and Klagenfurt am Wörthersee of how this can be applied in practice.

“Green city”

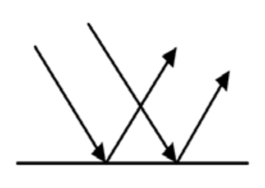
Vegetation, such as trees or parks, provide cooling through the effect of shading as well as evapotranspiration. Green roofs or vertical gardens, where a layer of vegetation grows on a rooftop or along a wall, also cool through this principle.

Implementation:	Parks, unsealing of soil, and creation of more permeable surfaces, green roofs, living walls, vertical gardens, green tracks, etc.
Cooling through:	Shading effect, evaporative cooling, insolation
Co-benefits:	Stormwater retention, energy savings, aesthetic value, recreation, biodiversity, ground water recharge, reduced subsidence

“Blue city”

Water bodies such as ponds, lakes, or rivers can cool by evaporation, heat absorption, and heat transport. Water spray from fountains, for example, can locally have an even greater cooling effect because of the large contact surface between the water and air, stimulating cooling through evaporation.

Implementation:	Ponds, lakes, fountains, canals, re-naturalization, etc.
Cooling through:	Evaporative cooling, increased ventilation
Co-benefits:	Recreation, biodiversity



“White city”

Causes of the UHI include high absorption of solar radiation as well as heat storage of paved surfaces or built-up areas. These can be counteracted by the use of „cool materials” that are generally lighter or reflect more solar radiation than traditional darker materials.

Implementation:	Bright (reflective) materials
Cooling through:	Reduced heat absorption through the reflection of solar radiation
Co-benefit:	Building energy savings, easy implementation

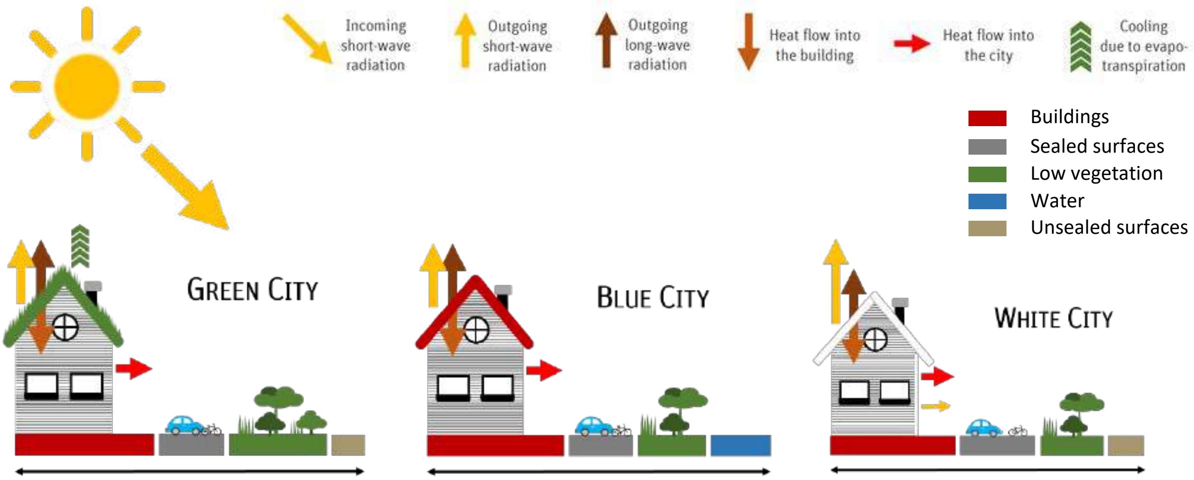


Figure 21. Illustration of different climate adaptation measures. Increasing the fraction of vegetation in urban areas, implementing green or white roofs, and adding water bodies can reduce urban heat load, contribute to health and well-being, and bring further benefits for the city. Credit: ZAMG/Kainz and Hollósi.

There are various options to counteract the UHI effect through **nature-based and technological solutions** (Figure 21). These adaptation measures broadly fall into three categories, related to increasing the ratio of plants and trees in a city (green city), implementing the smart use of water (blue city), and reducing the absorption of solar radiation by increasing its reflection (white city). "Cool" materials for roofs or pavements are generally brighter, hence the term "white city." Such surfaces stay cooler in the sun and help reduce the UHI effect, as less heat is transferred to the surrounding air (e.g., Akbari et al. 2001; Santamouris 2014). The green and water areas provide cooling through evapotranspiration, and trees' shading effects also keep the surfaces cool (e.g., Gill et al. 2007; Rizwan et al. 2008; Berardi et al. 2014). The success of these adaptation measures is clearly dependent on the climate conditions locally. In arid areas, measures requiring high water consumption, such as intensive greening, may not be sustainable. Moreover, the effectiveness in terms of UHI reduction depends strongly on the local climatological conditions and urban geometry. Certain measures, e.g., green roofs, can be applied only where the building construction allows it. Local wind circulation can enhance the propagation of cool air, however blocking of airflow can also weaken the cooling effect. Therefore, careful planning of adaptation measures is needed to provide the best solutions for cities.

CO-BENEFITS

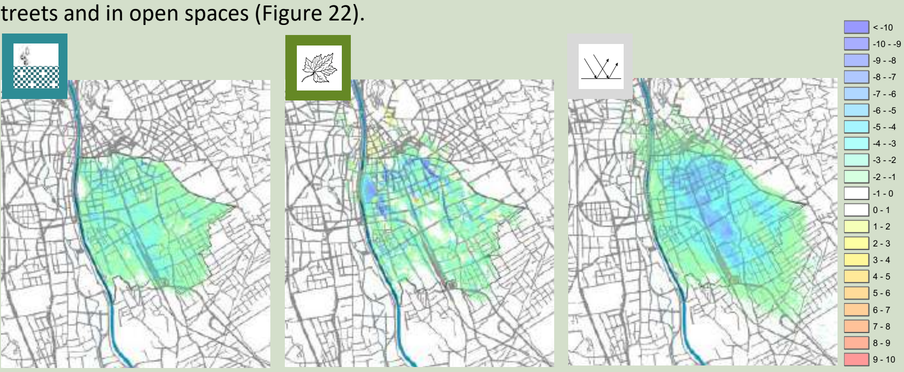
Measures to counter the UHI effect are very often at the same time measures to **improve the quality of life in cities.** Parks, ponds, and fountains provide room for recreation. Green roofs can be used for urban gardening and help maintain biodiversity in the urban area. Cool roofs, which reflect more solar radiation than ordinary roofs, transfer less heat to the building interior. In this way, human comfort is increased by reducing indoor temperatures. In case air conditioning is installed, such roofs help save energy needed for cooling and increase energy efficiency. Green roofs have a similar insulation effect, while additionally supporting stormwater runoff management by soaking up rain. These and other manifold advantages of adaptation measures are often sufficient to justify the initial costs and technical difficulties in implementation.

EVIDENCE-BASED ADAPTATION PLANNING

Urban climate models can be used to quantify the effect of different adaptation options

Example from Graz

In the densely built Jakomini district in the center of Graz, Austria, urban climate model simulations were used to evaluate the potential for local cooling considering using different adaptation measures. The modeling simulations show that a strong cooling effect can be achieved by applying materials with high reflectivity on buildings’ walls and roofs, reducing area of sealed off surfaces (pavement), and increasing the number of trees on streets and in open spaces (Figure 22).



287,995 (2018)

128 km²

63.0 summer days

1.2 tropical nights

Figure 22. Simulations of effectiveness of climate adaptation measures for the Jakomini district in Graz. The difference in mean annual number of summer days is shown in comparison to reference simulation in case of reduction of pavement by 50 percent (left), 30 thousands new trees of 10 m height on streets and open spaces (center), and increase in roof albedo (0.7) (right). Adapted from Zuvela-Aloise et al. 2017.

while considering local climate conditions and urban structure. Using urban climate simulations, enables **identification of critical zones** in the city with increased environmental risks and in this way support the prioritization of adaptation plans. It is also possible to evaluate the effectiveness of urban planning measures to reduce the heat load before the actual implementation. Examining climate “what if” scenarios with and without the implementation of adaption measures can show the extent to which heat load is reduced by optimizing thermal properties of buildings and open spaces through increased proportions of green and water areas. The major adaptation pathways in climate models are translated into modification in land use and urban structure characteristics, from which alternative urban heat load simulations can be calculated and compared. The white city scenarios consider enhanced sunlight reflectivity of sealed areas, i.e., roofs, walls, and streets/sidewalks, which can be applied to individual surfaces in different parts of the city. The green city scenarios include various options for increasing vegetation, mainly the addition of trees, bushes, or grass along streets and in open spaces, but also on building structures (either roofs or facades)

Unsealing of paved areas is an important adaptation measure, not necessarily because of its direct cooling effect, but rather through indirect effects of water retention in the soil.

Simulation of new green areas with urban climate models can help quantify the amount of vegetation necessary to provide a substantial cooling effect for a specific area of the city. The blue city scenarios, where water areas are the focus of climate adaptation, provide insight into how the cooling effect of water bodies, such as rivers, lakes, or ponds, can be enhanced through spatial planning, e.g., by planning of free corridors for ventilation along the water pathways (e.g., Theeuwes et al. 2013). Recent studies have shown that UHI mitigation measures should be applied extensively to have a sizable effect over the city (Zuvela-Aloise et al. 2016). However, many adaptation measures cannot be applied in the same way for each urban area. In some cases, instead of following one adaptation pathway, a city can achieve the best **cooling performance** with a combination of different adaptation measures dependent on the local urban characteristics. Although **adaptation pathways** can be generalized in many ways, the final adaptation plans are city specific, and need to consider many other aspects, including technical, institutional, regulatory, social, environmental, financial, and many others, which go beyond the scope of this report. With urban climate models, general strategies can be designed into tailored plans, then tested and tuned in different stages of implementation. In this way, urban climate modeling can help urban planners in the decision-making process of finding optimally cost-effective, scientifically sound, and consistent solutions for sustainable cities. A special challenge in climate-resilient urban planning is to find appropriate adaptation measures that provide a good cooling performance as well as fit into the already existing cityscape. As these interventions influence the social environment for people living in the area, interaction between planners and different stakeholders is necessary to ensure acceptance and successful implementation in compliance with building regulations and guidelines. Equally important is a good **communication process**, where stakeholders and users can contribute to the development of tailor-made applications. Practical solutions that encourage engagement of different actors are more likely to provide **long-term benefits** than top-down approaches. Analysis of adaptation measures' effectiveness can include future climate projections. Reference simulations for the most recent climate period are compared with the future RCP scenarios—e.g., RCP4.5 (peak of CO_2 emissions in 2050) and RCP8.5 — until the end of the 21st century with and without adaptation measures. The results show that in case no climate change mitigation is achieved globally (RCP8.5), the local climate adaptation measures are very likely not sufficient to compen-sate for the large-scale warming trend. However, if CO_2 emissions are reduced suffici-ently (RCP4.5) and adaptation measures are implemented on a local scale, an increase in heat load could be largely mitigated by the middle of the 21st century (Oswald et al. 2020). This finding emphasizes the fact that both climate adapta-tion measures and reduction of CO_2 emissions need to be considered in urban action plans.

Example from

Klagenfurt

am Wörthersee

100,851 (2018)

120 km^2

62.8 summer days

0.2 tropical n.

The city of Klagenfurt am Wörthersee, located in Austria's southern Alps, is affected by climate change and increasing temperatures in the urban area. In order to ensure that its conditions remain livable in the future for its citizens and visitors, the city joined the New Covenant of Mayors in 2016 and is taking actions to update the 2014 Sustainable Energy Action Plan and revise it with climate adaptation measures making it a Sustainable Energy and Climate Action Plan. Urban climate simulations have been performed to analyze the future projections and possibilities of climate adaptation in the city considering two major adaptation pathways, white city and green city (Figure 23).

The white city scenario for Klagenfurt am Wörthersee considers a 20 percent increase in sunlight reflectivity of roofs, walls, streets, and sidewalks, which could be achieved by using reflective materials, e.g., through white coating. The green city scenario takes into account the reduction of impervious surfaces by 30 percent, green roofs on 50 percent of suitable buildings, and an increase in the number of trees and vegetated areas. In addition, an afforestation area of 1.4 km^2 is considered near the city. The results of the simulations show a substantial decrease in heat load. In the white city scenario, the mean annual number of hot days decreased by up to 20.7 percent; for the green city scenario, the decrease was up to 20.2 percent (more trees) and up to 27.1 percent in case of afforestation near the city. An overall combination of adaptation measures (the combined white city and green city pathways including the afforestation) indicates an even stronger potential for the reduction of urban heat load. For this scenario, a decrease in average number of hot days of up to 44.0 percent is achieved. The daily temperature extremes are also reduced, resulting in maximum air temperature decrease by 1.7°C on a hot day. Climate adaptation under future climate is analyzed as well. If scenario RCP4.5 is considered and no adaptation measures are implemented, the heat load would increase by the middle of the 21st century by an average of up to 10 days a year. The adaption measures could reduce this increase to six hot days a year on average (white city) or8 hot days a year on average (green city). Moreover, if combined adaptation measures are implemented in the near future, an increase in hot days by the middle of the 21st century could be largely mitigated or even reduced to lower levels than today.

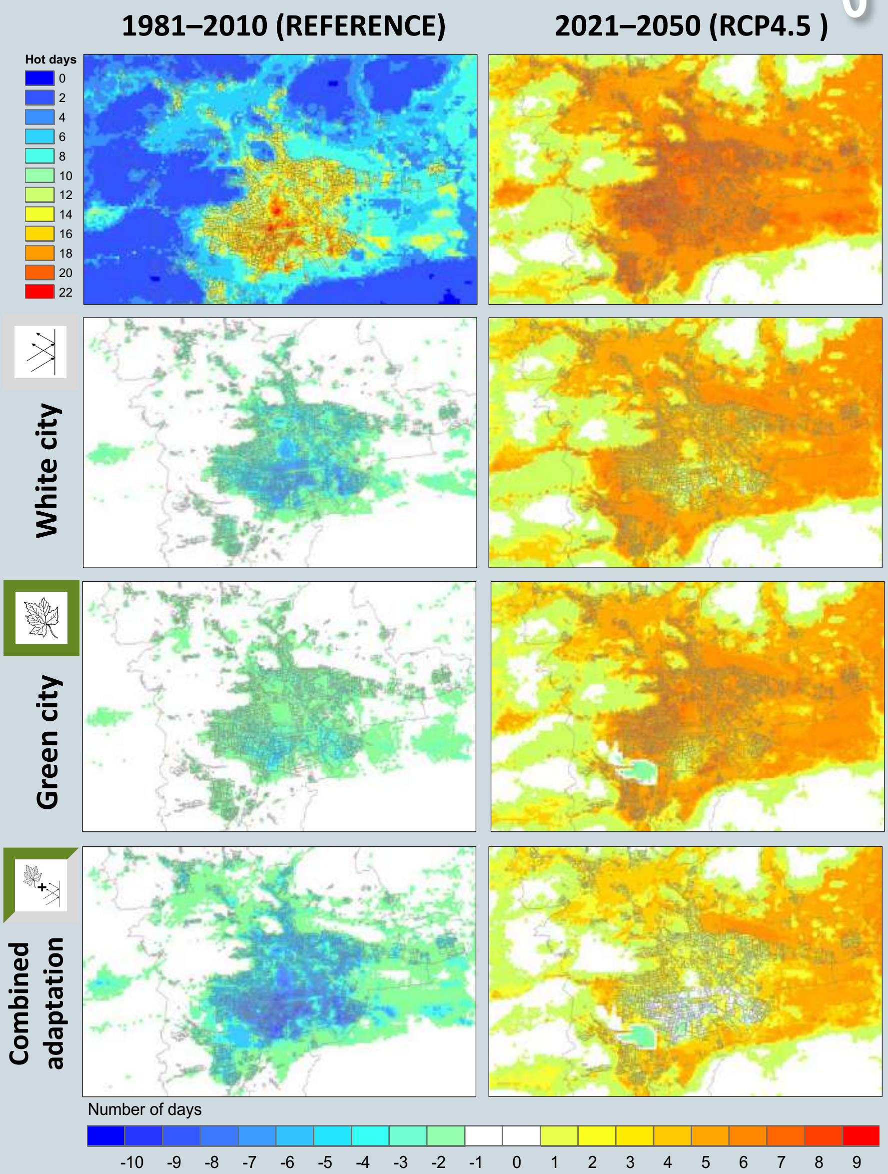


Figure 23. Mean annual number of hot days is shown for the time period 1981–2010 (top left) and 2021–2050 (top right). The difference in the mean annual number of hot days for adaptation scenarios corresponding to white city, green city, and a combination of the two, with and without adaptation measures, is shown for the current climate period 1981–2010 and future climate scenario RCP4.5 for the time period 2021–2050. Adapted from Oswald et al. 2020.

ROADMAP FOR INCREASED RESILIENCE TO URBAN HEAT

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. The roadmap presented in this report represents a general disaster risk management approach that focuses on an improved understanding of risk, which can in turn inform specific plans and investments and guide implementation and evaluation of actions taken. Heat waves and UHI are often not the only hazards that cities face. This framework allows cities to consider multiple hazards that may be prevalent, such as floods, earthquakes, storms, etc. A number of these steps provide opportunities to integrate a risk management approach with urban planning and development. Risk-informed urban planning and development can help minimize climate change–related loss to public, private, and combined investments; it can also contribute to more sustainable development and planning, and, ultimately, more resilient economies and societies. The risk management approach reflected in the roadmap can also be applied to specific project investment processes or to specific hazards such as UHI effects.

Cities need to gain a better understanding of what drives the heat waves and UHI effects they are subject to. They also need to understand the scope of their risk, including people and assets exposed and impacts of heat waves on specific areas or population groups, including the vulnerable or most at risk. Risk and impact information, together with information related to urban development (such as changes in the land cover, land use, or population growth) and climate change projections, forms the basis for identifying the most effective passive solutions, including green, blue, or white city measures. These measures should match local needs, preferences of stakeholders, and other considerations.

The action plan for increased resilience to UHI effects should identify specific public investments and actions to promote green, blue, or white adaptation measures. These may include for example investments in open green spaces and public cooling areas; regulations for public and private investments, including green or reflective roofing, shading, or use of specific materials; subsidies for households, etc. An overall framework defining the goals, priorities, and specific implementation and coordination arrangements would underpin the action plan. The benefits of and considerations for specific measures are detailed in a number of reports (e.g., World Bank, forthcoming) and should be carefully assessed.

There are analytics and models available to inform urban planning and infrastructure development resilient to future climate change. There is a range of tools and modeling techniques at different scales that can help compare potential benefits of specific measures and/or their combinations and thus inform decision making. The results can guide the subsequent development, implementation, and monitoring of an action plan with specific corrective or preventive actions and investments that address hazard risk and climate change. This report has used Urban Adaptation Support Tool (UAST) as presented in the *Urban Adaptation to Climate Change in Europe* report (EEA 2012). In 2011, the European Union published the "Non-paper Guidelines for Project Managers: Making Vulnerable Investments Climate Resilient" (EU–GL 2011). The methodology was updated within the EU-founded H2020 CLARITY project (https://clarity-h2020.eu, No. 730355) to comply with the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) and promote an integrated modeling approach for disaster risk reduction and climate change adaptation.

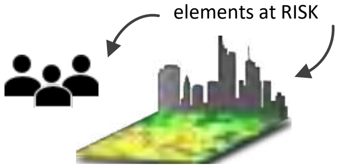
In parallel to improved urban planning, cities also need to also plan for improved preparedness and response to UHI effects. As part of this effort, cities need to clearly define arrangements and investments for HHWSs and HHAPs to address, manage, and reduce the residual health-related risks to populations, including vulnerable groups. Better information about the exposed and vulnerable population and assets can improve the targeting of critical systems and plans to better meet emergency situations and people's needs.

Knowledge base

- Definition of objectives
- Understanding drivers and purposes
- Inventory of existing knowledge and experience

2 Evaluate Exposure

- Analyzing the distribution of elements at risk considered (e.g., population, buildings, infrastructure) in space and time
- Allocating all elements at risk in the area of interst to vulnerability classes for each hazard type



3 Analyze Vulnerability

- Analyzing to what extent a given exposed element at risk is damaged by a certain hazard
- Defining vulnerability classes (e.g., children/adults/elderly) and functions for each element at risk

4 Assess Risk and Impact

- Relating hazard intensities to exposure and vulnerability conditions in a given area
- Taking into account the magnitudes and likelihoods of the impacts associated with the hazards
- Considering numerical modeling procedures in order to include various scenarios in the analysis with respect to the frequency of event occurrence and magnitude
- Considering existing and future climatic risks and impact scenarios

Identify Adaptation Options 5

- Selecting possible options
- Assessing different adaptation options, including their impact and effectiveness
- Discussing with experts and stakeholders

7 Implement Adaptation Action Plan

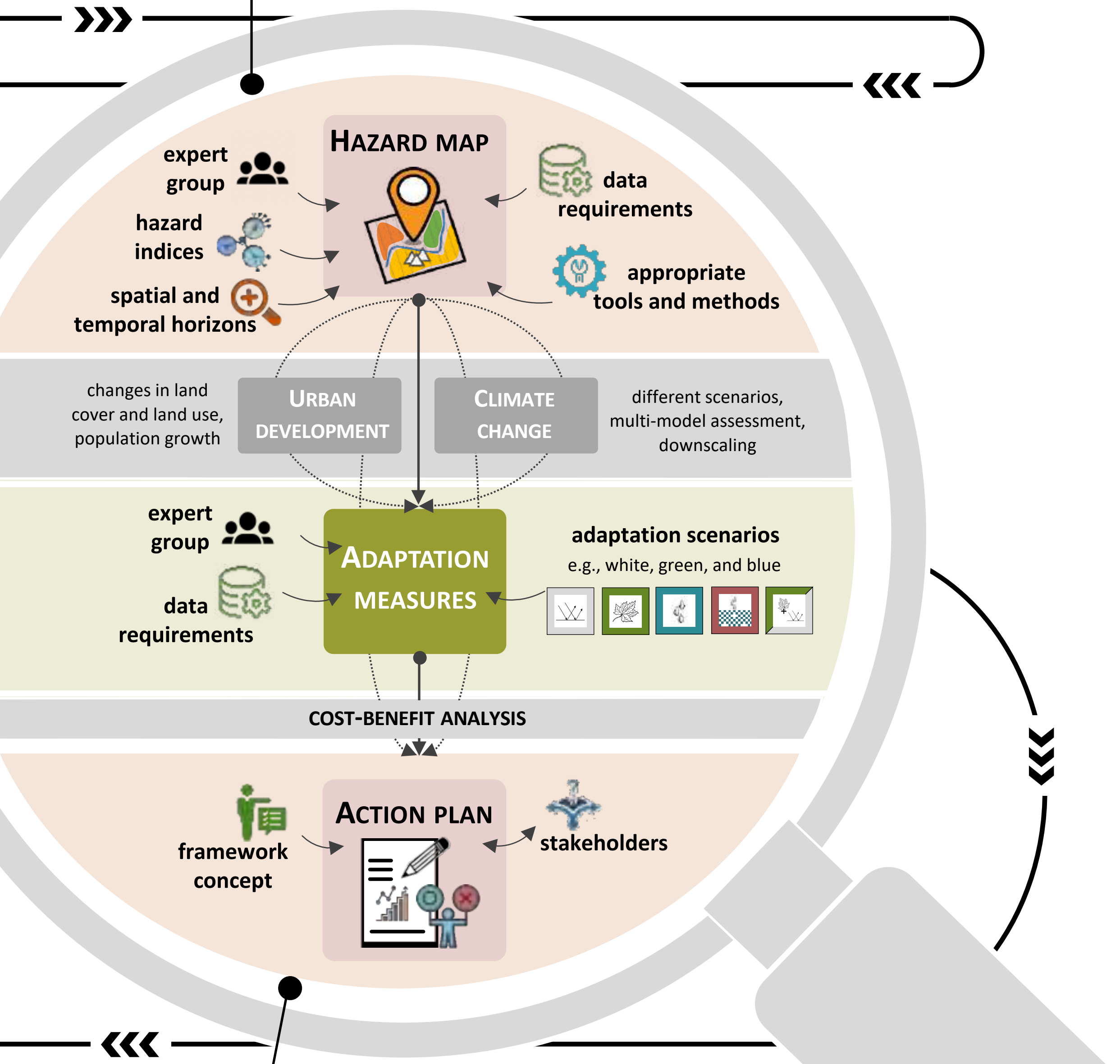
- Developing action plans for selected adaptation measures
- Making decisions
- Clarifying stakeholder roles and responsibilities

8 Monitor and Evaluate

- Consulting with stakeholders
- Communicating results
- Evaluating performance
- Monitoring changes in impact

1 Characterize Hazard

- Identifying hazard conditions, relevant climate variables, and the combination of different parameters
- Analyzing hazard based on its main characteristics under past and future climate conditions
- Downscaling information in the area of interest



6 Appraise Adaptation Options

- Undertaking an economic appraisal in form of a cost-benefit analysis of possible adaptation measures
- Determining project limits, objectives and aims
- Determining investment and operating costs
- Assessing impact and effectiveness of options

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Endnotes

i. The European Economic Area consists of the Member States of the European Union and three countries of the European Free Trade Association (Iceland, Liechtenstein and Norway; excluding Switzerland).

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City statistics

Population
Vienna, Graz, Linz, Klagenfurt: https://www.statistik.at/web_de/statistiken/menschen_und_gesellschaft/bevoelkerung/
Cluj-Napoca: http://www.insse.ro/cms/files/Audit%20urban/Audit_urban_2018.pdf
Zagreb: https://www.dzs.hr/default_e.htm
Krakow: https://stat.gov.pl/en/topics/statistical-yearbooks/

Area
Vienna, Graz, Linz, Klagenfurt: http://www.gemeinden.at/gemeinden/
Zagreb: http://www1.zagreb.hr/zgstat/documents/Ljetopis%202007/STATISTICKI%20LJETOPIS%202007.pdf
Krakow: https://www.krakow.pl/english/business/39148,artykul,krakow_in_numbers.html
Cluj-Napoca: https://www.citypopulation.de/en/romania/cluj/_/054975__cluj_napoca/

Mean annual number of summer days (Tmax ≥ 25°C) between 1981 and 2010
Vienna, Graz, Linz, Klagenfurt: ZAMG
Cluj-Napoca: European Climate Assessment and Dataset, Squintu et al. 2019
Zagreb: DHMZ
Krakow: Bokwa et al. 2018

Mean annual number of tropical nights (Tmin ≥ 20°C) between 1981 and 2010
same as above

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