Chapter 5
Human Adaptation to Higher Ambient Temperature

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Abstract The on-going climate change is leading to a progressively warmer world where extreme weather events, including heat waves (HWs), are going to be more frequent and intense. While limiting the anthropogenic contribution to the changing climate (through mitigation strategies), it is fundamental to put in place effective adaptation strategies for reducing overheating risks and enhancing communities' resiliency. In fact, the increasing exposure to higher ambient temperatures has negative effects on human health and the overheating risk is associated with individuals and communities' heat exposure and vulnerabilities. Hyperlocal environmental monitoring coupled to socioeconomical assessment is needed to point out the most vulnerable areas in a city, thus providing references on where and how to implement the proper adaptation strategy. In the body of this chapter, several strategies related to human adaptation to higher ambient temperature are presented by grouping those strategies according to their scale of application and impact. The proposed spatial scales are human, building, and city scales. Human adaptation can be physiological (related to body thermoregulatory systems) or behavioural (actions taken to increase thermal tolerance). Building and city adaptation are related to greenery (e.g. green roofs and façades and green urban infrastructure) and the development and implementation of new materials. Each strategy should be evaluated in terms of its local benefits, but to guarantee sustained societal functioning in this progressively hotter climate, these adaptation actions need to be implemented now.

Keywords Hyperlocal monitoring · Cross-scale adaptation · Human-centred solutions · Exposure · Vulnerability · Overheating risk

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1 Introduction

Climate change is currently one of the main concerns worldwide, with considerable impacts also at local and regional scales [21]. One of the consequences of climate change is the significant increase in frequency, intensity, and duration of extreme weather events, including heat waves [57]. People living in urban environments are even more vulnerable to heat extreme events because of the Urban Heat Island (UHI) phenomenon and the population density [3]. Indeed, the rapid urbanization and anthropogenic activities in cities contribute to increase the ambient temperature in considerable levels [70]. It is known that thermal properties of materials used in cities, urban canyons radiative distribution, urban greenhouse effect, and diminished evaporative surfaces and turbulent transfer are some of the factors causing urban overheating [70].

The higher air temperature in cities leads to a rise in energy consumption for cooling buildings and peak electricity demand [74]. It was also stated that urban overheating has negative impacts on air quality [35]. In addition, it harmfully affects human health by increasing heat-related mortality and morbidity [75]. However, these impacts are not the same for all. Some groups, like elderly people, subjects with pre-existing medical conditions, low-income communities, ethnic minorities, and socially isolated people, have a higher heat-related vulnerability [67].

Efficient reactions to the challenges involving the growing heat-related vulnerability are needed [73], and adaptation is one of the most common strategies adopted to deal with this [38]. Cirrincione et al. [8] mention that adaptation measures are important to make cities more sustainable and resilient.

According to the Intergovernmental Panel on Climate Change (IPCC, the United Nations body for assessing the science related to climate change), adaptation is the procedure of adjustments to actual or expected climate and its effects [25]. Some examples of adaptation include the intrinsic human acclimatization process, increasing the amount of greenery areas in the cities, and the development of new materials to be used in the built environment.

The IPCC [26] describes two types of adaptation: autonomous and planned. Autonomous adaptation is a reaction to the current climate and represents an additional change in an existing system. Planned adaptation is proactive; that is, it is designed to eliminate or reduce a problem before it happens and is characterized by an adjustment or a transformation of a system.

Rohat et al. [67] showed that the efficacy of an adaptation measure depends on "(i) the aspect of heat risk it targets, (ii) the type of socioeconomic development, (iii) the level of climate change (for strategies targeting the heat hazard), (iv) the communities it targets, and (v) the location where it is implemented". They also complement that the efficiency of planned adaptation is supplemented by autonomous adaptation. Therefore, both types of strategies need to be considered.

Despite the type of adaptation, these strategies need to be implemented. Santamouris [72] highlighted the importance of adaptation at both urban and building scales to effectively face the future growth of cooling energy needs and the increase of climatic vulnerability. Then, it is essential to evaluate the benefits of adaptation measures on minimizing the negative overheating effects, such as reducing emerging demand for cooling purposes, improving thermal comfort indoors and outdoors, and decreasing heat-related health risks.

This chapter explores the role of human adaptation triggered by higher ambient temperatures, especially in urban environments. Risks for humans and vulnerabilities associated with overheating are presented, highlighting the role of environmental and socioeconomical factors. Environmental data collection methods and the most common indexes for the human heat stress assessment are briefly pointed out as fundamentals for an accurate overheating risk mapping and thus an efficient adaptation strategies' planning. Finally, examples of adaptation in different scales are reported.

2 Human Overheating Risk and Vulnerabilities in the Framework of Climate Change

The IPCC recognized that human-induced warming reached approximately 1 °C above pre-industrial levels in 2017. This value is assessed accounting for the combination of surface air and sea surface temperatures averaged over the globe and over a 30-year period. Therefore, greater warming levels have already been experienced in many regions and during specific seasons. More specifically, land regions are facing higher rise in temperature than ocean regions that shows a slower warming rate. Within land regions, cities further experience the UHI phenomenon due to their specific metabolism and morphology. The construction materials in urban environments (e.g. concrete and asphalt) usually absorb heat more than natural surfaces, and the high density of buildings hinders air circulation, which causes an increase in air temperature in comparison with the surrounding less-urbanized areas [39].

Any further rise in temperature, beyond 1 °C, would likely be less than 0.5 °C on the next three decades by reducing all the anthropogenic emissions to zero immediately. In this view, the 1.5 °C emission pathways are defined as those scenarios providing high chance in limiting global warming below 1.5 °C or returning to 1.5 °C after an overshoot (of different magnitude according to the specific scenario) by 2100, at current knowledge state. The consistent 1.5 °C pathways propose to eliminate CO_2 emissions promptly and to reduce widely other Green House Gases (GHG) emissions, which can be accomplished through transformations in energy, land, urban and infrastructure (including transportations and buildings), and industrial systems. The industry sector, for example, could reach the target reductions by electrification, hydrogen, sustainable bio-based feedstock, product substitution, and carbon capture, utilization, and storage [27]. Different 1.5 °C pathways are associated with different projected impacts at a global average warming.

As observed and projected by the scientific community, climate change is associated with a global warming trend which additionally turns into weather extremes that are foreseen to be more frequent and intense in the coming future. Among these extreme events, heat waves (HW) are particularly dangerous for people due to the rapid increase in their occurrences and intensity, their synergistic interaction with the UHI, and the high mortality rate associated [18, 46, 66]. The World Meteorological Organization (WMO) recommended HW definition as follows [83]: *a period of marked unusual hot weather over a region persisting for at least three consecutive days during the warm period of the year based on local climatological conditions, with thermal conditions recorded above given threshold.* Such a general definition underlines the impossibility of providing a unique common definition worldwide. Different thresholds for the observed temperature and different durations of these temperatures have been used in different studies according to site-specific climate conditions and accounting for physical, social, and cultural adaptation capabilities. McCarthy et al. [44] re-adapt the WMO definition of HW for different regions of the UK by setting appropriate thresholds in accordance with the UK climate. Pascal et al. [56] test multiple methodologies for defining temperature thresholds in different cities in France, further accounting for the estimated excess in mortality associated with different HW temperature thresholds. Robinson [66] highlights that the basic HW definition implicitly accounts for two fundamental aspects named as the "physiological" (related to thermoregulation capability of the human body) and "sociological" (centred on local adaptation to climate) aspects. In this framework, the main driver for the HW definition results in being its impact on human health and that is also the reason behind the need of developing effective warning systems [52, 55]. The WMO [84] has also produced guidance on the development of heat-health warning systems, HHWS, whose aim is *to alert decision-makers and the general public to impending dangerous hot weather*. The following sub-section presents what are the heat-related health risks for humans, accounting for diversified population vulnerabilities and what has been done so far in literature for their recognition and quantification.

2.1 Overheating Risks for Humans

A prolonged heat exposure has negative impact on human health as it increases morbidity (e.g. heat exhaustion and heat stroke) and mortality (death) [5, 39]. Indeed, HWs are a major cause of weather-related deaths [42]. Prolonged exposition to extremely high temperatures impacts human health due to heat-related illnesses with syndromes that vary from less severe (heat syncope), to severe and lethal (heat stroke) [78]. Extreme heat also worsens the effects of chronic diseases (including respiratory diseases, cardiovascular diseases, and kidney problems) while it has been observed that high temperatures and air pollution lead to synergistic negative health effects [11]. High temperatures negatively impact also emotional and psychological health [50]. Extreme weather events, in general, affect mental health in several ways [51]. Negative health outcomes of urban climate extremes vary according to individuals' vulnerabilities meaning that some groups are more susceptible to these risks. More specifically, the health risk due to overheating results from the combination of both individuals' exposure and specific vulnerabilities. Characteristics that affect the individual vulnerabilities include age, pre-existing medical conditions, economic conditions (including energy poverty and poor housing), level of instruction, accessibility to urban services and facilities (such as the Public Leisure Spaces, PLSs), and health education and awareness, all affecting the adaptive capacity of people to environmental stressors. Greater heat-related vulnerability is associated with the elderly and very young, people with pre-existing medical conditions, low-income communities, people without access to air conditioning, ethnic minorities, and socially isolated individuals [67]. Climate change projections also show that Central and South America, Africa, Middle East, Pakistan, India, Bangladesh, eastern China, south-east Asia, and northern Australia are the regions at greater future heat-related risks [14, 48].

Mallen et al. [42] affirm that the vulnerability depends on the exposure, sensitivity, and adaptive capacity of a person. Regarding HWs, the exposure is related to the event intensity and its spatial distribution, the sensitivity is associated with how much the increased exposure to these events will affect people physically; and the adaptive capacity is the capability to diminish or deal with the increased personal exposure. Some specialists proposed vulnerability indexes, that is, a metric that combines indicators considered to be representative of this issue used to describe the vulnerability of a population [25]. Alonso and Renard [1], for example, presented a proposal for vulnerability indexes that included physiological (response capacity of the organism) and socioeconomical aspects. These indexes are important to identify the locations and groups of people more heat-vulnerable to plan pointed interventions and strategies that will be more effective [6, 42]. Another methodology for assessing population overheating vulnerability in urban contexts is provided by Macintyre et al. [39] by combining multiple factors associated with heat-health outcomes, mainly spatial distribution of the UHI intensity, dwelling types, and socioeconomic factors. The selection of proper indexes, highlighting human overheating risks, and of effective methods for mapping such risks is going to be the benchmarks for developing decision-makers' supporting tools, driving adaptation and mitigation strategies' implementation.

Even limiting global warming to 1.5 °C, adaptation actions still are fundamental to face the effects of climate change [54]. Adaptation to the changing climate accounts for any kind of action aimed at managing the impacts of climate change by lowering both vulnerability and exposure to its detrimental effects for individuals, communities, ecosystems, or the same built environment (e.g. deterioration of cultural heritage sites, of infrastructures, etc.). In addition to limit climate change-induced risks, to adapt to changing climate also means to exploit any potential benefits. Along with the adaptation capabilities in face of the on-going climate change, mitigation actions are urgent to limit the anthropogenic contribution to global warming. Indeed, mitigation actions are all those strategies implemented at different scales (international, national, local/community, and individual level) for directly limiting GHG emissions. While to adapt to changing climate is needed since we are already facing relevant effects, we cannot indefinitely adapt, and thus, mitigation is urgent to avoid worsening of the same effects. Adaptation and mitigation actions can interact with each other resulting in synergies or trade-offs, and this is recognized in several sectors, such as agricultural, infrastructure planning and construction, and tourism [28, 30]. This is the reason why policies and measure efficacy could be significantly enhanced by accounting for these types of actions jointly. Furthermore, planned adaptation is an important strategy to decrease the negative effects of climate change on health within the most vulnerable groups [67].

A quantitative description of the achievable benefits due to the implementation of adaptation or mitigation actions allows to present and compare more or less effective strategies to policy and decision-makers. The following sub-section specifically focusses on those indexes more commonly used to quantify human health outcomes of overheating risks.

2.2 Assessment of Human Heat Stress

The most common methodologies for assessing heat stress refer to (i) single meteorological variables, (ii) simple biometeorological indexes, or (iii) outputs from numerical human heat-budget models.

The physical environmental component of the heat accounts for the interactions among solar radiation, atmospheric temperature and moisture, and wind speed and direction. These data are generally retrieved by fix weather stations that may be located in not-highly populated areas, or in proximity of airports, sites that cannot be assumed as representative of the real conditions a citizen is exposed to. The weather data collection site has to be considered during the heat load analysis and forecast when the study output is the human health outcome. Recent studies present alternative methodologies for retrieving environmental data in areas more representative of daily citizen exposure (e.g. within the Urban Canopy). Among those proposals, Pigliautile and Pisello [60] developed a miniaturized weather station that can be worn as a common bike helmet. This system allowed to map microclimate variations within different neighbourhood of the same city [59]. Different microclimatic conditions correspond to different heat exposure within the monitored urban environment. The heat exposure is a main component in overheating heat assessment: the higher the spatial resolution of the monitoring, the higher the accuracy in risk mapping. For the heat exposure assessment, it is worth noting that people use to spend the majority of their life in indoors. In this view, the assessment of indoor climate for a range of dwellings typologies is needed. Important factors to be considered in the indoor thermal load estimation include building thermal mass and orientation, as well as force or passive ventilation.

Simplified biometeorological indexes combine more than one environmental parameter for describing the heat exchange between the human body and the surroundings. Many indexes have been developed throughout years, and reasons beyond the choice of a specific index could concern the availability of required data. All those indexes aim at determining an apparent temperature that humans perceive given a specific combination of two or more environmental parameters. Some biometeorological indexes are presented along with their computation equation in Table 1.

Other indexes further account for human body characteristics. These are the outcomes of simplified heat-budget models describing heat exchanges occurring between the body and the environment. In addition to the internal heat production (i.e. metabolic rate) and personal power expenditure (i.e. mechanical power) which are related to the individual performed activities, the heat stored in the body

Table 1 Some of the most common biometeorological indexes

Index	Acronym	Equation
Heat Index	HI	$\mathrm{HI} = -42.379 + 2.04901523(T_f) + 10.14333127(\mathrm{RH}) - 0.22475541(T_f)(\mathrm{RH}) - (6.83783 \times 10^{-3})(T_f^2) - (5.481717 \times 10^{-2})(\mathrm{RH}^2) + (1.22874 \times 10^{-3})(T_f^2)(\mathrm{RH}) + (8.5282 \times 10^{-4})(T_f)(\mathrm{RH}^2) - (1.99 \times 10^{-6})(T_f^2)(\mathrm{RH}^2)$ where T_f is the air temperature [°F] and RH is the relative humidity (expressed as a whole number)
Humidex	Humidex	$\mathrm{Humidex} = (\text{air temperature}) + h$ $h = (0.5555)(e - 10.0)$ $e = 6.11 \times \exp^{\left(5417.7530 \times \left(\left(\frac{1}{273.16}\right) - \left(\frac{1}{\text{dewpoint}}\right)\right)\right)}$
Net effective temperature	NET	$\mathrm{NET} = 37 - \frac{37 - T}{0.68 - 0.0014(\mathrm{RH}) + 1/(1.76 + 1.4v^{0.75})} - 0.29T(1 - 0.01(\mathrm{RH}))$ where T is the air temperature [°C], v is the wind speed [m/s], and RH is the relative humidity [%]
Wet-bulb globe temperature	WBGT	$\mathrm{WBGT} = 0.567 \times T_a + 0.393 \times e + 3.94$ where T_a is the air temperature (°C) and e is the water-vapour pressure (hPa)
Apparent temperature	AT	$\mathrm{AT} = T_a + 0.348 \times e - 0.70 \times \mathrm{ws} + 0.70 \times \frac{Q}{\mathrm{ws} + 10} - 4.25$ $\mathrm{AT} = T_a + 0.33 \times e - 0.70 \times \mathrm{ws} - 4.00$ where T_a is the dry-bulb temperature (°C), e is the water-vapour pressure (hPa), ws is the wind speed (m/s) at an elevation of 10 m, and Q is the net radiation absorbed per unit area of body surface (W/m^2)
Excess heat index	EHI	$\mathrm{EHI} = \frac{T_i + T_{i+1} + T_{i+2}}{3} - T_{95}$ where T_{95} is the 95th percentile of daily temperature (T_i) for a climate reference period, calculated using all days of the year

results from the balance of sensible and latent heat fluxes at the skin surface plus the respiratory component. Among the most used heat-budget-based indices, there are:

- Standard Effective Temperature (SET*), the equivalent temperature of an isothermal environment at 50% of humidity where the subject presents the same heat stress (i.e. skin temperature) and thermoregulatory strain (i.e. skin wettedness) as the actual environment; for the SET* computation, the human physiology model is the Pierce "two-node" model [17]. The same index is further adapted for the outdoors (OUT_SET*) [58],
- Predicted Mean Vote (PMV), perceived thermal sensation computed assuming that it depends on the physiological strain imposed to the human body by the surrounding environment;
- Physiological Equivalent Temperature (PET), the equivalent temperature of an isothermal reference environment characterized by a water-vapour pressure of 12 hPa and a light air of 0.1 m/s where the core and the skin temperature of a reference person are the same of the conditions to be assessed;
- Universal Thermal Climate Index (UTCI) [29], the equivalent temperature associated with a strain index representing the synergistic behaviour of core temperature, skin wettedness, blood flow, and sweat rate. This index resulted from the multidisciplinary cooperation of scientists from 22 countries.

3 The Scales of Human Adaptation

Despite the classification of adaptation strategies in autonomous or planned, they can also be differentiated among their different spatial scales [67]. Then, in this section, adaptation actions triggered by overheating will be explored on different scales, namely human, building, and city scales.

3.1 Human Scale

Bringing the general definition of adaptation to the human scale, it is the individual's ability to adjust to current or expected climate conditions [38]. In this context, human-scale adaptation can be physiological or behavioural. Both are autonomous adaptation types [70]; the previous associated with the energy balance of the body and its thermoregulatory systems, while the latter mainly related to individual exposure limitation.

Physiological adaptation is related to human acclimatization. According to IPCC [26], it is defined as the adjustment of functional or morphological characteristics that allow the body to adapt to new climatic conditions. These adjustments can occur once or seasonally and enable human performance maintenance under different environmental conditions [25]. It could take several years to get completely acclimatized to unfamiliar thermal environment (long-term adaptation). This process results in a lower rise in core temperature and a lower increase in heart rate at a given heat load. The main physiological responses to heat adaptation consist of "an earlier onset and higher rate of skin blood flow; an increased sweat rate with earlier onset and more dilute concentration of sweat; decreased electrolyte loss and greater resistance to dehydration; a decrease in basal metabolic rate and heart rate; a decrease in perceived exertion; and a decrease in oxygen consumption at a given activity level or metabolic rate" [10]. Physiological adaptation is one of the main reasons why same temperatures generate different health outcomes in different population. Indeed, these impacts are more related to the heat wave event duration, the local climate, and thus the acclimatization status of the population than to the magnitude of experienced temperature.

However, the physiological adaptation capability of a human body varies throughout life. Children [86] and elderly people [45] are more sensitive to heat than adults due to their different physiological characteristics. Elderly have reduced thermoregulatory responses (e.g. sweating rate, cardiovascular function, etc.) compared to young adults. Chronic diseases and the use of some medications can also limit acclimatization [23]. Moreover, it is still unknown to what extent physiological adaptation can mitigate the heat effects on health [24]. For this reason, it is impossible that human autonomous adaptation relies only on the physiological aspect.

Behavioural adaptation is related to changes in actions that people take to adapt [22]. Some examples of behavioural adaptations related to higher ambient temperature are wearing lighter clothes, reducing physical activity, going to a colder place outdoors (e.g. parks), opening windows, closing blinds or shades, and using air conditioning systems [69]. Behaviours usually complement the physiological adaptation to enlarge human thermal tolerance [23]. Furthermore, social mechanisms recognized in specific behavioural factors are the result of a long-term community adaptation. Adapting behaviours more specifically associated with cultural backgrounds of a community include the time spent in outdoors or local-specific working schedule (e.g. the siesta in southern Europe). As for the adaptation physiological capability, specific categories can be recognized as more vulnerable to overheating risk due to lack in their behavioural adaptation opportunities. For instance, either age extremes or cognitively impaired people generally rely upon others for an adequate liquid intake, and thus, these population are more prone to dehydration. Dehydration slows sweating rate and causes cardiac outputs becoming a common cause of hyperthermia and death [20].

3.2 Building Scale

Urban overheating will increase the air temperature and hours of discomfort in indoor environments, especially the non-conditioned ones [21]. Whenever active systems are at disposal, it will cause growth in cooling energy consumption of buildings and it will raise the peak in electricity demand [70]. These effects are highly correlated to individual building characteristics [43]. Therefore, the climate change adaptation process at the building scale concerns all those solutions thought to limit the consequences of overheating indoors. Their benefits are mostly evaluated in terms of thermal comfort improvements, indoor air temperature or superficial temperature reduction, and cooling loads decrease.

Many solutions of adaptation at building scale involve passive strategies to decrease the use of cooling systems while limiting the overheating risks for occupants. As the thermal comfort indoors is affected by the thermo-physical properties of the building envelope [47], building adaptation has a close relation to the development and implementation of new materials and techniques for the building envelope. Under hot conditions, the envelope needs to have low solar absorptance [79]. In this context, the application of cool materials is a good example of adaptation strategy at the building scale. These materials have properties that reduce solar energy gains and increase the longwave radiative heat dissipation leading to lower surface temperatures [34]. Cool clay tiles [62], cool roof membranes, and cool façade painting [61] are options that have already been demonstrated to contribute to reducing the indoor air temperature in the hot season. Figure 1 presents an example of the use of cool membranes and cool painting.

Fig. 1 Original prototype building (**a**) and implementation of a cool membrane (**b**) and cool painting (**c**, **d**) [61]

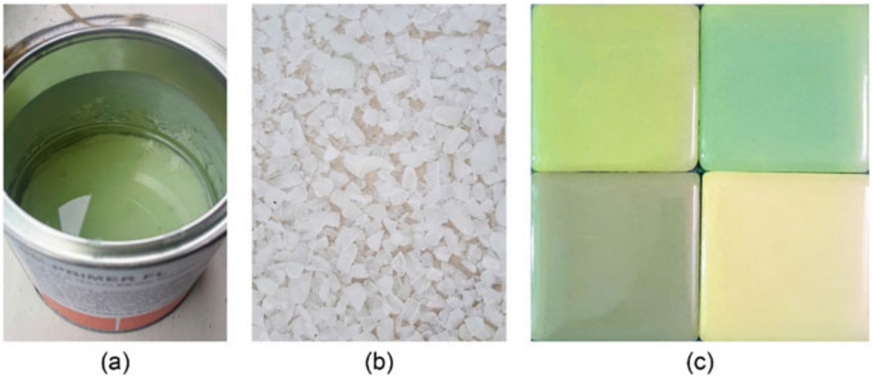

Fig. 2 Photoluminescent paint (**a**), grit (**b**), and tiles (**c**) [7]

Cool roof solutions can be improved by thermochromic roof as proposed by Fabiani et al. [16]. Thermochromic materials can alter their optical properties when the temperature reaches a determined value, and the results of the study showed that thermochromic roof is still capable of significantly reducing cooling loads while limiting winter penalties that are typical of cool finishing solutions, e.g. not raising the heating load during winter [34].

In the same context, photoluminescent materials are presented as an innovative solution to be implemented in the built environment with cooling potential. Photoluminescent materials absorb energy and re-emit it as visible light instead of longwave radiation [32]. Figure 2 presents some examples of photoluminescent materials. Chiatti et al. [7] presented a characterization of photoluminescent paints concerning their thermal emissivity and solar reflectance and found that they have good performance as cool materials. Rosso et al. [68] presented a study of applying photoluminescent paint as an external envelope finishing layer. They demonstrated that this solution can reduce indoor temperature because of its high solar reflectance.

Additionally, incorporating different phase change materials (PCMs) in building elements is a topic that has been gaining attention in terms of improving building thermal performance. PCMs absorb and release a large amount of latent heat during their phase transition [37]. This technology is useful in cold climates, but other investigations also revealed a high potential in reducing indoor temperature and peak cooling loads [4, 64, 77].

Green roofs [8] and façades [88] are also adaptation strategies that have proven to be very effective in keeping the internal temperature lower in hot conditions. The main effect of these green elements on enhancing indoor thermal comfort is by reducing the heat transfer to the building [8].

There are also adaptation strategies related to glazing. In hot conditions, glazing solutions should have a low solar heat gain coefficient, which according to [13] is the most important factor for reducing cooling loads. Examples of glasses that have been shown to maintain lower indoor air temperatures are double glazing and low-e (low emissive) coating [76].

Another passive adaptation option is shading, which avoids or reduces the amount of incoming solar radiation and that can be achieved, among others, through building's geometrical elements, vegetation, and blinds [79]. Some studies have already shown the main benefits associated with the shading systems in reducing indoor or superficial temperature [15, 41]. Shading strategies are often related to glazing because it was already demonstrated that shading could compensate for the low thermal performance of some glasses [36].

Several investigations on these passive strategies have already shown their benefits for improving the indoor environment under overheating conditions. However, the effectiveness of human adaptation at building scale may depend on the building typology and architecture and on the local climate. For this reason, simulation tools are important in choosing the best strategy since the design stage in order by testing one or combinations of different solutions and assessing their efficiency. Furthermore, given the projections in climate change, the simulation tool allows to assess the overheating adaptation efficacy of specific solutions even under future climate conditions [21].

Finally, it is worth noting that sometimes the passive solutions are not sufficient to maintain adequate thermal comfort levels, and in these cases, cooling systems are needed and their usage still belongs to human overheating adaptation solutions. The use of more efficient heat exchangers and compressors, more advanced fan motors, and appropriate control systems are the main factors on which the energy efficiency of cooling systems depends [72]. However, more efficient systems must be combined with actions to mitigate urban overheating and the implementation of buildings' passive solutions to compensate for the expressive increase in cooling energy demand that will be faced in the next years due to climate changes [72].

3.3 City Scale

Urban overheating is provoking a significant increase in energy consumption for cooling and peak energy demand, in addition to its negative effects on people's vulnerability level and the raised heat-related mortality and morbidity [70]. To minimize these consequences, efficient urban adaptation strategies need to be developed and implemented [73].

The urban green infrastructure has already proven to be a good alternative to mitigate urban heat [21, 53, 85]. The urban green infrastructure is the combination of planned and unplanned green areas and includes, for example, native vegetation, parks, street trees, green roofs, and green walls [53]. It cools the urban environments through evapotranspiration and shading, and the climatic factors, design, and plant selection affect its cooling efficiency [63]. Regarding parks, their size influence not only their cooling potential inside the park but also the outside effects [85].

In the same context, some studies have been investigating the effects of waterbodies to minimize urban heat. The main process by which water contributes to reducing urban heat is evapotranspiration [82]. Its cooling potential is influenced by the waterbody area and shape index and the land-use characteristics in the surrounding [89]. Recently, the combining effects of green infrastructure and waterbodies are also being studied, evaluating their mutual environmental results in counteracting urban overheating [9, 19, 87] and attesting their social and health benefits [31].

From the material point of view, academia and industry are studying and developing different solutions capable of reducing the negative impacts of urban overheating [34]. They can be evaluated considering their capacity to reduce the air temperature and the surface temperature.

Doulos et al. [12] compared several materials in terms of their thermal properties. They concluded that "cold" materials are the ones with a smooth and light-coloured surface made of marble, mosaic, and stone, while "warm" materials have a rough and dark-coloured surface made of pebble, pave stone, and asphalt. Other studies also found that increasing the surfaces (pavements, roofs, and/or walls) albedo can considerably reduce the air temperature [49, 80].

In fact, many adaptation measures developed for buildings (Sect. 3.2) have presented benefits also in the outdoor environment, such as cool roofs [40], thermochromic roofs [16], and photoluminescent materials [7]. If these materials are implemented on a large scale in buildings, they could help on minimizing the overheating effects in the urban environments besides contributing to keeping the indoor temperature lower.

Some adaptation strategies are also developed for being implemented in pavements. Permeable pavements, for example, can minimize urban overheating effects through evaporative cooling [81]. Santamouris [71] showed that white pavements, which have a higher albedo than dark surfaces, have a significantly lower surface temperature than asphalt. Kousis et al. [32] proposed a solution for concrete pavements with photoluminescent aggregates (Fig. 2b) to improve their reflectivity against surface overheating. They concluded that this pavement maintained lower superficial temperatures (up to 3.3 °C) than the reference (cool concrete).

The heterogeneity of the urban environment gives rise to variations on microclimatic conditions on a micro-scale (hyperlocal), and these differences should be investigated so that personalized and site-specific interventions can be proposed for each situation [59]. Then, the adaptation process on a city scale should involve microclimatic monitoring. The most used techniques used to map urban microclimate are remote sensing using satellite data [2], fixed weather station network [65], mobile transects equipped on dedicated vehicles [33], and, more recently, wearable devices able to monitor physical parameters from a pedestrian point of view [59, 60]. Each technique has its pros and cons, but, ideally, they should be combined to get a granular perspective of the microclimate on a large scale. Regardless of the method adopted, urban microclimate monitoring is important when choosing the best adaptation strategy for each specific case.

4 Conclusions

The climate change is recognized as an on-going process, mostly influenced by anthropogenic activities. The observed global warming suggests that we must put in place effective mitigation strategies, to slow down the process by reducing the anthropogenic impact, along with adaptation strategies. Humans need to enhance their capabilities of adapting to the changing climate and to enhance their resilience to extreme weather events (including heat waves) that are going to become more frequent and intense in the coming future. In this framework, overheating risk is a major concern for the global population that mainly live in urbanized areas, places already affected by the Urban Heat Island phenomenon. A hyperlocal assessment of the overheating risk is needed for planning effective adaptation and mitigation strategies, capable of addressing site-specific criticalities and local communities' vulnerabilities.

Moving from an overview of the current and the expected overheating risks, specifically focussing on the synergistic effect of HWs and UHI in terms of human health detriment, adaptation strategies have been presented, grouped according to their scale of application and impact in three categories, as follows: human-, building-, and city-scale adaptation strategies.

Adaptation at human scale involves individuals' capabilities of adapting to the changing climate by reducing their vulnerability and limiting their exposure to heat. Two main mechanisms are identified: physiological and behavioural adjustment. The human body has a thermoregulatory system that allows to keep almost constant its own core temperature reducing the heat stress. The physiological adjustment is observed on both the short and the long term. The latter guarantees the human body performance under different environmental conditions: it could take years to get acclimatized to unfamiliar thermal environment. Nevertheless, physiological adaptation can be compromised due to ageing or health status and cannot mitigate the heat-health outcomes completely. Behavioural adjustment procedures are generally put in place to limit the individual exposure to heat, being generally adapted to the cultural background and thus also related to local climate conditions (e.g. spending the hottest hours indoors, drinking water, adjust clothing insulation, etc.).

Adaptation strategies at the building scale mainly aim at enhancing indoor thermal conditions. Active and passive solutions are both considered adaptation practices but in the view of limiting anthropogenic contribution to climate change (mitigation actions), passive solutions are preferable and the main purpose of enhancing indoor thermal comfort must be combined to the aim of minimizing building energy consumptions. The most effective solutions for the building envelope belong to the broad category of "cool materials" characterized by specific radiative and optical properties which limit the warming-up process during day-time and the re-emitting energy component during night-time (e.g. cool paintings, thermochromic, photoluminescent, PCMs, etc.). Other constructive elements that contribute to reducing building internal heat loads include green roofs and green facades. A main component of the greenery mitigation potential concerns the evapotranspiration and so the increment of the latent component within the element energy budget with respect to the sensitive one.

Green and blue infrastructures are among the most effective overheating adaptation solutions at the urban scale. Cities are particularly critical areas due to a general lack of greenery and permeable surfaces and their complex morphology that limits the wind field and thus advection cooling process. A proper design of public spaces and parks, accounting for cool and permeable pavements and green and blue elements, could provide overheating mitigation not limited to the area of intervention but extended to its surroundings. Furthermore, urban microclimate would benefit from the large-scale application of the building-scale adaptation solutions.

In a warming world, it is fundamental to enhance humans' adaptation capability, especially given the well-stated relation between urban overheating and heat-related mortality and morbidity. Coordinated adaptation strategies in all scales are urgent to cope with the climate change harmful impacts by reducing the associated risks and vulnerability. Each strategy should be evaluated in terms of its local benefits, even if the particularities and complexities of urban environments hinder this process. However, to avoid worse consequences and guarantee sustained societal functioning in this progressively hotter climate, these adaptation actions need to be implemented now.

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